Risk Analysis of Ground Water Contamination Detection Networks, Using Stochastic Modeling and Decision Theory

PhD Thesis submitted by

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to Argyro and to Aella

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TABLE OF CONTENTS

Table of Figures

Table of Tables

SUMMARY

Groundwater is an important freshwater natural resource. People used to believe that natural filtering resulting from water working its way through the subsurface was enough to provide sufficient protection from contamination to allow untreated water to be delivered for domestic or agricultural uses. Then dramatic incidents in the 70s (e.g. Love Canal case) made everybody realize that groundwater had been contaminated from hundreds of thousands of leaking underground storage tanks, industrial waste pits, home septic systems, municipal and industrial landfills, accidental chemical spills, careless use of solvents, illegal dumping, as well as widespread use of agricultural chemicals. Groundwater contamination became the environmental issue of the 80s.

Once contaminated, groundwater is difficult to restore. Restoration of groundwater contaminated by releases of anthropogenic chemicals to a condition allowing for unrestricted use and unlimited exposure remains a significant technical and institutional challenge. Moreover, one dominant attribute on subsurface remediation efforts has been lengthy delays between discovery of the problem and its solution. Some reasons for these extended timeframes are ineffective subsurface investigations, difficulties in characterizing the nature and extent of the problem in highly heterogeneous subsurface environments, remedial technologies, and a variety of administrative, policy and political factors.

It is evident that, in order to control groundwater contamination by means of immediate alert and minimize remediation cost, an alarm system is required to constantly monitor subsoil water quality. A reliable and efficient monitoring system design is of great importance to the overall design of a facility that may pose a groundwater pollution threat. In the case of monitoring groundwater contamination pollution detection for sanitary landfills, EU regulations commonly require one background (upstream) well and two downgradient wells. The position, number (more than the minimum requirement) and depth of the monitoring wells are proposed by the facility's operator and/or by local authorities. In most cases, a quarterly sampling is undertaken.

Subsurface water pollution due to landfill leaks has become an important issue during the last three decades. While sanitary landfills constitute the most widely used management approach for the disposal of solid waste because of their simplicity and cost effectiveness, historical records indicate that landfills exhibit a high failure rate in terms of groundwater contamination. Subsurface heterogeneity and lack of information about the exact location and duration of a leak render it extremely difficult to predict and detect subsurface water pollution before it has already spread and become evident. Monitoring aquifer contamination via wells is influenced by many uncertain factors, where the heterogeneity of the geologic environment, the quantity and nature of the contaminants, the number and location of the monitoring wells, and the frequency of sampling are factors affecting successful detection. However, there is no recognition of uncertainty factors in regulations.

Successful detection of an underground pollutant transported into an aquifer is directly dependent on the possibility of calculating the movement and dispersion of the pollutant in an environment, about which very few things are actually known. This lack of information is caused by the difficulties of experimentally measuring, at any of its points, the various hydraulic properties of a geological field (hydraulic conductivity, hydraulic head, porosity etc.) so as to predict, or even approximate, the way a plume can propagate into the aquifer. Additional uncertainty factors of the problem are lack of information about the point from which pollution originates in a landfill waste, the duration of the leak and the extent of the plume, typically dependent on the nature of the polluting substance. Thus, it is impossible to know with certainty how the pollutant concentrations in the subsoil change, which means that we cannot directly predict the likelihood of successful detection of groundwater pollution into heterogeneous aquifers from a specific arrangement of monitoring wells.

In the present thesis a stochastic two-dimensional numerical model was developed and utilized to address the problem of evaluating the effectiveness of contaminant detection in heterogeneous aquifers by linear arrangements of monitoring wells. Although it can be said that the two-dimensional approach is not the most realistic description of the actual situation, it actually simplifies the computational problem, losing only the vertical information about the movement and the detection of plumes. Moreover, when the horizontal dimensions of an aquifer are much greater than its thickness, which is our case, then the results of two dimensions provide a good approximation of reality. In numerical experiments based on the Monte Carlo framework, geological heterogeneity was simulated by the Spectral Turning Bands method and groundwater pollution transportation and dispersion was simulated by the Random Walk Tracking Particle method. Simulations were conducted to determine the detection probabilities and areas of groundwater contamination assuming different levels of geologic heterogeneity as well as pollutant dispersion, and to evaluate the effectiveness of various monitoring wells sampling frequencies. Two different cases were examined, as far as duration of pollution is concerned, assuming instantaneous and precipitation triggered pollution, where pollution diffuses into the aquifer proportionally to rain height during the monitoring period of time.

This work introduces a new perspective for the correction of risk analysis. Contemporary risk analysis considers the cost of alternative remediation procedures by assuming that the contamination area to be remediated coincides with the area calculated at the time of detection. However, there is always a considerable lag between the time that a plume is detected and the time when remediation commences. This time lag constitutes a random variable that depends on available resources and technologies, as well as efficiency of administrative decision-making. A new risk analysis framework is proposed that corrects estimated costs due to remediation delays.

Initially, the objective of this work was to numerically estimate in two dimensions the probability of groundwater pollution detection, originating instantly from a point source inside the physical boundaries of a landfill cell, achieved by a linear arrangement of varying number monitoring wells. The monitoring installation was considered in different cases to be located in various distances from the landfill facility and perpendicular to the flow field. Sensitivity analysis was performed to define what is the minimum number of Monte Carlo realizations where stochastically calculated detection probability is stabilized. Results were compared with theoretical values that were analytically calculated in the case of a homogeneous field. Having determined a high resolution simulation scheme, the distances of monitoring wells from the landfill cell trailing edge were examined in order to define, for every hydro-geological case simulated, the maximum detection probability a monitoring setting may achieve.

Probabilities of detection and contaminated groundwater areas were calculated for different arrangements of monitoring wells. It was shown that detection decreased as heterogeneity increased. Monitoring with 20 wells provided high detection, while 3 wells resulted in four out of five contamination cases remaining undetected. For fixed heterogeneity, for each well arrangement, detection probability increased up to a certain value, with increasing transverse dispersion coefficient, and then it decreased. The impact of sampling frequency of wells on groundwater contamination detection was studied. The frequency of sampling was a critical factor in heterogeneous aquifers. It appeared that a minimum sampling should take place twice a year, with the monthly sampling being the optimum choice, considering the effort involved and the improvement in detection. In heterogeneous aquifers a large number of monitoring wells sampled infrequently did not perform better in terms of detection than a lower number of wells sampled regularly. Finally, remediation action delay time was introduced as an expression that accounted for the delay between detection and remedial action, in order to provide a correction to decision analysis that evaluated the economic worth of well monitoring. This expression illustrated the fact that delays longer than 3 years were equivalent to reducing the economic performance of 12 wells to that of a lower number of wells, meaning that higher failure costs should be considered than those assumed in current risk analysis.

Afterwards, high-resolution numerical Monte Carlo realizations were utilized to study the impact of sampling frequency on detection probability at contaminated sites located in heterogeneous subsurface environments, in conjunction with different hydro-geological parameters. For all types of soils detection probability was seen to decrease as sampling became less frequent. Irrespective of the density of a monitoring network at highly dispersive subsurface environments, a very rigorous sampling schedule had to be maintained in order to retain the detection performance of the network. Highly heterogeneous soils through the presence of low permeability zones appeared to impede the spread of the contaminants and, hence, restrict the effects of dispersion. Analysis of the time lag, between the time that contaminants first appeared at monitoring locations and the time they were actually observed, as well as of the increase of the plume area that resulted from this time lag, led to the conclusion that monthly sampling was required for a wide range of hydro-geological environments. Moreover, sampling frequency impact on remedial action delay was studied. It was demonstrated that in highly dispersive environments the remediation response must be of the order of a few months if one does not wish the contaminated areas and remediation costs to grow significantly.

Then, it was numerically studied how the number of point pollution sources, the size of the controlled area (landfill) and the quantity of an instantaneous aquifer injection pollution event affected detection probability by a linear monitoring well arrangement. For this purpose a two-dimensional high resolution Monte Carlo stochastic model was utilized. In each examined parameter it was considered that the rest of the factors affecting detection probability estimation remained constant. Simulations were performed in the context of uncertainty factors deriving from the environment itself, where the pollution was propagating, and the lack of information about certain parameters, concerning the initial conditions of the leak.

It was numerically verified in the cases examined that as the size of the control area became larger, while the number of wells remained constant, detection probability decreased. Consequently, if the width of a control area was increased, so should the number of monitoring wells, so that the same well density would be maintained. In all simulated cases, the general observation was that when two similar groundwater pollution sources were present, then contamination detection was easier as the average detection probability increased between 35% – 55%. The same trend in detection probability increase relative to single source cases was observed, regardless of the sampling frequency.

The simulation results indicated that when the initial concentration of pollution was below 1,000 mgr/lt, its detection was very hard, regardless of the aquifer's hydro-geological parameters. The efficiency of monitoring wells in low to medium dispersion aquifers reached a maximum, which was independent of the initial mass of pollution intruding the aquifer. The turning point of the concentration of the initial pollution was $C = 8,000 mgr / lt$, which was the value where detection probability reached a plateau. It was also observed that only in high dispersion environments increase of pollution resulted in higher detection probability. In every case lower concentrations were harder to be detected, dictating that in order for monitoring setting to be sensitive at least simulation level, even in small amounts of pollution, a minimum of 12 wells must be used.

Finally, considering a different way groundwater pollution in the context of triggering it according to local precipitation events, it was assumed that there was a point pollution source inside a controlled area of specific dimensions (landfill, industrial installation, military base), which injected a quantity of pollutant inside the aquifer, each time rain occurred. The quantity of the pollutant that diffused into groundwater was considered linearly proportional to the recorded daily average precipitation height. Data from a thirty-year time series of daily average rainfall from Macedonia airport was used and linearly coupled with the pollutant mass diffused directly into the aquifer, assuming that no recharge occurred. The two-dimensional area was downstream monitored by a linear arrangement of wells network, consisting of different numbers of drilling wells in each studied case. The ability of the monitoring installation was evaluated through the probability of successful pollution detection. The effects on successful pollution detection of the aquifer's hydro-geological parameters, as they were reflected in the field's hydraulic conductivity variance and dispersion coefficients, have been studied too. Moreover, the influences of the aquifer sampling frequency and of the remedial actions delay time were examined into detection probability that a monitoring wells arrangement can achieve. Results were directly compared to those of instantaneous pollution simulated cases, considering the rest of the computational parameters common.

It was shown that detection probability of a monitoring arrangement increased faster, as the number of wells increased, in precipitation related pollution than in instantaneous cases. In all simulations the main hydro-geological parameter affecting detection probability, average detection time and average contaminated area, was the dispersion of the field. In the case of precipitation triggered heterogeneous aquifer pollution, sampling frequency practically did not seem to affect detection probability of the monitoring network. In any simulated case, remedial action delay time was essential in estimating the risk concerning the detection ability of a groundwater monitoring installation, as it was a hidden parameter that might give a very big offset in risk calculation.

ΠΕΡΙΛΗΨΗ

Τα υπόγεια νερά αποτελούν σημαντική φυσική πηγή πόσιμου νερού. Οι άνθρωποι παλιά πίστευαν ότι το φυσικό φιλτράρισμα του νερού ως αποτέλεσμα της υπόγειας ροής του ήταν αρκετό για να παρέχει ικανή προστασία από μολύνσεις, έτσι ώστε χωρίς καμία επεξεργασία το νερό να μπορεί να διατεθεί για οικιακή και αγροτική χρήση. Τότε, δραματικά γεγονότα τη δεκαετία του 1970 (π.χ. η περίπτωση του Love Canal) έκαναν τους πάντες να συνειδητοποιήσουν ότι τα υπόγεια νερά είχαν μολυνθεί από εκατοντάδες χιλιάδες υπόγειες δεξαμενές αποθήκευσης που είχαν διαρροές, δεξαμενές βιομηχανικών αποβλήτων, οικιακά σηπτικά συστήματα, αστικούς και βιομηχανικούς χώρους ταφής απορριμμάτων, τυχαίες χημικές διαρροές, απρόσεκτη χρήση διαλυτών, παράνομη απόρριψη αποβλήτων, καθώς επίσης και από εκτεταμένη χρήση γεωργικών χημικών. Η μόλυνση των υπογείων υδάτων έγινε το σημαντικότερο περιβαλλοντικό ζήτημα της δεκαετίας του 1980.

Από τη στιγμή που θα μολυνθούν τα υπόγεια ύδατα, είναι δύσκολο να αποκατασταθούν. Η αποκατάσταση των υπογείων υδάτων που έχουν μολυνθεί από διάθεση ανθρωπογενών χημικών, σε τέτοιο βαθμό ώστε να επιτρέπεται η απεριόριστη χρήση αυτών των υδάτων και η έκθεση σ’ αυτά, παραμένει σημαντική τεχνική και θεσμική πρόκληση. Επιπλέον, ένα κυρίαρχο χαρακτηριστικό των προσπαθειών υπόγειας αποκατάστασης υδάτων αποτελούν οι χρονοβόρες καθυστερήσεις από τη στιγμή της ανακάλυψης του προβλήματος ως την επίλυσή του. Ορισμένες αιτίες γι’ αυτά τα εκτεταμένα χρονοδιαγράμματα περιλαμβάνουν τις αναποτελεσματικές υπόγειες έρευνες, τις δυσκολίες χαρακτηρισμού της φύσης και του μεγέθους του προβλήματος σε πολύ ετερογενή υπόγεια περιβάλλοντα, τις τεχνολογίες αποκατάστασης και μία πλειάδα διοικητικών, στρατηγικών και πολιτικών παραγόντων.

Είναι εμφανές ότι, για να ελεγχθεί η μόλυνση των υπογείων υδάτων μέσω ενός συστήματος άμεσης ειδοποίησης και να ελαχιστοποιηθεί το κόστος αποκατάστασης, απαιτείται ένα σύστημα συναγερμού που θα παρακολουθεί σε σταθερή βάση την ποιότητα των υπογείων υδάτων. Ο σχεδιασμός ενός αξιόπιστου και αποτελεσματικού συστήματος παρακολούθησης είναι εξαιρετικά σημαντικός για τον συνολικό σχεδιασμό μιας

εγκατάστασης που ίσως δημιουργήσει απειλή μόλυνσης σε υπόγεια ύδατα. Στην περίπτωση παρακολούθησης της ανίχνευσης μόλυνσης υπογείων υδάτων για χώρους υγειονομικής ταφής απορριμμάτων, οι κανονισμοί της Ε.Ε. συνήθως απαιτούν ένα πηγάδι υποβάθρου (ανάντη) και δύο πηγάδια κατάντη. Η θέση, ο αριθμός (πέραν της ελάχιστης απαίτησης) και το βάθος των πηγαδιών ελέγχου καθορίζονται από τον διαχειριστή της εγκατάστασης και/ή από τις τοπικές αρχές. Στις περισσότερες περιπτώσεις, διενεργείται τριμηνιαία δειγματοληψία.

Η υπόγεια ρύπανση υδάτων λόγω διαρροών σε χώρους ταφής απορριμμάτων αποτελεί ένα σημαντικό θέμα τις τρεις τελευταίες δεκαετίες. Ενώ οι χώροι υγειονομικής ταφής απορριμμάτων αποτελούν την πιο διαδεδομένη προσέγγιση διαχείρισης της τελικής διάθεσης στερεών αποβλήτων εξαιτίας της απλότητας στην κατασκευή και του χαμηλού κόστους λειτουργίας, τα ιστορικά δεδομένα μας δείχνουν ότι οι χώροι αυτοί παρουσιάζουν υψηλό βαθμό αστοχίας όσον αφορά στη μόλυνση υπογείων υδάτων. Η ετερογένεια του υπεδάφους και η έλλειψη πληροφορίας σχετικά με την ακριβή θέση και διάρκεια μιας διαρροής καθιστούν εξαιρετικά δύσκολη την πρόβλεψη και ανίχνευση υπόγειας μόλυνσης του νερού πριν αυτή εξαπλωθεί και γίνει εμφανής. Η παρακολούθηση της μόλυνσης του υδροφόρου ορίζοντα μέσω πηγαδιών ελέγχου επηρεάζεται από πολλούς παράγοντες αβεβαιότητας, όπως την ετερογένεια του γεωλογικού περιβάλλοντος, την ποσότητα και τη φύση των μολυσματικών ουσιών, τον αριθμό και τη θέση των πηγαδιών ελέγχου και τη συχνότητα δειγματοληψίας. Παρ’ όλα αυτά, δεν υπάρχει αναγνώριση των παραγόντων αβεβαιότητας σε θεσμικό επίπεδο.

Η επιτυχής ανίχνευση μιας μόλυνσης των υπογείων νερών που μεταφέρεται στον υδροφόρο ορίζοντα εξαρτάται άμεσα από την πιθανότητα υπολογισμού της κίνησης και της διασποράς του μολυσματικού παράγοντα στο περιβάλλον, κάτι για το οποίο ουσιαστικά πολύ λίγα πράγματα γνωρίζουμε. Αυτή η έλλειψη πληροφοριών προκαλείται από τις δυσκολίες πειραματικών μετρήσεων, σε οποιοδήποτε από τα σημεία του, των διαφόρων υδραυλικών ιδιοτήτων ενός γεωλογικού πεδίου (υδραυλική αγωγιμότητα, υδραυλικό μέτωπο, διαπερατότητα κτλ) για να προβλέψουμε, ή έστω να προσεγγίσουμε, τον τρόπο με τον οποίο ένα πλούμιο μπορεί να διαδοθεί στον υδροφόρο ορίζοντα. Επιπρόσθετοι παράγοντες αβεβαιότητας του προβλήματος είναι η έλλειψη πληροφοριών σχετικά με το σημείο από το οποίο ξεκινά η μόλυνση σε έναν χώρο ταφής απορριμμάτων, η διάρκεια της διαρροής και η έκταση του πλουμίου, τα οποία συνήθως εξαρτώνται από τη φύση του ρυπαντή. Κατά συνέπεια, είναι αδύνατο να ξέρουμε με βεβαιότητα πώς μεταβάλλονται οι συγκεντρώσεις του ρυπαντή στο υπέδαφος, κάτι που σημαίνει ότι δεν μπορούμε άμεσα να προβλέψουμε την πιθανότητα επιτυχούς ανίχνευσης μόλυνσης υπογείων υδάτων μέσα σε ετερογενείς υδροφόρους ορίζοντες από μία συγκεκριμένη διάταξη πηγαδιών ελέγχου.

Στην παρούσα διατριβή αναπτύχθηκε και χρησιμοποιήθηκε ένα στοχαστικό δισδιάστατο αριθμητικό μοντέλο για να αντιμετωπιστεί το πρόβλημα αξιολόγησης της αποτελεσματικότητας της ανίχνευσης υπόγειας ρύπανσης σε ετερογενείς υδροφόρους ορίζοντες μέσω γραμμικών διατάξεων πηγαδιών παρακολούθησης. Παρόλο που μπορεί να υποστηριχθεί ότι η δισδιάστατη προσέγγιση δεν είναι και η πιο ρεαλιστική περιγραφή της πραγματικής κατάστασης, στην ουσία απλοποιεί το υπολογιστικό πρόβλημα γιατί χάνει μόνο την κάθετη πληροφορία σχετικά με την κίνηση και την ανίχνευση των πλουμίων. Επιπλέον, όταν οι οριζόντιες διαστάσεις ενός υδροφόρου ορίζοντα υπερβαίνουν κατά πολύ το πάχος του, όπως στην περίπτωσή μας, τότε τα αποτελέσματα στις δύο διαστάσεις παρέχουν μία καλή προσέγγιση της πραγματικότητας. Στα αριθμητικά πειράματα που βασίζονται στην τεχνική Monte Carlo, η γεωλογική ετερογένεια προσομοιώθηκε με τη μέθοδο Spectral Turning Bands και η υπόγεια μεταφορά και διασπορά της ρύπανσης με τη μέθοδο Random Walk Tracking Particle. Οι προσομοιώσεις διεξήχθησαν για να προσδιοριστούν οι πιθανότητες ανίχνευσης και οι περιοχές μόλυνσης υπογείων υδάτων, προϋποθέτοντας διαφορετικά επίπεδα γεωλογικής ετερογένειας και διασποράς ρυπαντή, και να εκτιμηθεί η αποτελεσματικότητα διαφόρων συχνοτήτων δειγματοληψίας πηγαδιών παρακολούθησης. Δύο διαφορετικές περιπτώσεις εξετάστηκαν, όσον αφορά στη διάρκεια της ρύπανσης, υποθέτοντας στιγμιαία ρύπανση και ρύπανση λόγω βροχόπτωσης, όπου η ρύπανση διαχέεται στον υδροφόρο ορίζοντα κατ' αναλογία με το ύψος βροχόπτωσης την περίοδο παρακολούθησης.

Η παρούσα εργασία αναπτύσσει μία νέα οπτική για τη διόρθωση της ανάλυσης ρίσκου. Η σύγχρονη ανάλυση ρίσκου εξετάζει το κόστος εναλλακτικών διαδικασιών αποκατάστασης προϋποθέτοντας ότι η μολυσμένη περιοχή προς αποκατάσταση συμπίπτει με την περιοχή που υπολογίστηκε τη χρονική περίοδο της ανίχνευσης. Εν τούτοις, υπάρχει πάντοτε μια σημαντική καθυστέρηση μεταξύ της περιόδου που ένα πλούμιο ανιχνευθεί και της περιόδου που θα αρχίσει η αποκατάστασή του. Αυτή η χρονική καθυστέρηση αποτελεί τυχαία μεταβλητή που εξαρτάται από τους διαθέσιμους πόρους και τεχνολογίες, καθώς επίσης και από την αποτελεσματικότητα της διοικητικής λήψης αποφάσεων. Προτείνεται ένα νέο πλαίσιο ανάλυσης ρίσκου που διορθώνει το εκτιμώμενο κόστος λόγω καθυστερήσεων αποκατάστασης.

Αρχικά, ο στόχος της παρούσας εργασίας ήταν ο αριθμητικός υπολογισμός σε δύο διαστάσεις της πιθανότητας ανίχνευσης ρύπανσης υπογείων υδάτων, η οποία ξεκινά στιγμιαία από μία σημειακή πηγή εντός των φυσικών ορίων ενός χώρου απόθεσης απορριμμάτων και επιτυγχάνεται από μία γραμμική διάταξη πηγαδιών παρακολούθησης που αποτελείται κάθε φορά από διαφορετικούς αριθμούς πηγαδιών. Θεωρήθηκε ότι η εγκατάσταση παρακολούθησης, σε διαφορετικές περιπτώσεις, βρίσκεται σε διαφορετικές αποστάσεις από την εγκατάσταση του χώρου απόθεσης απορριμμάτων και κάθετα στο πεδίο ροής. Πραγματοποιήθηκε έλεγχος ευαισθησίας του μοντέλου για να προσδιοριστεί ο ελάχιστος αριθμός επαναλήψεων Monte Carlo όπου η στοχαστικά υπολογιζόμενη πιθανότητα ανίχνευσης σταθεροποιείται. Έγινε σύγκριση των αριθμητικών αποτελεσμάτων με τις θεωρητικές τιμές οι οποίες υπολογίζονται αναλυτικά στην περίπτωση ενός ομογενούς πεδίου. Έχοντας προσδιορίσει ένα υψηλής διακριτότητας σχήμα προσομοιώσεων, οι αποστάσεις των πηγαδιών παρακολούθησης από το χείλος εκφυγής του χώρου απόθεσης απορριμμάτων εξετάστηκαν με σκοπό να προσδιοριστεί, για κάθε υδρο-γεωλογική περίπτωση που προσομοιώθηκε, η μέγιστη πιθανότητα ανίχνευσης που μπορεί να επιτευχθεί από μία διάταξη παρακολούθησης.

Οι πιθανότητες ανίχνευσης και οι μολυσμένες περιοχές των υπογείων υδάτων υπολογίστηκαν για διαφορετικές διατάξεις πηγαδιών παρακολούθησης. Φάνηκε ότι η ανίχνευση μειωνόταν όσο η ετερογένεια αυξανόταν. Η παρακολούθηση με 20 πηγάδια παρείχε υψηλή ανιχνευσιμότητα, ενώ η ανίχνευση με 3 πηγάδια είχε ως αποτέλεσμα τη μη ανίχνευση τεσσάρων στις πέντε περιπτώσεις μόλυνσης. Θεωρώντας σταθερή την ετερογένεια του πεδίου, για κάθε διάταξη πηγαδιών, η πιθανότητα ανίχνευσης αυξήθηκε μέχρι μία συγκεκριμένη τιμή, καθώς αυξανόταν ο συντελεστής εγκάρσιας διασποράς, και μετά μειώθηκε. Μελετήθηκε η επίδραση της συχνότητας δειγματοληψίας των πηγαδιών στην ανίχνευση ρύπανσης υπογείων υδάτων. Η συχνότητα δειγματοληψίας ήταν κρίσιμος παράγοντας σε ετερογενείς υδροφορείς. Φάνηκε ότι η ελάχιστη δειγματοληψία θα έπρεπε να γίνεται δύο φορές ανά έτος, ενώ η μηνιαία δειγματοληψία φάνηκε ως η βέλτιστη λύση λαμβάνοντας υπ’ όψη την απαιτούμενη διαδικασία και τη βελτίωση ανίχνευσης. Σε ετερογενείς υδροφόρους ορίζοντες, μεγάλος αριθμός πηγαδιών παρακολούθησης από τα οποία δεν γινόταν συχνή δειγματοληψία δεν απέδωσαν καλύτερα σε όρους ανίχνευσης απ’ ότι μικρότερος αριθμός πηγαδιών από τα οποία γινόταν τακτική δειγματοληψία. Τέλος, ο χρόνος καθυστέρησης της ενέργειας αποκατάστασης εισήχθη ως έκφραση που αντιπροσώπευε την καθυστέρηση μεταξύ της ανίχνευσης και της ενέργειας αποκατάστασης, προκειμένου να εισάγει μία διόρθωση στην ανάλυση απόφασης η οποία αξιολογούσε οικονομικά τα πηγάδια παρακολούθησης. Αυτή η έκφραση κατέδειξε το γεγονός ότι καθυστερήσεις πέραν των 3 ετών ισοδυναμούσαν με μείωση της οικονομικής απόδοσης 12 πηγαδιών στα επίπεδα διατάξεων με μικρότερο αριθμό πηγαδιών, δηλαδή θα έπρεπε να ληφθεί υπ’ όψη μεγαλύτερο κόστος αστοχίας από αυτό που συνήθως θεωρείται στην ανάλυση ρίσκου.

Στη συνέχεια, χρησιμοποιήθηκαν υψηλής διακριτότητας αριθμητικές επαναλήψεις Monte Carlo για να μελετηθεί η επίδραση της συχνότητας δειγματοληψίας στην πιθανότητα ανίχνευσης, σε μολυσμένες περιοχές που εντοπίζονταν σε ετερογενή υπόγεια περιβάλλοντα, σε συνδυασμό με διαφορετικές υδρο-γεωλογικές παραμέτρους. Για όλους τους τύπους των εδαφών παρατηρήθηκε ότι η πιθανότητα ανίχνευσης μειωνόταν όσο η δειγματοληψία γινόταν λιγότερο συχνά. Ανεξάρτητα από την πυκνότητα του δικτύου παρακολούθησης σε υπόγεια περιβάλλοντα υψηλής διασποράς, έπρεπε να τηρηθεί ένα πολύ αυστηρό πρόγραμμα δειγματοληψίας έτσι ώστε να διατηρηθεί η απόδοση ανίχνευσης του δικτύου. Εδάφη υψηλής ετερογένειας, εξαιτίας της παρουσίας ζωνών χαμηλής διαπερατότητας, φάνηκε ότι εμπόδιζαν την εξάπλωση των ρυπαντών και, κατά συνέπεια, περιόριζαν την επίδραση της διασποράς. Η ανάλυση της καθυστέρησης μεταξύ του χρόνου πρώτης εμφάνισης των ρυπαντών στα σημεία παρακολούθησης και του χρόνου που πραγματικά παρατηρήθηκαν, καθώς επίσης και η αύξηση στην περιοχή του πλουμίου που προέκυψε από αυτή τη χρονική καθυστέρηση, οδήγησαν στο συμπέρασμα ότι απαιτούνταν μηνιαία δειγματοληψία για ένα μεγάλο εύρος υδρο-γεωλογικών παραμέτρων. Επιπλέον, μελετήθηκε η επίδραση της συχνότητας δειγματοληψίας στην καθυστέρηση ενέργειας αποκατάστασης. Φάνηκε ότι σε περιβάλλοντα υψηλής διασποράς η αντίδραση αποκατάστασης πρέπει να είναι της τάξης μερικών μηνών αν κάποιος δεν επιθυμεί σημαντική αύξηση των μολυσμένων περιοχών και του κόστους αποκατάστασης.

Έπειτα, μελετήθηκε αριθμητικά ο τρόπος με τον οποίον ο αριθμός των σημειακών πηγών ρύπανσης, το μέγεθος της περιοχής ελέγχου (χώρος απόθεσης αποβλήτων) και η ποσότητα μιας στιγμιαίας έγχυσης ρύπανσης στον υδροφόρο ορίζοντα επηρεάζουν την πιθανότητα ανίχνευσης μόλυνσης από μία γραμμική διάταξη πηγαδιών παρακολούθησης. Γι’ αυτόν τον σκοπό χρησιμοποιήθηκε ένα δισδιάστατο, υψηλής διακριτότητας, στοχαστικό μοντέλο Monte Carlo. Σε κάθε εξεταζόμενη παράμετρο θεωρήθηκε ότι οι υπόλοιποι παράγοντες που επηρεάζουν τον υπολογισμό της πιθανότητας ανίχνευσης παρέμεναν σταθεροί. Οι προσομοιώσεις πραγματοποιήθηκαν στα πλαίσια παραγόντων αβεβαιότητας που προκύπτουν από το ίδιο το περιβάλλον, όπου η ρύπανση μεταφέρεται, και από την έλλειψη πληροφοριών συγκεκριμένων παραμέτρων, που αφορούν στις αρχικές συνθήκες της διαρροής.

Επιβεβαιώθηκε αριθμητικά στις περιπτώσεις που εξετάστηκαν ότι καθώς αυξανόταν το μέγεθος της περιοχής ελέγχου, ενώ ο αριθμός των πηγαδιών παρέμενε σταθερός, μειωνόταν η πιθανότητα ανίχνευσης. Συνεπώς, αν αυξανόταν το πλάτος μιας περιοχής ελέγχου, το ίδιο θα έπρεπε να συμβεί και με τον αριθμό των πηγαδιών παρακολούθησης, έτσι ώστε να διατηρούνταν η πυκνότητά τους. Σε όλες τις περιπτώσεις που προσομοιώθηκαν, η γενική παρατήρηση ήταν ότι όταν υπήρχαν δύο παρόμοιες πηγές υπόγειας ρύπανσης τότε η ανίχνευση της μόλυνσης ήταν ευκολότερη, καθώς η μέση αύξηση της πιθανότητας ανίχνευσης ήταν μεταξύ 35% - 55%. Παρατηρήθηκε η ίδια αυξητική τάση στην πιθανότητα ανίχνευσης σε σχέση με τις περιπτώσεις μίας πηγής ρύπανσης, ανεξάρτητα από τη συχνότητα δειγματοληψίας.

Τα αποτελέσματα των προσομοιώσεων δείχνουν ότι όταν η αρχική συγκέντρωση της ρύπανσης ήταν κάτω από 1.000 mgr/lt, η ανίχνευσή της ήταν πολύ δύσκολη, ανεξάρτητα από τις υδρο-γεωλογικές παραμέτρους του υδροφορέα. Η αποτελεσματικότητα των πηγαδιών παρακολούθησης σε υδροφορείς με χαμηλή ως μέτρια διασπορά έφτασαν σε μία μέγιστη τιμή, ανεξάρτητη από την αρχική μάζα της ρύπανσης που διείσδυσε στον υδροφόρο ορίζοντα. Το σημείο καμπής της συγκέντρωσης της αρχικής ρύπανσης ήταν $C = 8,000 mgr/lt$, η οποία ήταν η τιμή στην οποία η πιθανότητα ανίχνευσης έφτασε σε σημείο πλατώ. Παρατηρήθηκε επίσης ότι μόνο σε περιβάλλοντα υψηλής διασποράς η αύξηση της μόλυνσης είχε ως αποτέλεσμα υψηλότερη πιθανότητα ανίχνευσης. Σε κάθε περίπτωση, ήταν δύσκολο να ανιχνευθούν χαμηλέ τιμές συγκέντρωσης, υποδεικνύοντας ότι προκειμένου μία διάταξη παρακολούθησης να είναι ευαίσθητη, τουλάχιστο κατά την προσομοίωσή της, ακόμη και για μικρές ποσότητες ρύπανσης, απαιτείται η χρήση ενός ελάχιστου αριθμού 12 πηγαδιών.

Τέλος, μελετώντας έναν διαφορετικό τρόπο ρύπανσης υπόγειων υδάτων στα πλαίσια της πρόκλησής της σύμφωνα την τοπική βροχόπτωση, υποθέσαμε ότι υπήρχε μία σημειακή πηγή ρύπανσης μέσα σε ελεγχόμενη περιοχή συγκεκριμένων διαστάσεων (χώροι απόθεσης αποβλήτων, βιομηχανικές εγκαταστάσεις, στρατιωτικές βάσεις) η οποία διοχέτευε μια ποσότητα ρύπανσης εντός του υδροφόρου ορίζοντα σε κάθε βροχόπτωση. Η ποσότητα του ρυπαντή που διαχεόταν στα υπόγεια ύδατα θεωρήθηκε γραμμικά ανάλογη ως προς την ημερήσια καταγραφή του μέσου ύψους βροχόπτωσης. Χρησιμοποιήθηκαν δεδομένα από μία χρονοσειρά 30 ετών μέσης ημερήσιας βροχόπτωσης στο αεροδρόμιο «Μακεδονία» και συσχετίστηκαν γραμμικά με τη μάζα του ρυπαντή που διαχεόταν απευθείας στον υδροφόρο ορίζοντα, υποθέτοντας ότι δεν είχαμε επαναφόρτισή του. Η δισδιάστατη περιοχή επιτηρούνταν κατάντη από γραμμική διάταξη δικτύου πηγαδιών, το οποίο αποτελούνταν από διαφορετικό αριθμό γεωτρήσεων-πηγαδιών σε κάθε περίπτωση που μελετήθηκε. Μελετήθηκαν επίσης οι επιδράσεις των υδρο-γεωλογικών παραμέτρων του υδροφορέα στην επιτυχή ανίχνευση της ρύπανσης, όπως εκφράστηκαν στη διακύμανση υδραυλικής αγωγιμότητας του πεδίου και στους συντελεστές διασποράς. Επιπλέον, εξετάστηκαν οι επιδράσεις της συχνότητας δειγματοληψίας του υδροφόρου ορίζοντα και του χρόνου καθυστέρησης ενεργειών αποκατάστασης στην πιθανότητα ανίχνευσης που μπορεί να πετύχει μια διάταξη πηγαδιών παρακολούθησης. Τα αποτελέσματα συγκρίθηκαν άμεσα με αυτά των προσομοιωμένων περιπτώσεων στιγμιαίας ρύπανσης, θεωρώντας ότι οι υπόλοιπες υπολογιστικές παράμετροι ήταν κοινές.

Φάνηκε ότι η πιθανότητα ανίχνευσης μίας διάταξης παρακολούθησης αυξανόταν γρηγορότερα, όταν αυξανόταν κι ο αριθμός των πηγαδιών, σε ρύπανση σχετιζόμενη με βροχόπτωση απ' ότι στις περιπτώσεις στιγμιαίας ρύπανσης. Σε όλες τις προσομοιώσεις η κύρια υδρο-γεωλογική παράμετρος που επηρέαζε την πιθανότητα ανίχνευσης, τον μέσο χρόνο ανίχνευσης και τη μέση μολυσμένη περιοχή ήταν η διασπορά του πεδίου. Στην περίπτωση πρόκλησης από βροχόπτωση ρύπανσης ετερογενούς υδροφορέα, η συχνότητα δειγματοληψίας πρακτικά δεν φάνηκε να επηρεάζει την πιθανότητα ανίχνευσης ενός δικτύου παρακολούθησης. Σε κάθε περίπτωση που προσομοιώθηκε, η καθυστέρηση των ενεργειών αποκατάστασης ήταν ουσιώδης για τον υπολογισμό του ρίσκου που αφορούσε στην ικανότητα ανίχνευσης μίας εγκατάστασης παρακολούθησης υπογείων υδάτων, καθώς αποτελούσε κρυφή παράμετρο που θα μπορούσε να προκαλέσει μεγάλη απόκλιση στον υπολογισμό του ρίσκου.

CHAPTER 1

Introduction

1.1 Groundwater Pollution

Safe drinking water is essential to human and other life form survival. Actually, it is the special physical and chemical properties of water which render it a significant factor for the existence of life on Earth; at least in the form we know it. Yet, not all of this water is suitable for humans to use. In fact, only 2.5% of the Earth's water is freshwater. Less than 0.3% of all freshwater is found in rivers, lakes and the atmosphere, whereas an even smaller amount (0.003%) is contained within biological bodies and manufactured products (Gleick, 1993).This natural resource is becoming scarcer in certain places, and its availability is a major social and economic concern. Water, however, is not a finite resource, but rather re-circulates during the Earth's water cycle, where it moves continually through evaporation and transpiration (evapo-transpiration), condensation, precipitation and surface runoff, usually reaching the sea. Some runoff infiltrates the ground and goes into aquifers. This groundwater later flows back to the surface from springs and ends up recharging rivers or flowing directly into the sea. Groundwater storage is important since clean freshwater is essential to the survival of humans and other land-based life.

Groundwater, which is thought of as liquid water flowing through shallow aquifers, is a natural resource which constitutes the largest reservoir of freshwater in the world, accounting for over 97% of all freshwaters available on earth (EU/Groundwater-Directive, 2008). Technically, groundwater can also include soil moisture, permafrost, immobile water in very low permeability bedrock and deep geothermal or oil formation water. Until recently, focus on groundwater has mainly concerned its use as drinking water (e.g. about 75% of European Union (EU) residents depend on groundwater for their water supply), and groundwater has also been recognized as an important resource for industry (e.g. cooling waters) and agriculture (irrigation). It has, however, become increasingly obvious that groundwater should not only be viewed as a water supply reservoir, but should also be protected because of its environmental value (EU/Groundwater-Directive, 2008).

Most concern over groundwater contamination has focused on pollution associated with human activities. Human groundwater contamination can either be directly related to waste disposal (private sewage disposal systems, land disposal of solid waste, municipal wastewater, wastewater impoundments, land spreading of sludge, brine disposal from the petroleum industry, mine waste, deep-well disposal of liquid waste, animal feedlot waste, radioactive waste) or not (accidents, military operations, certain agricultural activities, mining, highway de-icing, acid rain, improper well construction and maintenance, road salt) (LENNTECH, 2013). Since groundwater moves slowly through the subsurface, the impact of anthropogenic activities may last for a long time. This means that pollution which occurred some decades ago — originating from agriculture, industry or other human activities — may still be threatening groundwater quality today and, in some cases, will continue to do so for several generations to come.

Large quantities of organic compounds are manufactured and used by industries, agriculture and municipalities. Recent reports show that pollution from domestic, agricultural and industrial sources is still a major concern, despite the progress in some fields, either directly through discharges (effluents) or indirectly through the spread of nitrogen fertilizers and pesticides, as well as leaching from old contaminated industrial or waste disposal sites (e.g. landfills, mines, heavy manufacturing industry etc.). While point sources have caused most of the pollution identified to date, there is evidence that diffuse sources are having an increasing impact on groundwater. For example, nitrate concentrations currently exceed the nitrate guideline values in approximately one third of groundwater bodies in Europe (EU/Groundwater-Directive, 2008).

These man-made organic compounds are of most concern. In many locations groundwater has been contaminated by chemicals for many decades, though this form of pollution was not recognized as a serious environmental problem until the 1980s. According to *Lenntech* website, contamination sources may be:

Natural: groundwater contains some impurities, even if it is unaffected by human activities. The types and concentrations of natural impurities depend on the nature of the geological material through which groundwater moves and the quality of the recharge water. Groundwater moving through sedimentary rocks and soils may pick up a wide range of compounds such as magnesium, calcium and chlorides. Some aquifers have a high natural concentration of dissolved constituents such as arsenic, boron, selenium and chromium. The effects of these natural sources of contamination of groundwater quality depend on the type of contaminant and its concentrations.

Agricultural: Pesticides, fertilizers, herbicides and animal waste are agricultural sources of groundwater contamination. Their manifestations are varied and numerous: spillage of fertilizers and pesticides during handling, runoff from the loading and washing of pesticide sprayers or other application equipment, use of chemicals uphill from or within a few hundred feet of a well, storage of agricultural chemicals near conduits to groundwater, such as open and abandoned wells, sink holes, or surface depressions where ponded water is likely to accumulate. Contamination may also occur when chemicals are stored in uncovered areas, unprotected from wind and rain, or are stored in locations where groundwater flows from the direction of the chemical storage to the well.

Industrial: Manufacturing and service industries have high demands for cooling water, processing water and water for cleaning purposes. Groundwater pollution occurs when used water is returned to the hydrological cycle. Modern economic activity requires transportation and storage of material used in manufacturing, processing, and construction. Along the way, some of this material can be lost through spillage, leakage or improper handling. The disposal of waste associated with the above activities contributes to yet another source of groundwater contamination. Some businesses, usually without access to sewer systems, rely on shallow underground disposal. They use cesspools or dry holes, or send the wastewater into septic tanks. Any of these forms of disposal can lead to contamination of underground sources of drinking water. Dry holes and cesspools introduce waste directly into the ground, whereas septic systems cannot treat industrial waste. Wastewater disposal practices of certain types of businesses, such as automobile service stations, dry cleaners, electrical component or machine manufacturers, photo processors and metal fabricators, are of particular concern because the waste they generate is likely to contain toxic chemicals. Other industrial sources of contamination include cleaning off holding tanks, spraying equipment on the open ground, waste disposal in septic systems or dry wells and storage of hazardous materials in uncovered areas or in areas that do not have pads with drains or catchment basins. Moreover, underground and above ground storage tanks holding petroleum products, acids, solvents and chemicals can develop leaks from corrosion, defects, improper installation or mechanical failure of the pipes and fittings. Furthermore, mining of fuel and non-fuel minerals can create many opportunities for groundwater contamination. The problems stem from the mining process itself, the disposal of waste and the processing of the ores and the waste they create.

Military: operations and maintenance of military systems, such as fighter aircrafts, ships and vehicles, are activities similar to industrial ones, producing a great amount of pollutants. Even if national regulations are applied to all of these military activities concerning waste handling, there are cases on the battlefield during military operations where environmental issues are not the first priority. In addition, usage of weapons that cause infrastructure damage may create uncontrolled groundwater pollution, as storage facilities or industrial resources destruction can release chemicals into the ground, which will infiltrate the aquifer or may be transported away from the theatre of operations, affecting people and polluting communities not invoked in the confrontation.

Residential: Residential wastewater systems can be a source of many categories of contaminants, including bacteria, viruses, nitrates from human waste, as well as organic compounds. Injection wells used for domestic wastewater disposal (septic systems, cesspools, drainage wells for storm water runoff, groundwater recharge wells) are of particular concern to groundwater quality if located close to drinking water wells. Improper storage or disposal of household chemicals such as paints, synthetic detergents, solvents, oils, medicines, disinfectants, pool chemicals, pesticides, batteries, gasoline and diesel fuel can also lead to groundwater contamination. When these chemicals are stored in garages or basements with floor drains, spills and flooding may introduce them as contaminants into the groundwater. When thrown in the household trash, these products will eventually be carried into groundwater because community landfills are not equipped to handle hazardous materials. Similarly, waste dumped or buried in the ground can contaminate the soil and leach into groundwater.

Once contaminated, groundwater is difficult to restore. A study by the United States of America National Research Council (U.S.N.R.C., 2012) indicated that there are at least 126,000 groundwater sites that may have contaminated soil or groundwater, requiring some form of remediation. Almost 10 percent of these sites are considered "complex," meaning restoration is unlikely to be achieved in the next 50 to 100 years due to technological limitations. The same report adds that the estimated cost of complete cleanup at these sites ranges from $110 billion to $127 billion, but the figures for both the number of sites and the costs are likely underestimations.

One dominant attribute of subsurface remediation efforts has been the lengthy delays between discovery of the problem and its solution (U.S.N.R.C., 2012). The reasons for these extended timeframes are now well-known: ineffective subsurface investigations, difficulties in characterizing the nature and extent of the problem in highly heterogeneous subsurface environments, remedial technologies incapable of achieving restoration in many geological settings, continued improvements in analytical detection limits leading to discovery of additional chemicals of concern, evolution of more stringent drinking water standards, and the realization that other exposure pathways, such as vapor intrusion, pose unacceptable health risks. A variety of administrative and policy factors also result in extensive delays, including, but not limited to, high regulatory personnel turnover, the difficulty in determining cost-effective remedies to meet cleanup goals and allocation of responsibility at multiparty sites.

1.2 Groundwater Protection

Groundwater protection describes the management processes by which groundwater quality and resources are protected against pollution and over-exploitation. This can mainly be achieved by three interwoven factors: environmental legislation, ethics and education. Each of these plays its part in influencing national-level environmental decisions and personal-level environmental values and behaviors. For environmental and, consequently, groundwater protection to become a reality, it is important for societies to develop each of these areas that, together, will inform and drive environmental decisions (Solomon, 2010). In the present study, only the component of environmental legislation will be of immediate concern and will be used as a reference system, as this factor sets liability limits on the way various human activities are controlled.

A policy establishment on groundwater protection expresses a political willingness towards that direction and the way this policy will be applied is by setting regulations. In the case of EU, laws designed to protect groundwater against pollution and deterioration are part of a larger regulatory framework that can be traced back to the 1990s. The concept of groundwater protection as tackled by different pieces of legislation is now fully integrated into the basic measures of the EU Water Framework Directive.

There are specific basic regulatory measures of direct relevance to groundwater protection. One in particular, the Landfill Directive, is of immediate concern in the present study, as its limits have been applied to compare with simulation results. The Landfill Directive seeks to prevent or reduce the negative effects of landfill waste on the environment, including groundwater. It establishes provisions for issuing permits based on a range of conditions, including impact assessment studies. For each site, groundwater, geological, and hydrogeological conditions in the area must be identified. The sites must be designed so as to prevent groundwater from entering landfill waste, so as to collect and treat contaminated water and leachate, as well as prevent the pollution of soils, groundwater or surface water by using the appropriate technical precautions, such as geological barriers and bottom liners. The Landfill Directive also sets a minimum requirement on groundwater quality monitoring. It establishes criteria for waste testing and acceptance, taking into consideration the protection of the surrounding environment, including groundwater.

Regarding municipal landfills, an initial sampling must be carried out in at least three locations before the filling operations, in order to establish reference values for future sampling. Having started the operation of the facility, a groundwater pollution detection monitoring program must be established, which must consist of at least one up-gradient background well and two down-gradient wells (EU, 1999/31/EC). The purpose of detection monitoring is early detection of a release to groundwater based on comparison of down-gradient well data to background data for a limited number of water quality parameters. The number of monitoring wells can be increased on the basis of a specific hydro-geological survey and the need of the operator to control the risk and the liabilities in case of groundwater pollution. Regulation compliance of monitoring samples for an expanded suite of hazardous constituents requires establishment of concentration limits (compliance or cleanup standards), should any of these constituents be detected. Down-gradient well data is compared to concentration limits for each well on a periodic basis. The purpose of compliance monitoring is to determine if the release to groundwater is significant enough to warrant corrective action. Corrective action typically requires leachate leak source location identification and control, as well as groundwater remedial measures. The issues of a monitoring system design for detection, along with a sampling policy and timely remedial action compliance, are addressed in this thesis.

1.3 Landfills and Leachate

Increasingly affluent lifestyles and the continuing industrial and commercial growth in many countries around the world in the past decade have been accompanied by rapid increases in both municipal and industrial solid waste production. The sanitary landfill method for the ultimate disposal of solid waste material continues to be widely accepted and used due to its economic advantages (Renou et al., 2008). A municipal solid waste landfill system is an engineered deposit of waste onto or into the ground in such a way that pollution to the environment is prevented (ISWA, 1992). Alternatively a sanitary landfill, as defined in Article 2 of the European Directive 1999/31/EC, is any area onto or into the ground used for at least a year for the disposal of solid waste. The critical components of a sanitary landfill are a natural element, the hydro-geological setting, and four engineered ones: the bottom liner, the cover, the leachate collection system and the monitoring system for the detection of a potential contamination leak (Paleologos, 2008). The bottom liner and the leachate collection system are complementary elements. The bottom liner constitutes the barrier to the environment for liquid and gas leaks from a landfill, and the leachate collection system, which is placed immediately below the waste, collects the leachate before it reaches the bottom liner. If collection of the leachate were to fail, the hydraulic load would make the liquid waste penetrate the bottom liner and be released in the environment (Figure 1.1). The basic operation of the cover is to prevent the infiltration of water into a landfill and the monitoring system checks the total operation of a landfill and its impact on the environment.

The main objective of landfilling is to provide a place for the final storage of waste in a way that does not impair human health and the surrounding environment. This objective can be reached by isolating the waste disposed of from the environment, so that emissions from the disposal site can be collected and treated prior to their release to the environment (Munawar & Fellner, 2013). Globally, more than 70% of municipal waste generated is disposed of in landfills (Zacarias-Farah & Geyer-Allely, 2003).

The main landfill emissions are biogas, airborne particulates and leachate. Biogas is produced during the biodegradation of the organic matter inside the waste bulk, while airborne particulates are generated during waste mechanical compression. Leachate is defined as the aqueous effluent generated as a consequence of rainwater percolation through waste, in conjunction with the biochemical processes in waste cells and the inherent water content of the waste (Renou et al., 2008). During landfill operation, leachates are produced mainly due to infiltration of rainwater through the refuse tips (Tatsi & Zouboulis, 2002). Leachate may contain large amounts of organic matter (biodegradable, but also refractory to biodegradation), where humic-type constituents consist an important group, as well as ammonia-nitrogen, heavy metals and chlorinated organic or inorganic salts. The composition of landfill leachates varies greatly depending on the age of the facility (Lema et al., 1988).

While landfills in many countries are currently designed and manufactured to minimize releases through the use of leachate barrier systems, capping of the site, leachate removal for treatment and barrier failure or degradation over time make groundwater pollution possible, while low rates of leachate removal in comparison to inflow to leachate treatment plants, for instance due to a rainfall, can result in seepage to both surface and groundwater (Slack et al., 2007). Despite all counter measures aiming at eliminating the chance of barrier leakage, the risk of leachate groundwater contamination cannot be completely eliminated or even, in some cases, controlled. The impact of landfill leachates on underlying aquifers has prompted a great number of studies (Apgar & Langmuir, 1971; Miller & Mishra, 1989b, 1989a; Kjeldsen, 1993; Kaczmarek et al., 1997; Gau & Chow, 1998; Riediker, 2000; De Cortázar et al., 2002; Tatsi & Zouboulis, 2002; Slack et al., 2007; Renou et al., 2008). It is estimated by the U.S. Environmental Protection Agency that all landfills, irrespectively of the type of bottom liner, may present contamination leaks with time, and at least 40% of the operating landfills in the United States exhibit "some type of leak" (ITRC, 2003).

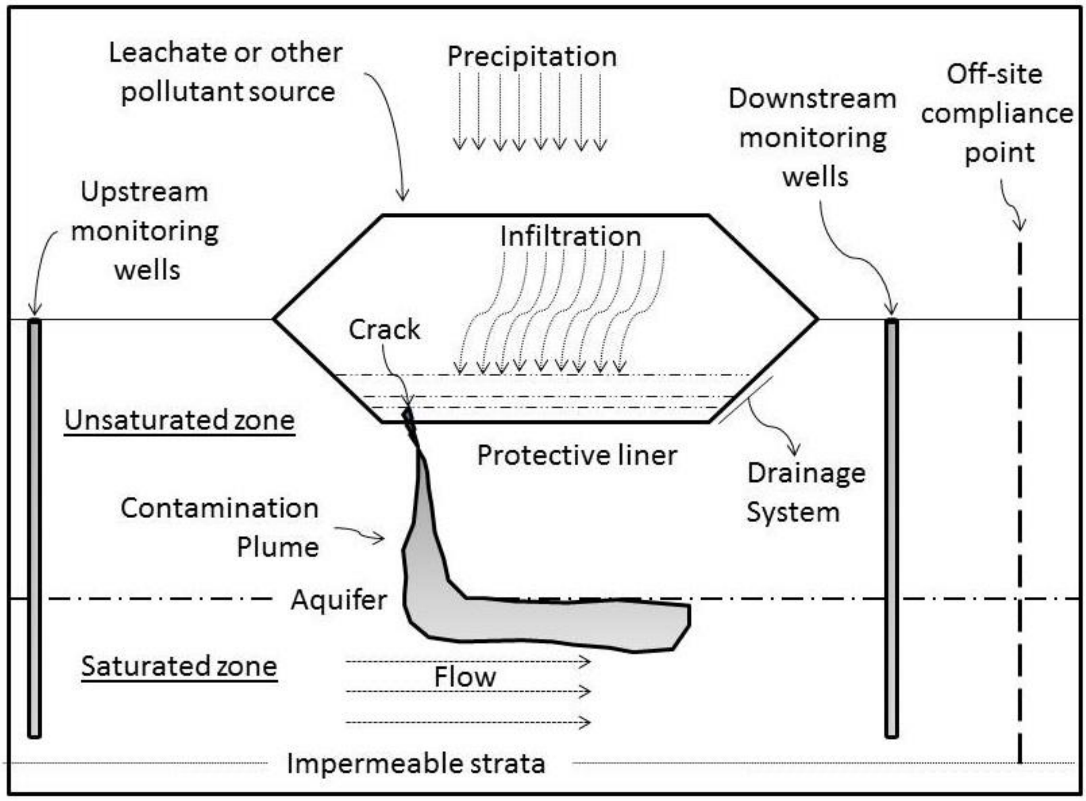

Figure 1.1: Main landfill characteristics and leachate escape into saturated zone

1.4 Problem Definition

Leachate production and management is now recognized as one of the greatest problems associated with the environmentally sound operation of sanitary landfills, because this liquid waste can cause considerable pollution problems by contacting the surrounding soil, ground or surface waters, and therefore it is considered a major pollution hazard unless precautionary measures are implemented (Baccini et al., 1987). The leachate problem is made worse by the fact that many landfill sites are operating without an appropriate impermeable bottom liner or an effective collection and subsequent treatment system (Lema et al., 1988), meaning that after the facility closes it is highly probable for pollution to escape into groundwater. Moreover, in abandoned landfills there is rarely any leachate collection and removal system available. Thus, leachate gravitationally drains through the waste mass and eventually develops a hydraulic head on the base of the facility (or liner, if one is present). Either leakage is accelerated due to this increased head or the head continues to build in the waste mass, creating groundwater pollution threat (Koerner & Soong, 2000).

In order for aquifer leachate contamination to be discovered, regulations impose the use of a groundwater monitoring system. The objective of a monitoring network is to gather information to be used for such purposes as characterization of ambient conditions, detection of the existence or location of undesirable conditions, and verification of compliance with regulations (Loaiciga et al., 1992). Therefore, the design of a reliable and efficient groundwater monitoring system is of great importance for groundwater protection policy, as it helps to determine the likelihood and severity of contamination problems. In addition, an early warning would minimize the landfill operator's liabilities.

However, because of the numerous and significant uncertainties involved, often it is difficult to ensure that a specific monitoring system will perform as initially expected. Uncertainty stems from the fact that we do not know exactly when and where the pollution will originate and how it is going to evolve into underground environment for which very few things are known. It is not possible to know beforehand when a containment installation or a protective barrier will fail, allowing pollutants to intrude into groundwater, as long-term durability of synthetic lining systems is in doubt (Allen, 2001; Zhao et al., 2007). Consequently, the best thing to do is set an "alarm" mechanism in case of failure and aquifer contamination.

Even though identifying leaks in landfill liners is an essential part of waste management and there are leak detection tools, such as electro-chemical sensing (Rumer & Mitchell, 1995; Laine et al., 1997), that can be installed to identify them soon after they occur, legislation does not oblige facility operators to install such a tool. Because leak detection tools are costly to install initially, landfill operators detect contaminant plumes caused by leaks in the landfill liner by collecting groundwater samples and analyzing them. One limitation of this method is that it does not prevent groundwater from becoming contaminated. Another limitation is the expense of comprehensive monitoring for all groundwater which comes in contact with a landfill.

Because the majority of landfills are lined with geo-membranes, most leaks are point sources, not widespread (Giroud & Bonaparte, 1989; Rumer & Mitchell, 1995). This is mainly due to the fact that usually leaks are developed at the bottom of the protective barriers, underneath great quantities of waste, where there is no access to perform a direct inspection.

Either due to a functional failure (material or leachate removal failure) or due to an accidental event (liner tear or puncture) the footprint of the contamination source is usually very small. If there is no monitoring well in the path of a plume, it is possible for the front of the plume to pass by the line of wells at the point of compliance without being detected. This could also happen in case sampling intervals of monitoring wells allow contamination to pass over undetected. 99/31/ EU Directive states that the sampling frequency must be based on possibility for remedial actions between two samplings if a trigger level is reached. In general, groundwater should be monitored quarterly, biannually or annually, depending on the type of waste, size and design of the landfill, along with aquifer material. In most cases a quarterly monitoring is required. However, annual monitoring can be undertaken for small landfills located in remote places far away from any groundwater use source. Installing enough monitoring wells to be sure of intercepting a narrow plume in any position can be prohibitively expensive (Godfrey et al., 1987). In addition, a very rigorous sampling policy in order to detect small plume pollution briefly injected into groundwater may increase a landfill's operating cost too much. Consequently, it is rather impossible to predict the exact location of the failure and the source of pollution. Potentially, every point inside a landfill's vicinity may be a contamination source.

As soon as pollution enters the saturated zone, it is very difficult to determine the exact path of its propagation. Spreading of solutes in transport through geological formations (aquifers, petroleum reservoirs) is governed by the large-scale spatial variability of permeability (Dagan, 1994). Geological formations that act as flow conduits are often characterized by highly variable three-dimensional structures consisting of layers, lenses and, perhaps, fractures in various materials, ranging from sand and gravel to clay or rods. Corresponding to these material fluctuations is a similar variability in the characteristic hydraulic parameters used for the description of both flow and transport in porous media scale balance equations (Tompson et al., 1987a). Because of the seemingly erratic spatial variation of hydraulic conductivity K and the scarcity of field data, it is very difficult, if not impossible, to deterministically define the path of plume contamination. Field uncertainty is an important factor in hydrological applications (unlike controlled laboratory experiments), where there is usually large uncertainty in characterizing even the statistical structure of K (Fiori et al., 2006).

Finally, another factor of uncertainty stems from the fact that there is no exact time provision in pollution control and in environmental restoration after contamination has been discovered. Even if regulations prompt landfill operators to apply an emergency plan so as for pollution to be controlled, additional remediation actions must be taken in order for environmental damage to be restored and further pollution danger to be eliminated. In real life, though, immediate remediation actions are not the case. Even the EU 99/31 Directive on landfill operation states that when a monitoring well sample analysis indicates evidence of groundwater pollution, another sample must be taken and, if pollution is verified again, then measures are to be taken. However, as time passes plume contamination areal coverage gets bigger. Time between groundwater pollution detection and the line of action that someone is willing to follow as soon as it is successfully discovered defines the worthiness of the detection information. Thus, holistic consideration of leachate groundwater contamination detection entails uncertainty as to restoration time.

A reliable groundwater detection monitoring system entails various challenges due to the nature of the problem. The performance of a landfill's monitoring wells for leachate polluted groundwater has prompted a great number of studies (Morisawa & Inoue, 1991; Hudak & Loaiciga, 1992; Loaiciga et al., 1992; Meyer et al., 1994; Hudak, 2001; Kim & Lee, 2007) mainly focusing on the optimization of pollution detection probability in relation to the number and location of the wells. Additional research has been done in order to determine how hydro-geological or monitoring installation parameters affect successful groundwater pollution (Hudak, 1998; Warrick et al., 1998; Hudak, 2005; Yenigül et al., 2005; Yenigül et al., 2011), as well as studies have been done to develop methods to reduce the costs associated with long term monitoring of sites groundwater contamination (Reed et al., 2000; Wu et al., 2005).

However, landfills are not the only groundwater pollution sources. For many industrial activities, such as those taking place at oil refineries and chemical plants, it is almost impossible to prevent pollution. If shallow groundwater is present, it is likely that the industrial site will become polluted somewhere in the future or has been polluted at some point in the past. It is of vital importance to human health and the public acceptance of these activities that groundwater pollution is detected before it crosses the terrain boundary of the refinery or plant (Bierkens, 2006). This way it can be hydrologically contained or cleaned up. Hence, many refineries and plants have a monitoring network at the boundary of their sites to detect plumes of polluted groundwater.

Much of the literature on optimizing monitoring networks for groundwater quality is concerned with mapping contaminant plumes from landfills (Loaiciga, 1989; Loaiciga et al., 1992; McLaughlin et al., 1993; Yenigul et al., 2006). In case of larger sites with industrial activities, the plumes themselves are usually not of interest. Interest is focused on detecting the plumes before they leave the site at some distance from the boundary (Bierkens, 2006). Although the present study started mainly by examining municipal waste sanitary landfill cases, results were expanded in every facility where groundwater monitoring is legally implemented or simply advised, in order for aquifer pollution to be detected and liabilities to be avoided.

1.5 Research Objectives

The purpose of this research is to numerically investigate groundwater contamination detection probability achieved by a linear monitoring arrangement of wells and to provide a novel framework that modifies traditional risk analyses by supplying a corrected detection probability that accounts for delays in remedial actions. A stochastic 2-D model has been developed that performs high resolution Monte Carlo simulation, which accounts for uncertainties stemming from:

i. Geological heterogeneity, as reflected to hydraulic conductivity K
ii. Dispersion of pollution, as described by longitudinal and transverse dispersion coefficients a_L, a_T
iii. Size of a landfill or a controlled area where groundwater pollution may occur
iv. Location of contamination source
v. Number of contamination sources
vi. Quantity of pollution that infiltrates groundwater
vii. Duration of leak
viii. Sampling frequency
ix. Delays in remediation actions

The numerical experiment results of the present thesis are used to acquire an insight on the way field heterogeneity, pollution source location, duration and quantity in relation to sampling frequency as well as remediation delay affect the efficiency of an established monitoring network of groundwater pollution and its operating policy. Even if numerical simulations are not equivalent to field experiments, results are adequate to provide a quick and affordable first estimation on what to expect from such a running monitoring system or from one under consideration.

First estimation is defined as the preliminary calculation of detection probability that a specific monitoring installation may provide, without performing any field measures but only using an expert's views and observations on assigning values at mean hydraulic conductivity, at heterogeneity, as this is reflected into hydraulic conductivity variations, and at dispersion coefficient. By applying all these parameters at the present work model, in conjunction with sampling policy and an estimation of possible pollution control or remediation delay, the outcome probabilities can help an engineer perform risk analysis in terms of cost for a specific monitoring installation easily and decide what would be the best tradeoff choice among the number of monitoring wells, an adopted sampling policy and a possible pollution detection failure. Moreover, additional costs originating from remediation delay, depending on available resources and technologies, as well as efficiency of administration decision-making, are also introduced as decision parameters.

1.6 Thesis Outline

This thesis comprises seven chapters, which describe the objectives and results obtained in this study. *Chapter 2* provides an outline of the basic simulation schemes that are used and describes the numerical techniques of the computational model that simulates transportation and dispersion of contaminant plumes originating from a groundwater pollution controlled area leakage, such as a landfill. The numerical methods of the solution of governing flow and contaminant transport equations are described in this chapter. A brief introduction is made on subsurface heterogeneity simulation using the Spectral Turning Bands method, as well as pollution advection and dispersion simulation using Random Walking Particles method. At the end of Chapter 2 the model's structure is analyzed and a brief description of the source code is referenced.

In *Chapter 3*, a high resolution Monte Carlo stochastic model is developed to simulate contaminant transport from an instantaneous source into heterogeneous two-dimensional aquifers. The effect of a representative number of particles on the plume's description is studied and compared with its theoretical detection probability in case of a homogeneous aquifer. Probabilities of detection P_d and contaminated groundwater areas are calculated for different arrangements of monitoring wells. An expression is proposed that accounts for the delay between detection and remedial action in order to provide a correction to decision analyses that evaluate the economic worth of well monitoring. *Chapter 3* has been adapted from *Papapetridis K., Paleologos EK.*, (2012), "Sampling Frequency of Groundwater Monitoring and Remediation Delay at Contaminated Sites", Water Resources Management 26(9), pp.2673-2688, doi: 10.1007/s11269-012-0039-8.

Chapter 4 examines the monitoring wells frequency of sampling at contaminated sites located in two-dimensional heterogeneous subsurface environments. Aquifer heterogeneity and the pollution dispersion effect on detection probability, in conjunction with the sampling policy adopted, are examined. The impact of delays in remedial response is also investigated in terms of the growth that such delays incur on contaminated areas and remediation costs. High-resolution numerical Monte Carlo realizations are utilized to simulate contaminant movement in heterogeneous two-dimensional aquifers and to calculate the probabilities of detection Pd attained by various monitoring well arrangements. *Chapter 4* has been adapted from *Papapetridis K., Paleologos EK.,* (2011), "Contaminant detection probability in heterogeneous aquifers and corrected risk analysis for remedial response delay", Water Resources Research 47(10), doi:10.1029/2011WR010652.

Chapter 5 studies how the number of point sources, the size of the controlled area (landfill) and the quantity of an instantaneous aquifer injection pollution event affect detection of an instantaneous pollution into a two-dimensional aquifer by a monitoring network of wells. A two-dimensional stochastic model is utilized to perform numerical experiments. In each examined parameter it is considered that the rest of the factors affecting detection probability estimation remain constant. Simulations are performed in the context of uncertainty factors deriving from the environment itself, where the pollution is propagating, and the lack of information about certain parameters concerning the initial conditions of the leak.

In *Chapter 6* a two-dimensional stochastic model is developed in order to study, in terms of detection probability, the efficiency of linear groundwater pollution monitoring well networks, as pollution originates from a random point source inside a controlled area and is triggered by precipitation events. A thirty-year time series of daily average rain data has been used and linearly coupled with the pollutant mass diffused directly into the aquifer. The effects on successful pollution detection of the aquifer's hydro-geological parameters, as reflected in the field's hydraulic conductivity variance and dispersion coefficients, have been studied. In addition, the influence of the aquifer's sampling frequency and remedial action delay time is examined, referring to the detection probability that a monitoring well arrangement can succeed from the moment a successful detection has been recorded. Results are directly compared with these of instantaneous pollution simulated cases, as they have been studied in previous Chapters, considering the rest of the computational parameters common.

Chapter 7 concludes the thesis with a summary of the main results and some recommendations for practical application and future research are proposed.

Thesis concludes with two Appendixes. In *Appendix A* the FORTRAN source code is listed for both cases of pollution duration that have been studied. In addition, STUBA listing is provided along with flow equations arithmetic solution subroutine. Finally, in *Appendix B* all the simulation numerical results are presented.

CHAPTER 2

Two-dimensions model structure

2.1 Introduction

Geological field observations at various scales have shown that both physical and chemical properties exhibit high spatial variability or, otherwise, heterogeneity. This is due to the fact that many of the characteristics of geological formations - such as cracks and voids containing the horizontal and vertical stratification, or the type and age of the rocks exhibit also great variability in space. Experimentally, for example, it has been found that the hydraulic conductivity of a geological field can vary between several orders of magnitude, with a discontinuous manner, thereby making its description in a deterministic way almost impossible (Gelhar et al., 1992).

Contaminant transport depends on the nature of the contaminant and the hydro-geological parameters that form an aquifer's flow field. In a steady flow, flow stream lines remain constant over time, while otherwise in transient cases they change, making the study of the problem much more difficult both on a physical level, in understanding the evolution of the same phenomenon, and for the computational requirements in order to achieve a numerical description of the flow. The aim, however, of this work is not the general study of heterogeneous aquifer transport phenomena, but the study of groundwater pollution detection probability by a monitoring wells network under conditions of uncertainty regarding environmental and operating parameters. For this reason, in order to simplify our problem, a steady flow will be considered.

Although in the present study two-dimensional (2-D) fields are utilized to simulate a plume's evolution and its detection, during the following paragraphs the case of three-dimensional (3-D) geological field equations are developed, in order for the presentation of the equations in space to be considered complete. Although it can be said that the two-dimensional approach is not the most realistic description of the actual situation, it simplifies the computational problem, losing only the vertical information about the movement and the detection of plumes. Moreover, when the horizontal dimensions of an aquifer are much greater than its thickness, which is our case, then the results of two dimensions provide a good approximation of reality (Dagan, 1986; Dagan et al., 2009). On the other hand, running simulations in 2-D saves computational time. The reduction of the 3-D equations to 2-D is simply done by ignoring the factors of the third component.

2.2 Stochastic Approach

Natural heterogeneity of aquifer materials provides the direct motivation to approach many groundwater problems in a probabilistic framework. As a consequence of the variable processes involved in the genesis of permeable earth materials, it seems that such complex heterogeneity will be omnipresent. The fundamental problem is how to deal with this heterogeneous reality as we attempt to develop quantitative descriptions of flow in large-scale aquifer systems. More specifically, engineers would like to know how to find appropriate average parameters which can be applied to large-scale flow models and, at the same time, how to be able to evaluate the influence of modeled heterogeneity on the quality of predictions from such models.

One approach to deal with the complex heterogeneity of natural aquifer materials would be to construct a detailed deterministic model which represents the actual heterogeneity of the aquifer. However, for realistic field problems, this degree of spatial resolution would require enormous computational resources and, more importantly, would be impractical in terms of the amount of data required to specify the actual complex three-dimensional heterogeneity. Furthermore, this level of detail in the output would be excessive in relation to predictive requirements for many applications.

Alternatively, the heterogeneity can be represented in terms of random hydraulic parameters characterized by a limited number of statistical parameters. These random parameters will then appear as coefficients in partial differential equations which express our classical laboratory-based physical understanding of the flow processes. Consequently, the resulting predictions are represented through probability distributions or, more realistically, in terms of statistical moments (Gelhar, 1986).

In a stochastic approach we attempt to gain useful information about the behavior of naturally heterogeneous systems by treating them as if the hydraulic parameters were random. More specifically, to represent the spatial structure, parameters such as hydraulic conductivity

K can be viewed as random processes or spatial random fields. The spatial persistence of the random field of the hydraulic conductivity natural logarithm can be characterized in terms of the second moment, that is, the covariance between two different locations.

Carefully designed natural gradient field-scale tracer experiments have been conducted to study the movement of contaminants in heterogeneous aquifers with a high sampling resolution in space and time, from which stochastic theories have been partially validated at the Borden (Freyberg, 1986; Mackay et al., 1986; Woodbury & Sudicky, 1991; Farrell et al., 1994) and Cape Cod (LeBlanc et al., 1991; Hess et al., 1992) aquifers. These two aquifers are relatively homogeneous $\left(\sigma_{\ln K}^2 \simeq 0.2\right)$ and the successful application of stochastic theories at these sites does not establish their validity in more heterogeneous aquifers (Fernàndez-Garcia et al., 2005). The MADE (Boggs et al., 1992) field-scale tracer test was conducted in a substantially more heterogeneous aquifer $\left(\sigma_{\ln K}^2 \simeq 2.7\right)$ but a spatial trend in hydraulic conductivity and nonuniform flows prevented the macrodispersivity from approaching a constant value (Adams & Gelhar, 1992). Thus the basic predictions of stochastic theories (effective conductivity and dispersion) could not be directly verified at the MADE site (Fernàndez-Garcia et al., 2005).

The ergodic hypothesis which underlies the treatment of aquifer flows in a probabilistic sense is a fundamental admission. In simple terms, the ergodic hypothesis presumes that the behavior of a spatially averaged property of an aquifer is represented probabilistically by the ensemble average over a large number of realizations of aquifers having the same underlying statistical properties. For the spatial averaging process to be meaningful, the heterogeneities must be relatively small in terms of their spatial scale, as compared with the overall scale of observation. If there is this disparity in the scales, it should be possible to view larger-scale variations as deterministic trends around which there are more localized variations which can be viewed as stationary. The requirement for the result to be applicable is that the mean hydraulic gradient does not change significantly over a distance corresponding to the correlation scale of the head process (Gelhar, 1986).

2.3 Simulating Random Fields: Turning Bands

The Turning Bands method is a simulation technique which was developed to create stationary, correlated, multi-dimensional Gaussian fields from a normal distribution with mean zero (0) and a specific covariance function. This method was first developed and applied by *Journel* (1974) and developed for the general case of the 2-D field by *Mantoglou* *and Wilson* (1982) as Spectral Turning Bands method (STUBA), because of the use of a spectral method for line generation.

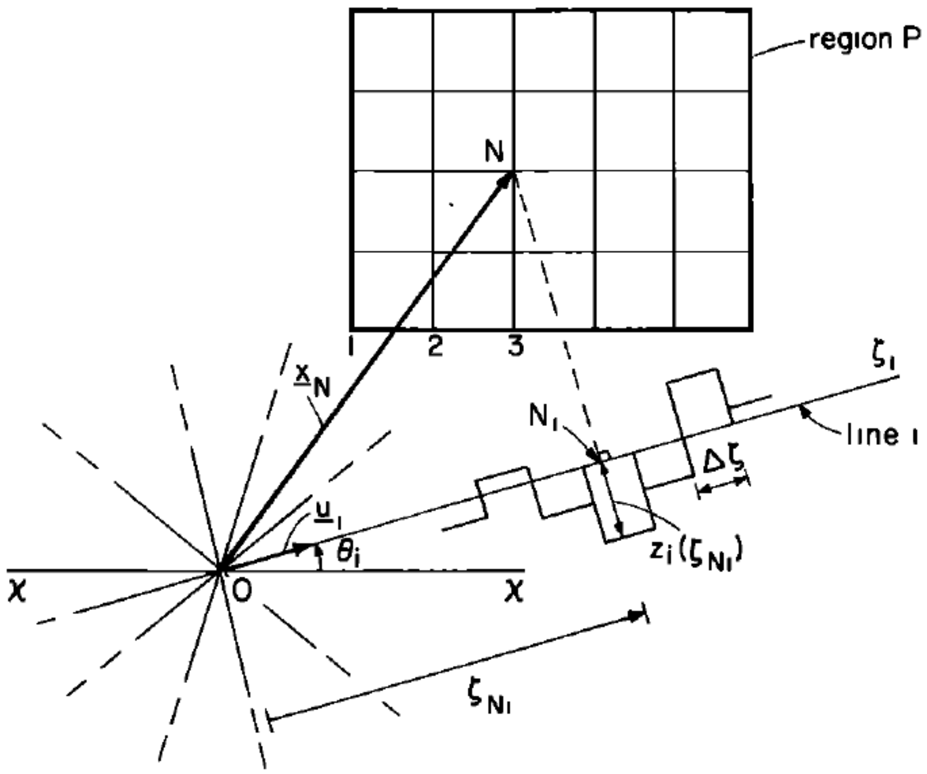

Figure 2.1: Turning Bands Mechanism (Mantoglou and Wilson,1982)

The Turning Bands method is based on the theory of multivariate stochastic processes. The basic idea of the method is converted into a multi-dimensional simulation of a sum of equivalent dimensional simulations. The operation of the algorithm is, in short, to create 2-D and 3-D fields by successively promoting and combining the values derived from the simulations of random numbers with a certain autocorrelation function along lines which are launched by a random point in space outside the scope. This technique has the effect of creating output random fields, which can simulate a hydraulic capacity of the studied, as is hydraulic conductivity. Although the random field was generated by specifying geostatistical parameters, estimates of these parameters from single realizations of the generated field are variable (Shafer & Varljen, 1990; Rehfeldt et al., 1992).

STUBA is an iterative method of two main steps. First, it creates a reflective process (random numbers) along a line given covariance function and mean value zero (0). Then, it creates an orthogonal projection of this line on each point of the simulated field matching, at this point, the value of the linear stochastic process. We consider a large number of lines which, however, have a common starting point, leading to the above procedure being repeated several times (Figure 2.1). Visually this can be represented as areas that revolve around their common center. The final result for each point, which is the random number of stochastic processes implemented, is the weighted average of these projections.

Today there are two main ways for the production of one-dimensional stochastic processes along the lines. The first concerns the approximation of spatial areas (Space Domain) and can handle functions only with specific covariance. The second approach relates to the spectral region (Spectral Domain) and can handle a larger number of 2-D processes.

2.3.1 TBM Theoretical Background

We consider $Z_i(u)=1,2,...,N$ a set of N independent implementations of a one-dimensional second order stationary stochastic process along a line, with autocorrelation function $\rho_l(u_0)$, where u_0 is the spatial hysteresis on the line. The values we get from the relationship are:

$$Z_s(x,y,z)=\frac{1}{\sqrt{N}}\sum_{i=1}^{N}Z_i(u) \tag{2.1}$$

This is essentially the simulation of the random field, which is indicated by the index s (simulated). The field generated by this equation has a mean value equal to zero (0). The relationship between the autocorrelation function of the linear process $\rho_l(u_0)$ and that of the three dimensional random field $\rho(u_0)$ is given by *Mantoglou and Wilson* (1982), and *Mantoglou* (1987):

$$\rho_l(u_0)=\frac{d}{du_0}\left[u_0\rho(u_0)\right] \tag{2.2}$$

while for a two-dimensional random field the relationship becomes:

$$\int_0^s \frac{\rho_l du_0}{\sqrt{\left(s^2-u_0^2\right)}}=\frac{\pi}{2}\rho(s) \tag{2.3}$$

where s is spatial hysteresis. From Eq.(2.3) it is not easy to extract $\rho_l(u_0)$ directly as a function of $\rho(s)$. For this reason, a spectral method has been created by *Mantoglou and Wilson* (1982) which extracts the autocorrelation function of the process along the lines of various autocorrelation functions of a two-dimensional field.

To create 2-D random fields it is required to solve the integral Eq. (2.3), which cannot readily be expressed as $\rho_l = f\left(\rho(s)\right)$. To overcome this difficulty, an expression is created that connects the spectral density function of the one-dimension process with the function of radial spectral density of the two-dimensional process used. This expression in Fourier space is given by:

$$S_l(\omega) = \frac{\sigma_Z^2}{2} S(\boldsymbol{\omega}) \tag{2.4}$$

and connects $S_l(\omega)$ with the product of $S(\boldsymbol{\omega})$ over half of the variation of the two-dimensional process. The steps followed in the implementation of SSTUBA are outlined below.

2.3.2 Establishment of the One-dimensional Linear Process

There are two main techniques for the creation of the process lines. The first is the Fourier transformation (Fast Fourier Transformation), which can be used to give us the complex process, $X(u) = Z(u) + iY(u)$, which is given by *Tompson et al.* (1989) as:

$$X(u) = \int_{all\omega} e^{i\omega u} dW(\omega) \approx \sum_{all\omega} e^{i\omega_j u} dW(\omega_j) \tag{2.5}$$

where X is the sum of sinusoidal functions of complex sequences with different wavelengths, where each increases by a random complex of average size equal to zero (0). The second technique is called Normal Integration by Fourier (Standard Fourier Integration). According to this method, the real part of the complex process $X(u)$ is given by:

$$\operatorname{Re} X(u) = Z(u) = \int_{all\omega} |dW(\omega)| \cos(\omega u + \phi_\omega) \tag{2.6}$$

and can be directly used to create distinct approaches using positive frequencies:

$$Z_i(u) = \sum_{j=1}^{M} |dW(\omega_j)| \cos(\omega_j u + \phi_j) \tag{2.7}$$

where ϕ_j are independent random angles with uniform distribution between 0 and 2π, M is the number of harmonics used in the simulation, $\omega_j = (j - 0.5)\Delta\omega$, $j = 1, 2, ..., M$, $\Delta\omega$ is the discretized frequency which is given by $\omega_{\max}/M$, and $\omega_{\max}$ is the maximum frequency used in all calculations. $|dW(\omega_j)|$ is calculated deterministically from the spectrum range as

$$|dW(\omega_j)| = \left[4S_l(\omega_j)\Delta\omega\right]^{1/2} \tag{2.8}$$

where $S_l(\omega_j)$ is the spectral density function of the actual process $Z(u)$ on the lines.

$S_l\left(\omega_j\right)$ is considered negligible outside the region $\left[-\omega_{\max},+\omega_{\max}\right]$. Substituting (2.8) in (2.7) we obtain the generator function of the one-dimensional process on each line i as (Shinozuka & Jan, 1972):

$$Z_i\left(u\right)=2\sum_{j=1}^{M}\left[S_l\left(\omega_j\right)\Delta\omega\right]^{1/2}\cos\left(\omega_j' u+\phi_j\right) \tag{2.9}$$

where $\omega_j' = \omega_j + \delta\omega$. Frequency $\delta\omega$ is a small frequency range, uniformly distributed between $-\Delta\omega'/2$ and $\Delta\omega'/2$, where $\Delta\omega' = \Delta\omega/20$, which is added in order for periodic phenomena to be avoided.

The approach of this methodology results in a discrete frequency $\Delta\omega$ as the maximum cutoff frequency is $\omega_{\max} = M\Delta\omega$. This method requires more computational time than the FFT, but is much more flexible in the choice of parameter values $M, \Delta\omega, \Delta u, \omega_{\max}$ and $u_{\max}$ (Tompson et al., 1989).

2.3.3 Number and Distribution of Turning Bands

The theory of STUBA is based on the approach that we have an infinite number of rotating lines. Let us assume that the lines have random orientations, as resulting from a uniform distribution of a unit circle or sphere of a unit for the case of 2-D or 3-D fields, respectively. It has been shown (Mantoglou & Wilson, 1982) that if the lines are selected on the unit circle or on the unit sphere, with equal angles between them and with predetermined directions, then the autocorrelation function of the random field we try to simulate converges faster towards the theoretical form. Usually, a number of lines between eight (8) to sixteen (16) is a good choice for an isotropic autocorrelated function. In case an anisotropic situation is dealt with, it is necessary to select a larger number of lines.

2.3.4 Spectral Discretization and Random Fields Generation

The implementation process $Z_i\left(u_n\right)$ on line i at the point n is done by integrating a series of discretized random components coming from the whole spectral range. Discretization factor of frequency $\Delta\omega$ must be small enough to achieve an adequate degree of precision, while the number of harmonics M must be large enough to be counted as contributions of spectral edges at $\omega_{\max} = M\Delta\omega$. *Mantoglou and Wilson* (1982) have calculated that the values can vary between 50 and 100, while $\omega_{\max}$ in each case was 40 times larger than the correlation length.

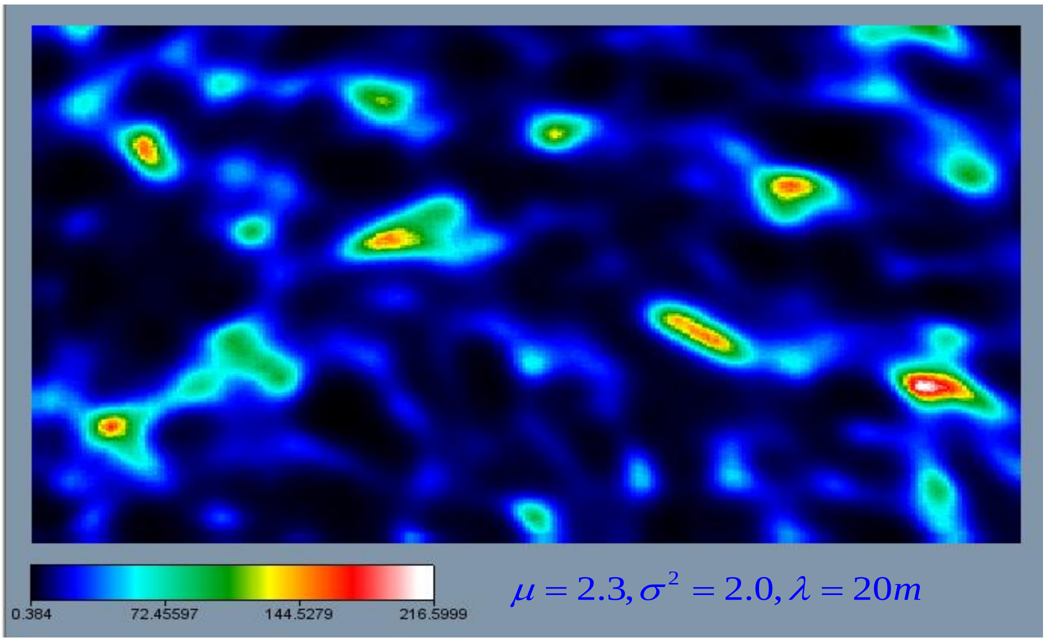

Figure 2.2: A 2-D hydraulic conductivity field generated by STUBA, where $\mu_K = 2.3$, $\sigma_{\ln K}{}^2 = 2.0$ and $\lambda = 20m$.

The length of the discretization Δu used on the lines should be chosen smaller than the respective lengths $\Delta x, \Delta y$ of the simulated field. This is a more general rule that should be applied to avoid arithmetical errors during calculations (Mantoglou & Wilson, 1982). Additionally, the minimum length of the lines is defined by their orientation and the size of the field that we wish to simulate.

Generation of random fields $Z_s(x,y,z)$ will ultimately derive from the entire selection of a finite number of lines L and their specified orientation, from the discretization of the single dimensional process $Z_i(u)$ by assigning a random value on each discrete point n of each line, from the following orthogonal projection of these values on points x of the simulated field and, finally, by dividing the sum of the projections at each point by the factor $L^{1/2}$ to obtain the final value (Elfeki, 1996) (

Figure **2.2**).

2.4 Flow Equation

The equations which describe the flow of a permanent incompressible fluid through a porous material are the continuity equation of the mass:

$$\nabla \cdot q(\mathbf{x}) = 0 \tag{2.10}$$

and Darcy Law:

$$q(\mathbf{x}) = -K(\mathbf{x})\nabla h \tag{2.11}$$

where $x \in \mathbb{R}^3$, where $h[L]$ is hydraulic front, $K(\mathbf{x})\,[L/T]$ is hydraulic conductivity and $B[L]$ is the aquifer's depth. Combining the above equations we get,

$$\nabla \cdot \left(K(\mathbf{x})\nabla h\right) = 0 \tag{2.12}$$

which in $\mathbb{R}^3$ is written,

$$\frac{\partial}{\partial x}\left(K(\mathbf{x})\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K(\mathbf{x})\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K(\mathbf{x})\frac{\partial h}{\partial z}\right) = 0 \tag{2.13}$$

The above partial differential equation describes the permanent groundwater flow in 3-D within the saturated zone of an isotropic, heterogeneous, porous material with a constant depth aquifer (Bear & Buchlin, 1987). The resolution, in conjunction with the boundary conditions specified for the particular model, gives values of the hydraulic front as distinct change in space within the heterogeneous saturated control volume.

We assume a 3-D dimensional elementary parallelepiped volume of dimensions L_x, L_y and L_z which it simulates a heterogeneous, saturated aquifer (Figure 2.3). The reference axes of the system are oriented so that the to coincide with the flow direction. The flow field is described by uniformly hydraulic head difference in perpendicular planes to $x - axis$, which are applied at the boundaries 0 and L_x of the volume control. This results in the coincidence of the hydraulic gradient direction with that of the average flow. The boundary condition of zero flow is applied to the two remaining directions, i.e. $\partial h/\partial y = 0$ and $\partial h/\partial z = 0$.

At the volume control that has been defined the flow equation is solved numerically, considering the hydraulic conductivity as a second order random function. The method used in this work is that of finite differences calculated at seven (7) adjacent points (Desbarats, 1992; Sarris, 1999), defined in the center of the elementary cubes of the lattice in which the parallelepiped is discretized. If, for example, the point (i, j, k) is considered, then that function value on it is calculated according to points $(i+1, j, k)$, $(i-1, j, k)$, $(i, j+1, k)$, $(i, j-1, k)$, $(i, j, k+1)$ and $(i, j, k-1)$. The central scheme of the hydraulic head calculation was used in order the same volume to correspond to the hydraulic conductivity parameters, so as each of them to acquire the same weight into arithmetic calculation of the differential flow equation.

The flow equation discretization into the centers of the elementary volumes, which are also called nodes of the grid, with dimensions D_x, D_y and D_z is made by approaching the second and first derivatives with the differences of the hydraulic heads. By analyzing each term of the equation flow separately, it is for the direction of the $x-axis$,

$$K\frac{\partial h}{\partial x} \approx K\left(i+\frac{1}{2}, j, k\right)\left[\frac{h(i+1, j, k)-h(i, j, k)}{\Delta x}\right] \tag{2.14}$$

where $K(i+1/2, j, k)$ is the value of hydraulic conductivity in the mid-space between nodes (i, j, k) and $(i+1, j, k)$, which is approximated with the harmonic mean of the two adjacent nodes in X direction and is given by,

$$K\left(i+\frac{1}{2}, j, k\right) = \frac{2K(i+1, j, k)K(i, j, k)}{K(i, j, k)+K(i+1, j, k)} \tag{2.15}$$

Similarly, we have for directions Y and Z,

$$K\frac{\partial h}{\partial y} \approx K\left(i, j+\frac{1}{2}, k\right)\left[\frac{h(i, j+1, k)-h(i, j, k)}{\Delta y}\right] \tag{2.16}$$

$$K\frac{\partial h}{\partial z} \approx K\left(i, j, k+\frac{1}{2}\right)\left[\frac{h(i, j, k+1)-h(i, j, k)}{\Delta z}\right] \tag{2.17}$$

where $K\left(i, j+\frac{1}{2}, k\right) = 2K(i, j+1, k)K(i, j, k)/K(i, j, k)+K(i, j+1, k)$ and

$$K\left(i, j, k+\frac{1}{2}\right) = 2K(i, j, k+1)K(i, j, k)/K(i, j, k)+K(i, j, k+1).$$

The above equation is discretized to

$$\frac{K\left(i+\frac{1}{2},j,k\right)\left[\frac{h(i+1,j,k)-h(i,j,k)}{\Delta x}\right]-K\left(i-\frac{1}{2},j,k\right)\left[\frac{h(i,j,k)-h(i-1,j,k)}{\Delta x}\right]}{\Delta x}+$$
$$\frac{K\left(i,j+\frac{1}{2},k\right)\left[\frac{h(i,j+1,k)-h(i,j,k)}{\Delta y}\right]-K\left(i,j-\frac{1}{2},k\right)\left[\frac{h(i,j,k)-h(i,j-1,k)}{\Delta y}\right]}{\Delta y}+ \qquad (2.18)$$
$$\frac{K\left(i,j,k+\frac{1}{2}\right)\left[\frac{h(i,j,k+1)-h(i,j,k)}{\Delta z}\right]-K\left(i,j,k-\frac{1}{2}\right)\left[\frac{h(i,j,k)-h(i,j,k-1)}{\Delta z}\right]}{\Delta z}=0$$

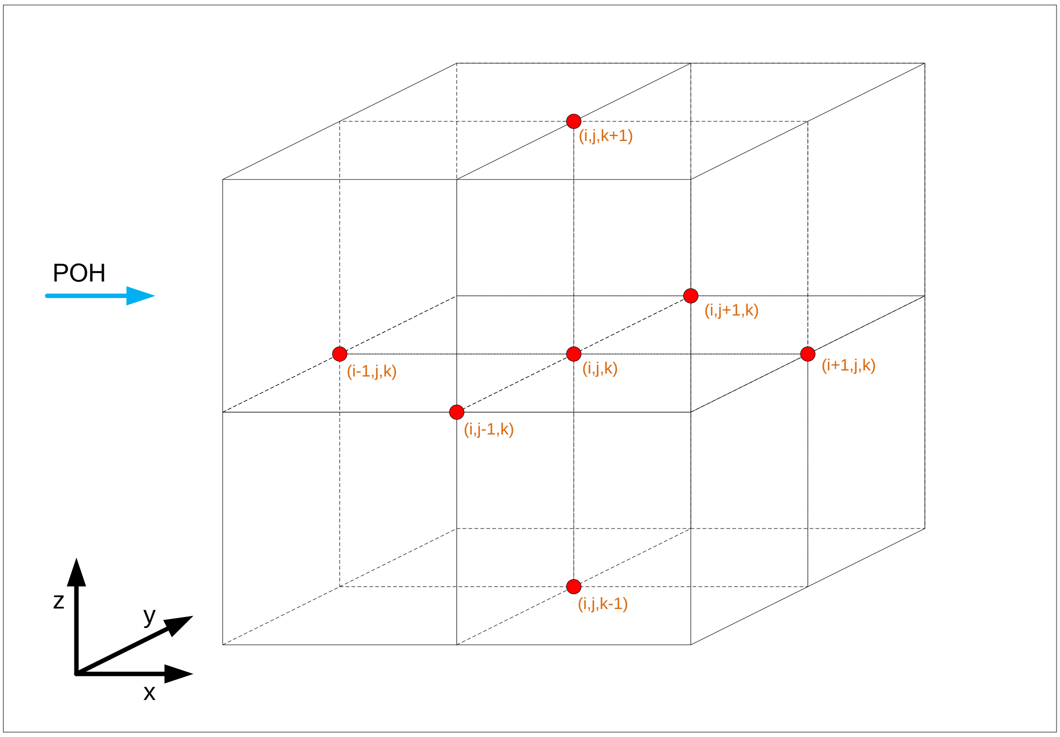

Figure 2.3: 3-D Field Discretization

We are forming and calculating, using the known values of hydraulic conductivity on each node, the terms below,

$$A(i,j,k)=K\left(i+\frac{1}{2},j,k\right)\Big/\Delta x^{2} \tag{2.19}$$

$$B(i,j,k)=K\left(i,j+\frac{1}{2},k\right)\Big/\Delta y^{2} \tag{2.20}$$

$$C(i,j,k)=K\left(i,j,k+\frac{1}{2}\right)\Big/\Delta z^{2} \tag{2.21}$$

$$D(i,j,k)=K\left(i-\frac{1}{2},j,k\right)\Big/\Delta x^{2} \tag{2.22}$$

$$E(i,j,k)=K\left(i,j-\frac{1}{2},k\right)\Big/\Delta y^{2} \tag{2.23}$$

$$F(i,j,k)=K\left(i,j,k-\frac{1}{2}\right)\Big/\Delta z^{2} \tag{2.24}$$

$$G(i,j,k)=A(i,j,k)+B(i,j,k)+C(i,j,k)+D(i,j,k)+E(i,j,k)+F(i,j,k) \tag{2.25}$$

Consequently, the three-dimensional approximation using the finite differences scheme of the flow equation is written as

$$G(i,j,k)h(i,j,k)=A(i,j,k)h\left(i+\frac{1}{2},j,k\right)+B(i,j,k)h\left(i,j+\frac{1}{2},k\right)+$$
$$C(i,j,k)h\left(i,j,k+\frac{1}{2}\right)+D(i,j,k)h\left(i-\frac{1}{2},j,k\right)+E(i,j,k)h\left(i,j-\frac{1}{2},k\right)+ \tag{2.26}$$
$$+F(i,j,k)h\left(i,j,k-\frac{1}{2}\right)$$

To solve the above equation we consider Dirichlet boundary conditions on X-axis, where we assume known values of hydraulic front at *X=0* and $X=L_x$. On Y-axis and Z-axis we consider Neumann boundary conditions, assuming no flow at the boundaries of *Y=0*, $Y=L_y$, *Z=0* and $Z=L_z$. Algebraic equations along with their boundary conditions are computationally solved, using the iterative scheme of Line Successive Over Relaxation Method (LSORM) (Young, 1954), whose source code was developed by *Desbarats* (1992) and adopted directly by the work of *Sarris* (1999). According to this arithmetic method, hydraulic head values on grid nodes are continuously updated until the difference between the last two successive values becomes less than a predefined limit, which in this case was set equal to 10^{-5}. The final results of this computational process are hydraulic heads on every node $h(i,j,1)$ of the simulated area's grid.

2.5 Velocity Field

Using Darcy's law velocity field components were calculated on each grid node. Velocities were calculated according to

$$\mathbf{u}=\frac{K_{xx}}{\varepsilon}\frac{\partial h(x,y,z)}{\partial x}\hat{u}+\frac{K_{yy}}{\varepsilon}\frac{\partial h(x,y,z)}{\partial y}\hat{v}+\frac{K_{zz}}{\varepsilon}\frac{\partial h(x,y,z)}{\partial z}\hat{k} \tag{2.27}$$

where ε is the field's effective porosity. Due to isotropy, it is $K=K_{xx}=K_{yy}=K_{zz}$ and every component is calculated as

$$u_x=\frac{K}{\varepsilon}\frac{\partial h(x,y,z)}{\partial x},\ u_y=\frac{K}{\varepsilon}\frac{\partial h(x,y,z)}{\partial y}\ \text{and}\ u_z=\frac{K}{\varepsilon}\frac{\partial h(x,y,z)}{\partial z} \tag{2.28}$$

The partial derivative on each node *i,j,k* is given by the three-point approximation where

$$\frac{\partial h(x,y,z)}{\partial x}=\frac{h(x_{i+1},y,z)-h(x_{i-1},y,z)}{2\Delta x} \tag{2.29}$$

$$\frac{\partial h(x,y,z)}{\partial y} = \frac{h\left(x, y_{j+1}, z\right) - h(x, y_{j-1}, z)}{2\Delta y} \tag{2.30}$$

$$\frac{\partial h(x,y,z)}{\partial z} = \frac{h\left(x, y, z_{k+1}\right) - h(x, y, z_{k-1})}{2\Delta z} \tag{2.31}$$

where -1 and +1 indexes indicate hydraulic head on nodes before and after the node whose velocity components we want to calculate. At boundaries of the simulated area, where $\left(x = 0, x = L_x\right)$ and $\left(y = 0, y = L_y\right)$, the difference between two adjacent nodes was used.

2.6 Conservation Hypothesis and Diffusion – Dispersion Equation

A basic assumption in this work is that pollution is caused by a single substance, which is chemically inert in the environment. In addition, no sorption occurs. This means that groundwater plume transportation and dispersion depend only on the speed of the flow field and the heterogeneity of the subsoil. Although this assumption is not realistic, it allows us to study the phenomenon of pollution transportation and monitoring system performance, only as a function of the heterogeneity of the subsoil. In fact, various pollutants during groundwater transportation are suffering biological processes (biodegradation) as well as chemical changes which, as a rule, slow down the flow of plumes without necessarily reducing their toxic effects (Rowe, 1995; Fatta et al., 1999; Renou et al., 2008). In the case of 3-D steady flow, the transport-diffusion can be written (Bear, 1988)

$$\begin{aligned} &\frac{\partial C}{\partial t} + v_x \frac{\partial C}{\partial x} + v_y \frac{\partial C}{\partial y} + v_z \frac{\partial C}{\partial z} - \frac{\partial}{\partial x}\left[D_{xx} \frac{\partial C}{\partial x} + D_{xy} \frac{\partial C}{\partial y} + D_{xz} \frac{\partial C}{\partial z} \right] - \\ &- \frac{\partial}{\partial y}\left[D_{yx} \frac{\partial C}{\partial x} + D_{yy} \frac{\partial C}{\partial y} + D_{yz} \frac{\partial C}{\partial z} \right] - \frac{\partial}{\partial z}\left[D_{zx} \frac{\partial C}{\partial x} + D_{zy} \frac{\partial C}{\partial y} + D_{zz} \frac{\partial C}{\partial z} \right] = 0 \end{aligned} \tag{2.32}$$

where C is pollution concentration at time t at position (x, y, z), and v_x, v_y, v_z are the measures of flow velocity components at directions x, y, z respectively. Factors D_{ij}, where $i, j = 1, 2, 3$, are components of the hydro – dispersion tensor and are given by (Bear, 1988; Feyen et al., 1998)

$$D_{i,j} = \left(a_T |v| + D_m\right)\delta_{ij} + \left(a_L - a_T\right)\frac{v_i v_j}{|v|} \tag{2.33}$$

where δ_{ij} is Kronecker's operator, a_L $[L]$ is the longitudal dispersion coefficient, a_T $[L]$ is the transverse dispersion coefficient, D_m the molecular diffusion coefficient and

$|v| = \sqrt{v_x^2 + v_y^2 + v_z^2}$ is the measure of groundwater flow velocity. Concentration C boundary conditions of the 2-D simulation is $\partial C / \partial y(x, 0, t) = 0,\ \partial C / \partial y(x, L_y, t) = 0$ for every $t \geq 0$ and $C(x, y, 0) = 0$ when $0 \leq x \leq L_x, 0 \leq y \leq L_y$.

2.7 Random Walk Tracking Particle

The Random Walk Tracking Particle (RWTP) method treats the transport of a solute mass via a large number of particles. It moves each particle through the porous medium using the velocity field obtained from the solution of the flow equation to simulate advection and adds a random displacement to simulate dispersion. This approach avoids solving the transport equation directly and therefore is virtually free of numerical dispersion and artificial oscillations (Salamon et al., 2006b).

RWTP is a method from Statistical Physics which has been used in the analysis of dispersion and diffusion processes in porous media. It was observed that particles accumulate in low permeability zones, resulting in unrealistic concentrations (Kinzelbach, 1987). This is due to the fact that a slight dissimilarity between the random walk equation, better known as the Fokker-Planck equation, and the advection-dispersion equation exists. In mildly heterogeneous systems, where groundwater flow velocity changes only slightly, this difference is negligible. However, in aquifers with a high variability in groundwater flow velocity, i.e. very heterogeneous hydraulic conductivity fields or areas with strong sink/source conditions, this difference gains importance, and a correction term to retrieve the advection-dispersion equation has to be included.

Mathematical formulation of RWTP begins with the transport equation of a conservative solute in an aquifer, which at the representative elemental volume scale is given by the following equation

$$\frac{\partial c}{\partial t} + \nabla \cdot (\mathbf{u} c) = \nabla \cdot (\mathbf{D} \nabla c) \tag{2.34}$$

where D is the dispersion coefficient tensor, usually denoted as

$$\mathbf{D} = (a_T |\mathbf{u}| + D_m)\mathbf{I} + (a_L - a_T)\frac{\mathbf{u}\mathbf{u}^t}{|\mathbf{u}|} \tag{2.35}$$

c is the dissolved concentration, t is the time, a_L and a_T are the longitudinal and transverse dispersivity respectively, D_m is the molecular diffusion coefficient, u is the velocity vector obtained from the solution of the steady-state flow equation, and $|u|$ is the magnitude of the velocity vector. Here, porosity is assumed constant and velocity fluctuations are mainly attributed to a spatially varying hydraulic conductivity. This represents a second-order partial differential equation, which can be solved using an Eulerian approach by standard finite difference or finite element methods.

RWTP simulates solute transport by partitioning the solute mass into a large number of representative particles. The evolution of a particle in time is driven by a drift term that relates to the advective movement and a superposed Brownian motion responsible for dispersion. The displacement of a particle is written in its traditional form, given by the Itô -Taylor integration scheme (Gardiner, 1990)

$$\mathbf{X}_p(t+\Delta t)=\mathbf{X}_p(t)+\mathbf{A}\left(\mathbf{X}_p,t\right)\Delta t+\mathbf{B}\left(\mathbf{X}_p,t\right)\cdot\boldsymbol{\xi}(t)\sqrt{\Delta t} \tag{2.36}$$

where Δt is the time step, $\mathbf{X}_p(t)$ is the position of a particle at time t, $\mathbf{A}$ is a drift vector, the displacement matrix $\mathbf{B}$ is a tensor defining the strength of dispersion and $\xi(t)$ is a vector of independent, normally distributed random variables with zero mean and unit variance.

It has been demonstrated by Itô (1951) that the particle density distribution $f\left(\mathbf{X}_p,t\right)$, defined as the probability of finding a particle within a given interval $\left[\mathbf{X}_p,\mathbf{X}_p+d\mathbf{X}_p\right]$ at a given time t and obtained from Eq.(2.36) fulfills, in the limit of large particle numbers and an infinitesimally small step size, the Fokker-Planck equation, which describes the motion of the particle density distribution f , and is given by

$$\frac{\partial f}{\partial t}+\nabla\cdot(\mathbf{u}f)=\nabla\nabla:(\mathbf{D}f) \tag{2.37}$$

where the colon refers to the outer product for multiplying two tensors and thus

$$\nabla\nabla:(\mathbf{D}f)\equiv\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{\partial^2 D_{ij}}{\partial x_i\partial x_j}f \tag{2.38}$$

where n denotes the dimensions number.

Both the advection-dispersion and the Fokker-Planck equation are similar to each other as both are composed of an advection-drift term and a dispersion-diffusion term. In order, though, for an analogy to be established between them, Eq. (2.34) has to be modified as (Kinzelbach, 1987):

$$\frac{\partial c}{\partial t}+\nabla\cdot(\mathbf{u}c)+\nabla\cdot(c\nabla\cdot\mathbf{D})=\nabla\nabla:(\mathbf{D}c) \tag{2.39}$$

Using a modified velocity term where

$$\mathbf{u}^* = \mathbf{u} + \nabla \cdot \mathbf{D} \tag{2.40}$$

it can be shown that the solute transport equation for heterogeneous porous media can be transformed into an equivalent of the Fokker-Planck equation (Itô's interpretation)

$$\frac{\partial c}{\partial t} + \nabla \cdot \left(\mathbf{u}^* c \right) = \nabla\nabla : \left(\mathbf{D} c \right) \tag{2.41}$$

Substituting the drift vector $\mathbf{A}$ in Eq.(2.36), the RWTP final scheme is obtained,

$$\mathbf{X}_p\left(t+\Delta t\right) = \mathbf{X}_p\left(t\right) + \left(\mathbf{u}\left(\mathbf{X}_p, t\right) + \nabla \cdot \mathbf{D}\left(\mathbf{X}_p, t\right)\right)\Delta t + \mathbf{B}\left(\mathbf{X}_p, t\right) \cdot \xi\left(t\right)\sqrt{\Delta t} \tag{2.42}$$

where the displacement matrix $\mathbf{B}$ is related to the dispersion tensor according to the relationship

$$2\mathbf{D} = \mathbf{B} \cdot \mathbf{B}^T \tag{2.43}$$

It must be noted that $\mathbf{D}$ is defined in terms of u and not of u^*. For isotropic porous media the three-dimensional form of the displacement matrix $\mathbf{B}$, ignoring the molecular diffusion coefficient, can be expressed as (Tompson et al., 1987a)

$$\mathbf{B} = \begin{pmatrix} \dfrac{u_x}{|u|}\sqrt{2a_L|u|} & -\dfrac{u_x u_z}{|u|\sqrt{u_x^2+u_y^2}}\sqrt{2a_T|u|} & -\dfrac{u_y}{\sqrt{u_x^2+u_y^2}}\sqrt{2a_T|u|} \\ \dfrac{u_y}{|u|}\sqrt{2a_L|u|} & -\dfrac{u_y u_z}{|u|\sqrt{u_x^2+u_y^2}}\sqrt{2a_T|u|} & \dfrac{u_x}{\sqrt{u_x^2+u_y^2}}\sqrt{2a_T|u|} \\ \dfrac{u_z}{|u|}\sqrt{2a_L|u|} & \dfrac{\sqrt{u_x^2+u_y^2}}{|u|}\sqrt{2a_T|u|} & 0 \end{pmatrix} \tag{2.44}$$

or in two dimensions

$$\mathbf{B} = \begin{pmatrix} \dfrac{u_x}{|u|}\sqrt{2a_L|u|} & -\dfrac{u_y}{\sqrt{u_x^2+u_y^2}}\sqrt{2a_T|u|} \\ \dfrac{u_y}{|u|}\sqrt{2a_L|u|} & \dfrac{u_x}{\sqrt{u_x^2+u_y^2}}\sqrt{2a_T|u|} \end{pmatrix} \tag{2.45}$$

The components $\partial D_{ij} / \partial X_j$ can be evaluated using the general expression for D_{ij} (Uffink, 1990),

$$D_{i,j} = a_T |v| \delta_{ij} + \left(a_L - a_T\right)\frac{v_i v_j}{|v|} \tag{2.46}$$

which in matrix form in three dimensions is

$$D=\begin{pmatrix} a_T|u|+(a_L-a_T)\dfrac{u_x^2}{|u|} & (a_L-a_T)\dfrac{u_xu_y}{|u|} & (a_L-a_T)\dfrac{u_xu_z}{|u|} \\ (a_L-a_T)\dfrac{u_yu_x}{|u|} & a_T|u|+(a_L-a_T)\dfrac{u_y^2}{|u|} & (a_L-a_T)\dfrac{u_yu_z}{|u|} \\ (a_L-a_T)\dfrac{u_zu_x}{|u|} & (a_L-a_T)\dfrac{u_zu_y}{|u|} & a_T|u|+(a_L-a_T)\dfrac{u_z^2}{|u|} \end{pmatrix} \tag{2.47}$$

and its gradient is

$$\nabla\cdot\mathbf{D}\left(\mathbf{X}_p,t\right)=\begin{pmatrix} \dfrac{\partial D_{xx}}{\partial x} & \dfrac{\partial D_{xy}}{\partial x} & \dfrac{\partial D_{xz}}{\partial x} \\ \dfrac{\partial D_{yx}}{\partial y} & \dfrac{\partial D_{yy}}{\partial y} & \dfrac{\partial D_{yz}}{\partial y} \\ \dfrac{\partial D_{zx}}{\partial z} & \dfrac{\partial D_{zy}}{\partial z} & \dfrac{\partial D_{zz}}{\partial z} \end{pmatrix} \tag{2.48}$$

where every single component is written

$$\begin{aligned}\frac{\partial D_{xx}}{\partial x}=&\frac{\left(a_Lu_x^3+2a_Lu_xu_y^2+2a_Lu_xu_z^2-a_Tu_xu_y^2-a_Tu_xu_z^2\right)}{|u|^3}\frac{\partial u_x}{\partial x}+\\ &\frac{\left(2a_Tu_x^2u_y+a_Tu_y^3+a_Tu_yu_z^2-a_Lu_x^2u_y\right)}{|u|^3}\frac{\partial u_y}{\partial x}+\\ &\frac{\left(2a_Tu_x^2u_z+a_Tu_y^2u_z+a_Tu_z^3-a_Lu_x^2u_z\right)}{|u|^3}\frac{\partial u_z}{\partial x}\end{aligned} \tag{2.49}$$

$$\begin{aligned}\frac{\partial D_{xy}}{\partial x}=&\frac{(a_L-a_T)\left(1-u_x^2\right)u_y}{|u|^3}\frac{\partial u_x}{\partial x}+\frac{(a_L-a_T)\left(1-u_y^2\right)u_x}{|u|^3}\frac{\partial u_y}{\partial x}-\\ &\frac{(a_L-a_T)u_xu_yu_z}{|u|^3}\frac{\partial u_z}{\partial x}\end{aligned} \tag{2.50}$$

$$\begin{aligned}\frac{\partial D_{xz}}{\partial x}=&\frac{(a_L-a_T)\left(1-u_x^2\right)u_z}{|u|^3}\frac{\partial u_x}{\partial x}-\frac{(a_L-a_T)u_xu_yu_z}{|u|^3}\frac{\partial u_y}{\partial x}+\\ &\frac{(a_L-a_T)\left(1-u_z^2\right)u_x}{|u|^3}\frac{\partial u_z}{\partial x}\end{aligned} \tag{2.51}$$

$$\frac{\partial D_{yx}}{\partial y}=\frac{\left(a_L-a_T\right)\left(1-u_x^2\right)u_y}{|u|^3}\frac{\partial u_x}{\partial y}+\frac{\left(a_L-a_T\right)\left(1-u_y^2\right)u_x}{|u|^3}\frac{\partial u_y}{\partial y}-\frac{\left(a_L-a_T\right)u_xu_yu_z}{|u|^3}\frac{\partial u_z}{\partial y} \tag{2.52}$$

$$\frac{\partial D_{yy}}{\partial y}=\frac{\left(a_Tu_x^3+2a_Tu_xu_y^2+a_Tu_xu_z^2-a_Lu_xu_y^2\right)}{|u|^3}\frac{\partial u_x}{\partial y}+\frac{\left(2a_Lu_x^2u_y+a_Lu_y^3+2a_Lu_yu_z^2-a_Tu_x^2u_y-a_Tu_yu_z^2\right)}{|u|^3}\frac{\partial u_y}{\partial y}+\frac{\left(a_Tu_x^2u_z+2a_Tu_y^2u_z+a_Tu_z^3-a_Lu_y^2u_z\right)}{|u|^3}\frac{\partial u_z}{\partial y} \tag{2.53}$$

$$\frac{\partial D_{yz}}{\partial y}=-\frac{\left(a_L-a_T\right)u_xu_yu_z}{|u|^3}\frac{\partial u_x}{\partial y}+\frac{\left(a_L-a_T\right)\left(1-u_y^2\right)u_z}{|u|^3}\frac{\partial u_y}{\partial y}+\frac{\left(a_L-a_T\right)\left(1-u_z^2\right)u_y}{|u|^3}\frac{\partial u_z}{\partial y} \tag{2.54}$$

$$\frac{\partial D_{zx}}{\partial z}=\frac{\left(a_L-a_T\right)\left(1-u_x^2\right)u_z}{|u|^3}\frac{\partial u_x}{\partial z}-\frac{\left(a_L-a_T\right)u_xu_yu_z}{|u|^3}\frac{\partial u_y}{\partial z}+\frac{\left(a_L-a_T\right)\left(1-u_z^2\right)u_x}{|u|^3}\frac{\partial u_z}{\partial z} \tag{2.55}$$

$$\frac{\partial D_{zy}}{\partial z}=-\frac{\left(a_L-a_T\right)u_xu_yu_z}{|u|^3}\frac{\partial u_x}{\partial z}+\frac{\left(a_L-a_T\right)\left(1-u_y^2\right)u_z}{|u|^3}\frac{\partial u_y}{\partial z}+\frac{\left(a_L-a_T\right)\left(1-u_z^2\right)u_y}{|u|^3}\frac{\partial u_z}{\partial z} \tag{2.56}$$

$$\frac{\partial D_{zz}}{\partial z}=\frac{\left(a_T u_x^3+a_T u_x u_y+2a_T u_x u_z^2-a_L u_x u_z^2\right)}{|u|^3}\frac{\partial u_x}{\partial z}+\frac{\left(a_T u_x^2 u_y+a_T u_y^3+2a_T u_y u_z^2-a_L u_y u_z^2\right)}{|u|^3}\frac{\partial u_y}{\partial z}+\frac{\left(2a_L u_x^2 u_z+2a_L u_y^2 u_z+a_L u_z^3-a_T u_y^2 u_z-a_T u_x^2 u_z\right)}{|u|^3}\frac{\partial u_z}{\partial z} \tag{2.57}$$

Accordingly in two dimensions it is

$$D=\begin{pmatrix} a_T|u|+\left(a_L-a_T\right)\frac{u_x^2}{|u|} & \left(a_L-a_T\right)\frac{u_x u_y}{|u|} \\ \left(a_L-a_T\right)\frac{u_y u_x}{|u|} & a_T|u|+\left(a_L-a_T\right)\frac{u_y^2}{|u|} \end{pmatrix} \tag{2.58}$$

and its gradient is

$$\nabla\cdot\mathbf{D}\left(\mathbf{X}_p,t\right)=\begin{pmatrix} \frac{\partial D_{xx}}{\partial x} & \frac{\partial D_{xy}}{\partial x} \\ \frac{\partial D_{yx}}{\partial y} & \frac{\partial D_{yy}}{\partial y} \end{pmatrix} \tag{2.59}$$

where,

$$\frac{\partial D_{xx}}{\partial x}=\frac{\left(a_L u_x^3+2a_L u_x u_y^2-a_T u_x u_y^2\right)}{|u|^3}\frac{\partial u_x}{\partial x}+\frac{\left(2a_T u_x^2 u_y+a_T u_y^3-a_L u_x^2 u_y\right)}{|u|^3}\frac{\partial u_y}{\partial x} \tag{2.60}$$

$$\frac{\partial D_{xy}}{\partial x}=\frac{\left(a_L-a_T\right)\left(1-u_x^2\right)u_y}{|u|^3}\frac{\partial u_x}{\partial x}+\frac{\left(a_L-a_T\right)\left(1-u_y^2\right)u_x}{|u|^3}\frac{\partial u_y}{\partial x} \tag{2.61}$$

$$\frac{\partial D_{yx}}{\partial y}=\frac{\left(a_L-a_T\right)\left(1-u_x^2\right)u_y}{|u|^3}\frac{\partial u_x}{\partial y}+\frac{\left(a_L-a_T\right)\left(1-u_y^2\right)u_x}{|u|^3}\frac{\partial u_y}{\partial y} \tag{2.62}$$

$$\frac{\partial D_{yy}}{\partial y}=\frac{\left(a_T u_x^3+2a_T u_x u_y^2-a_L u_x u_y^2\right)}{|u|^3}\frac{\partial u_x}{\partial y}+\frac{\left(2a_L u_x^2 u_y+a_L u_y^3-a_T u_x^2 u_y\right)}{|u|^3}\frac{\partial u_y}{\partial y} \tag{2.63}$$

An extensive review of the method can be found in the work of *Tompson et al.* (1989), *Salamon et al.* (2006b), and *Delay et al.*(2005).

Numerical implementation of the random walk equations is relatively simple with one exception. When solving the flow equation using numerical methods, the resulting hydraulic heads and the associated velocity field are usually given as discrete point information. Yet, simulation of solute transport by the random walk methodology requires continuous information of the velocity field. Therefore, a map of velocities from this discrete information has to be generated. This velocity map should fulfill the local fluid mass balance at any location and the local solute mass conservation at any grid-cell interface. In practice, this means that there is a need for a velocity interpolation scheme. The velocity interpolation approach addresses the problem of discontinuities in the dispersion tensor.

During the present study the bilinear interpolation scheme was used. In this approach the velocities are first linearly interpolated in one direction and then in the orthogonal direction using their neighboring grid-cells, so that velocities are obtained for each corner of the cell. The velocity at any point can then be calculated as a weighed average of these four velocities as is shown in Eq.(2.64) and Eq.(2.65). Approaching the cell interface of cells (i, j) and $(i, j+1)$ from either side, it results in a smooth transition of the velocity u_x and thus in an equal dispersive solute mass flux from either side,

$$\begin{aligned} u_x = &\left(\Delta x - F_x\right)\left(\Delta_y - F_y\right)u_{x,(i-1/2,\, j-1/2)} + F_x\left(\Delta_y - F_y\right)u_{x,(i+1/2,\, j-1/2)} + \\ &\left(\Delta x - F_x\right)F_y u_{x,(i+1/2,\, j-1/2)} + F_x F_y u_{x,(i+1/2,\, j+1/2)} \end{aligned} \tag{2.64}$$

$$\begin{aligned} u_y = &\left(\Delta x - F_x\right)\left(\Delta_y - F_y\right)u_{y,(i-1/2,\, j-1/2)} + F_x\left(\Delta_y - F_y\right)u_{y,(i+1/2,\, j-1/2)} + \\ &\left(\Delta x - F_x\right)F_y u_{y,(i+1/2,\, j-1/2)} + F_x F_y u_{y,(i+1/2,\, j+1/2)} \end{aligned} \tag{2.65}$$

2.8 Problem Uncertainties and Model Structure

The problem involves essentially five different factors of uncertainty: the natural variability of the geological field, the dispersion of pollution, the initiation point of pollution, the size of the source and the duration of the leak. Each of these factors will be addressed during simulations, either within a stochastic framework or a deterministic one, setting a baseline which will remain constant during each different study.

Hydraulic conductivity is one of the major uncertainties of the model (Gelhar, 1986; Gómez-Hernández & Gorelick, 1989; Gelhar et al., 1992; Harvey & Gorelick, 1995)(Yenigul, 2005). Available experimental evidence from studies in different geological areas has shown that hydraulic conductivity can be simulated by a stochastic process (Freeze, 1975; Gutjahr et al., 1978), which means that this parameter can be simulated by a random variable which, however, follows a specific probability distribution. Consequently, neighboring hydraulic conductivity values are statistically correlated. It has been seen in former surveys (Freeze, 1975; Gelhar, 1986; Sudicky, 1986) that hydraulic conductivity is better simulated as a function of logarithmic normal distribution (log-normal). Although there are several ways to create random geological fields, such as the Sequential Gaussian simulation (Dimitrakopoulos & Luo, 2004) and geo-statistical technics such as kriging (Hoeksema & Kitanidis, 1985), the Spectral Turning Bands Method (STUBA), which is very fast computationally, was used to simulate the two-dimensional geological field.

Upon the time the pollutant enters the aquifer's flow field, it starts to move along the streamlines. In addition to this movement, there is another velocity component which comes from the diffusion and the dispersion of the pollutant inside the medium. There are a number of possible numerical approaches for solving the transport problem and simulating this kind of movement. In this study the Particle Tracking method based upon 'Random Walk' approach (Tompson et al., 1987a; Uffink, 1990; Yenigül et al., 2005; Salamon et al., 2006b; Salamon et al., 2006a; Yenigül et al., 2011) has been utilized. This choice is based on the algorithm's ease of implementation, its mass conservative nature and its computational effort economy, since it is independent from the control area we want to simulate. Sensitivity analysis to the number of the tracking particles used was conducted in order to better describe the contaminated plume transportation.

It is assumed that the start of a leak comes from a single point in the area of control and that all the quantity of leachate enters instantly into the aquifer's field of flow. This assumption holds true either for the instantaneous or for the precipitation triggered pollution case. It is also assumed that the only possibility of detection of underground contamination is through the wells of the monitoring system installation.

During each simulation a different, equally-probable point of the control area is selected, within its natural boundaries, as a starting point of pollution. In this way, the uncertainty of the starting point of pollution is simulated, as every point within a controlled area has the same potential, as any other point, to be the one where the pollution starts. It is considered that at the beginning of the simulation or, in the case precipitation triggered pollution, at the beginning of every simulated day the total concentration of the pollutant is injected into the flow field of the aquifer's saturated zone and thereafter starts to move and disperse.

2.9 Simulation Model

2.9.1 Model Structure

The basic assumption of the Monte Carlo simulation framework is that the hydraulic conductivity of a geological field can be simulated by random numbers, which have specific statistical moments (Freeze 1975). According to this method, a random number generator function produces, via a particular process, hypothetical values of hydraulic conductivity of each point of the geological field that is to be simulated and which is required to be used in further calculations. These values are derived from a function with a given probability density, resulting in a certain distribution with a known mean and other statistical moments. By doing so, a geological field is created which simulates the real field about which hydraulic conductivity and its change are known in detail. The variogram of the field that is constructed, which captures the correlation of a point of the field with its neighbors according to the distance between them, is close to that of the real field. With this mechanism it is possible to "know" the heterogeneity of the hydro-geological environment. This process is repeated several times and each time it creates a different but equally probable geological field simulation. In each of these realizations the classical differential equations describing the respective problem can be solved to compute, for example, the flow field of a pollutant in the subsoil. From the total realization of the equally probable flux fields the statistical measures of the parameters of interest can be calculated, such as the hydraulic front, the speed of pollutants or the size and geometry of the created plumes. An illustrative way of how the Monte Carlo method works is depicted in Figure 2.4.

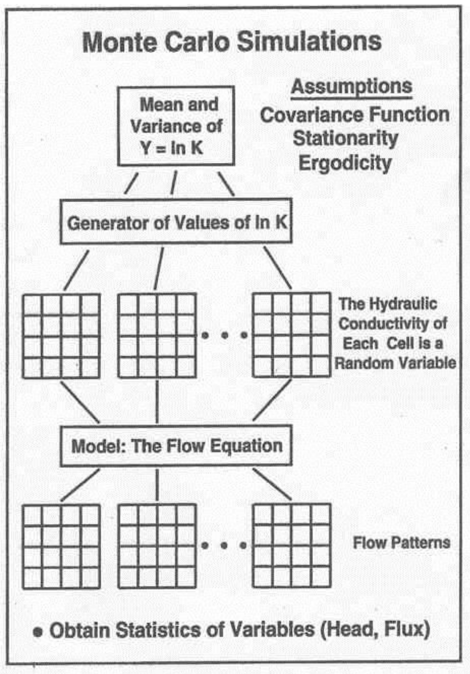

Figure 2.4: Operating principle of Monte Carlo method

This approach has the major advantage that it is relatively simple and easily applicable even to complex problems of three-dimensional hydro-geological environments. The only requirement is computing power. Of course, the rationale on which the operation of Monte Carlo stochastic modeling is established is that of ergodicity, which is axiomatically accepted. This enables us to assume that true values of the parameters of the geological field are approximated, as they are statistically calculated using numerous fantastic realizations of the random fields.

According to this framework, a number of outputs of hydraulic conductivity fields is derived and the plume's detection from the specific arrangement of wells is evaluated separately in each of these realizations. The steps that the model follows are:

Step 1: A 2-D random hydraulic conductivity field is created using the STUBA. The field is 1000 m L_x long and 400 m L_y wide. Heterogeneity is expressed through the variance of hydraulic conductivity $\sigma^2_{\ln K}$, which varies between 0.0 (homogeneous field) and 2.0 (highly heterogeneous field), depending on the cases studied. Hydraulic conductivity logarithmic mean is constant and equal to 2.3 in all cases. Moreover, the correlation length λ of the field is considered to be equal to 20 m for both directions x and y (isotropic medium).

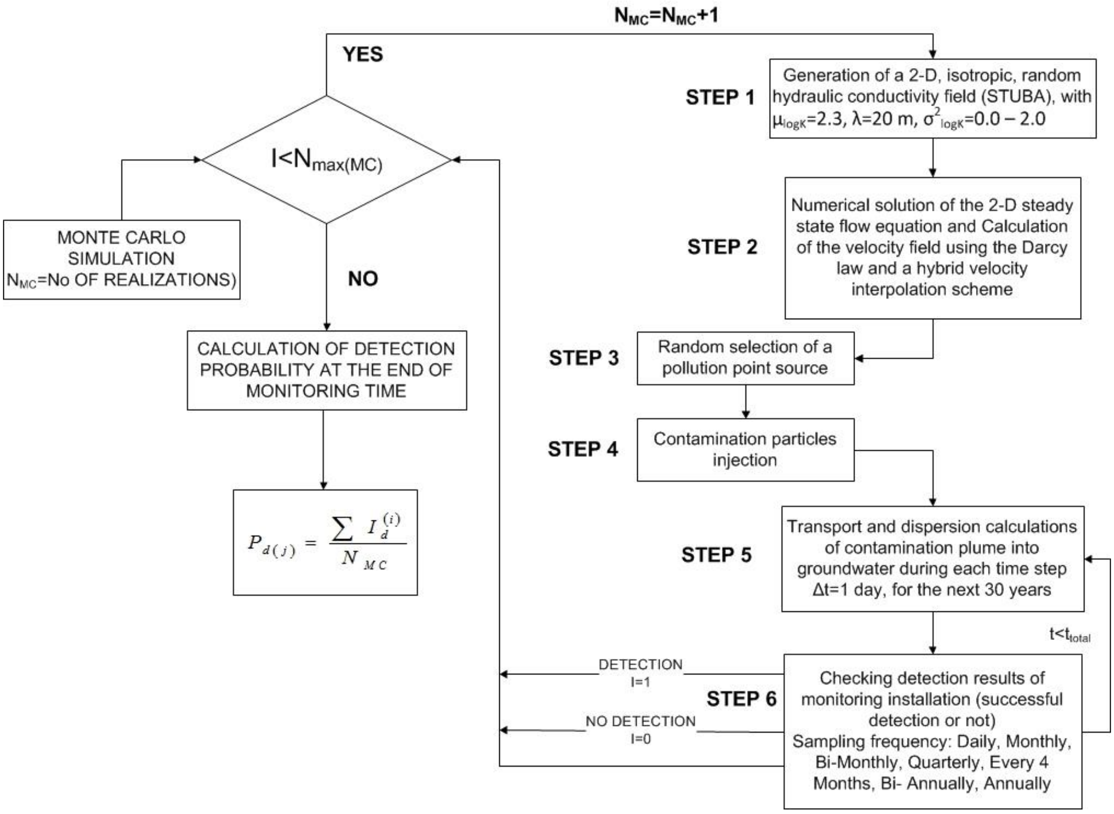

Figure 2.5: Instantaneous case pollution Monte Carlo simulation process diagram

Step 2: The hydraulic head field is calculated, numerically solving the partial differential equation describing the steady state flow of groundwater in two dimensions within the saturated zone of an isotropic, heterogeneous, porous medium with a fixed depth of aquifer Eq.(2.13) (Bear, 1988). The boundary conditions set for the model are constant hydraulic pressure equal to 0.001 m between nodes perpendicular to the direction of flow and no-flow conditions at the lower and upper boundaries of the control area. The region was discretized setting $\Delta x = \Delta y = 2m$. Eq.(2.13) is numerically solved on each grid's node according to the method of seven point finite differences, using an algorithm that has been developed by *Desbarats* (1992). The calculation of velocity field on each node of the control area takes place using Darcy's law.

Step 3: A point is randomly selected inside the boundaries of the control area, which may be considered as a landfill cell, where the pollution is thought to have started. The landfill facility is assumed to be located between 50m and 100m in $x - axis$ direction and 140m and 260m in $y - axis$ direction.

Step 4: At instantaneous cases, the total mass of the pollutant injected into the aquifer is 1000gr, and the initial concentration of the contaminant is calculated equal to 4000 mgr/lt, assuming effective porosity equal to 0.25. Threshold C_{TH} concentration that is detectable from monitoring wells is set to 0.35% (or 28 particles per cell) of the initial concentration. At the precipitation triggered pollution case, it was considered that if during a simulation time step a rainfall took place, then a certain quantity of pollution, proportional to the total rain height, would have been injected into the aquifer and diffused into the flow very rapidly, without disturbing groundwater flow. Threshold detection limit was also set at $C_{Th} = 14$mgr/lt, which indicates the presence of chemicals into groundwater in such a degree that remediation actions should take place.

Step 5: Evolution of the contaminant plume is obtained by employing the Random Walk Particle algorithm, where several individual random movements of particles form a dispersing particle cloud characterizing the contaminant's mass distribution. Eq. (2.42) in two dimensions provides the displacement of each particle in every time step Δt. In all simulations at this survey the values of longitude and transverse dispersion coefficients, α_L, α_T, are interrelated through the $\alpha_T = a_L / 10$. Different cases of dispersion have been studied, where α_T varies between 0.001m for low dispersion subsoil and 0.50m for high dispersion cases.

Step 6: The contaminant's concentration has been monitored at each well, whether it is equal to or greater than the threshold concentration of detection. Because the solution of advection-dispersion transport equation by the Random Walk method provides discrete displacement of particles and not the concentration values themselves, a new grid similar to the one used for the solution of groundwater flow equations is superimposed onto the control area, so as for particle density in each grid to be converted into concentrations. The average concentration in a grid cell (i,j), with dimensions Δx and Δy in $x-axis$ and $y-axis$ directions respectively, is given by:

$$C_{ij}(t)=\frac{M_0 n_{ij}(t)}{Nnb\Delta x\Delta y} \tag{2.66}$$

where $C_{ij}(t)$ is the volume average concentration in grid cell (i,j) at time t, M_0 is the total initial mass of the particles, $n_{ij}(t)$ is the number of particles in grid cell (i,j), N is the total number of particles, n is effective porosity and b is the depth of the aquifer, considered equal to one. If contamination in any of the wells'configuration is

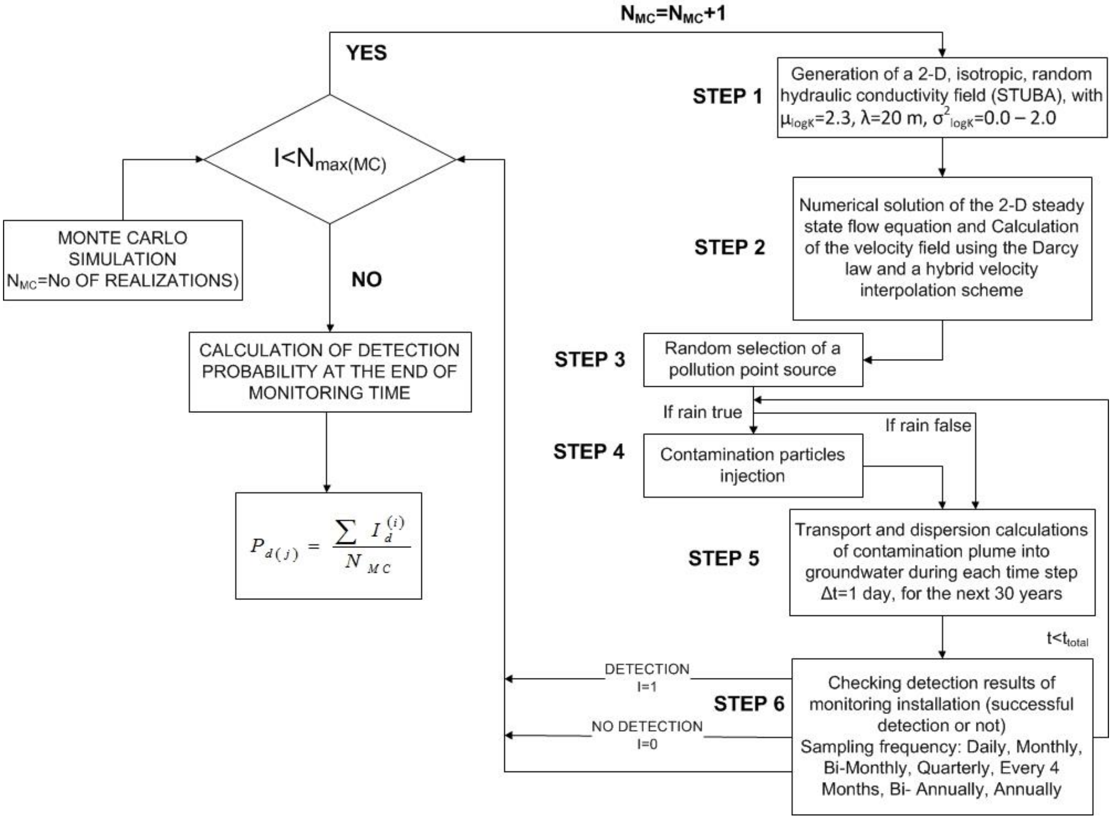

Figure 2.6: Precipitation triggered pollution case Monte Carlo simulation process diagram

detected at any time step during monitoring time, which is set to 30 years, a successful detection is logged as a unit value (1). If the total running time is less than the monitoring period and the examined case concerns the instantaneous pollution case, the process goes to STEP 5 (Figure 2.5) . If it is the precipitation triggered pollution case examined and the total running time is less than the monitoring period, the process goes before STEP 4, where pollution is added if there is rainfall recorded

(Figure 2.6). If the total running time is equal to the monitoring period (30 years=10,950 days) and the number of total realizations is less than 3,000, the process goes to STEP 1 and restarts. Before that, if there is a successful detection, then its time is recorded and the total contaminated area is calculated. At the end of the 3,000 simulations, the average time of detection and the average contaminated area are calculated if daily (ED) sampling is assumed. Moreover, the average contaminated area is also calculated assuming different sampling frequencies, namely monthly (1 M), bimonthly (2 M), quarterly (3 M), every 4 months, biannual (6 M) and annual (A). The polluted area is additionally calculated every 3 months, every 6 months, once a year, every 2 years and every 3 years after successful detection, in order for remedial action delay time to be evaluated. If, on the other hand, there hasn't been any contamination detection, then at the end of the monitoring time a zero value (0) is logged and the process begins once more from Step 1. The average contaminated area is calculated in case of failure. The detection probability of the specific arrangement of monitoring wells is calculated by the ratio of simulations in which we have successfully detected the pollution to the total number of simulations, which is:

$$P_d = \frac{1}{N_{MC}} \sum_{i=1}^{N_{MC}} I_d^{(i)} \tag{2.67}$$

CHAPTER 3

Instantaneous groundwater pollution detection probability in heterogeneous aquifers

3.1 Introduction

Successful detection of aquifer contamination via monitoring wells is a complicated problem with many factors, such as the heterogeneity of the geologic environment, the quantity and nature of the contaminants, the number and location of the monitoring wells, and the frequency of sampling, all contributing to the uncertainty of early detection. Detection of contaminants, of course, is of value if remedial actions follow as soon as possible, so that the volume of contaminated groundwater to be treated is minimized. The current article addresses these issues by investigating the case of instantaneous leakage from a landfill facility into a heterogeneous aquifer.

There are several factors that influence the likelihood of early detection of an aquifer's contamination by a landfill leak. Dispersion of the contaminants in heterogeneous geologic formations determines the spread and evolution of a plume. The stochastic Monte Carlo framework has been used to address the problem of optimizing the number and location of monitoring wells in heterogeneous aquifers (Hudak & Loaiciga, 1992; McLaughlin et al., 1993; Meyer et al., 1994; Storck et al., 1997; Bierkens, 2006; Salamon et al., 2006a) in order to determine the maximum detection probability or minimum contaminated area.

A second source of uncertainty arises from lack of knowledge about the leak itself. The location of the source, the quantities and chemical composition of the contaminants, and the time when a leak originated are questions with significant uncertainties involved. Simulation studies (Meyer et al., 1994; Storck et al., 1997; Yenigül et al., 2005; Bierkens, 2006; Yenigul et al., 2006; Yenigül et al., 2011) usually assume conservative contaminants, with continuous or instantaneous leakages, and with the source's location randomly selected within a landfill's area.

The frequency of a sampling program that is implemented at a monitoring well system is another component that defines the likelihood or not of detecting contaminant concentrations above regulatory threshold values. The EU Directive 1999/31/EU on "the landfill of waste" states that sampling for monitoring purposes should be conducted *"…At a frequency to be determined by the competent authority and in any event at least once a year…"* The dependence of the probability of detection on the sampling frequency can be explained if one considers the sub-region of the plume characterized by concentrations, which are above the threshold regulatory limits. This sub-region changes, continually, in space and time, as a result of its advective and dispersive movement, and hence infrequent sampling may result in obtaining samples at wells that are used as regulatory check points when this critical part of the plume has already travelled elsewhere. Our article investigates the dependence of contaminant detection probabilities on aquifer heterogeneity and dispersion, as well as of the interaction between sampling frequency and monitoring well-arrangement.

Yet contaminant detection is of value if followed by quick remedial response. Indeed, most risk cost-analysis studies (Freeze et al., 1990; Bierkens, 2006; Yenigul et al., 2006), when analyzing the economic performance of different monitoring well systems assume that remedial actions are instantaneous, i.e., remediation activities commence exactly when detection is attained. According to this risk framework the contaminated groundwater volume at detection time is estimated; multiplied by the remediation cost per unit volume, and then this total remediation cost enters a decision analysis.

A different probabilistic risk analysis framework in subsurface contamination is proposed *by (Tartakovsky, 2007),* and (Bolster et al., 2009) where the probability of aquifer contamination is based on a rare event approximation and it depends on the probabilities of the system's constitutive parts (natural attenuation and remediation) failing.

Practically, there is always a time lag between contaminant detection and remedial action response. The EU directive 1999/31/EU on *"the landfill of waste,"* for example, states that landfill operators should notify competent authorities first of any significant adverse environmental effects revealed by the monitoring procedures, and then follow the authorities' decision on the nature and timing of the corrective measures. Considering the time needed for administrative decisions and for arrangements with local contractors in order to initiate remedial procedures introduces a time lag between detection and remediation time. During this time lag a plume continues to move into an aquifer contaminating larger groundwater volumes.

The effect of this time lag, named as remedial action response delay by us, on the outcome of decision analyses is investigated in this study. Our article provides a novel framework to modify traditional risk analyses by supplying corrected detection probabilities that account for delays in remedial actions. In our approach the weights that detection probabilities provide onto remediation costs in traditional decision analyses are downgraded the further away a remedial response has moved from the time of detection. Correspondingly, the weights applied on failure costs are increased, effectively penalizing delayed remedial actions.

3.2 Model Description

Our study involved the stochastic simulation of groundwater flow and contaminant transport in heterogeneous aquifers of horizontal dimensions much greater than their thickness (Meyer et al., 1994; Yenigül et al., 2005; Yenigül et al., 2011). The wells were assumed to fully penetrate the aquifer resulting in vertically-averaged concentration measurements.

The physical problem at hand involves five sources of uncertainty: The heterogeneity of the two-dimensional geologic field, the dispersion of the contaminant, and the initiation point, size, and duration of a leak. The contaminant was assumed to be conservative, and fully water soluble.

The heterogeneity of the geologic environment was addressed through the hydraulic conductivity, which was simulated as a log-normal, stationary, second order, isotropic stochastic process (Gelhar, 1986; Sudicky, 1986; Elfeki, 1996) using the Spectral Turning Bands Method (STUBA) (Mantoglou & Wilson, 1982; Brooker, 1985; Mantoglou, 1987; Tompson et al., 1987a). The second source of uncertainty arises from the way a pollutant is transported into the subsurface heterogeneous environment. Upon entering an aquifer's flow field, a pollutant starts not only to move along the streamlines, but in addition to diffuse and disperse into the geologic medium. The particle tracking method based on the 'random walk' approach (Ahlstrom et al., 1977; Prickett et al., 1981; Kinzelbach, 1987; Tompson et al., 1987b; Tompson & Gelhar, 1990b; Uffink, 1990; Zimmermann et al., 2001; Hassan & Mohamed, 2003; Delay et al., 2005b; Salamon et al., 2006b; Salamon et al., 2006a) was adopted to simulate a plume's advective and dispersive movement. Our choice of algorithm was based on its ease of implementation, its mass conservative nature, its numerical dispersion-free characteristic and its computational economy.

The contaminant was assumed to be conservative and water soluble. While, some contaminants are conservative (e.g. chloride), (Fatta et al., 1999), the majority are prone to biological and chemical transformations that tend to alter the transport rate and lead to concentration reduction (Renou et al., 2008). Although a plume's evolution is determined by the contaminants' chemical characteristics and the site-specific physical, chemical, and biological conditions - for example, the existence of low permeability zones that may lead to fingering and the creation of diffusion-dominated 'hot spots' (*National Academies*, 1994), or the development of geochemical conditions that may activate natural source contaminant production (for example, chromium from ophiolites) (Izbicki et al., 2008), etc. - the assumption of a conservative contaminant is useful in order isolate the impact on the detection probability of sampling frequency and remedial action delay in heterogeneous subsurface environments.

Other sources of uncertainty relate to the location and areal extent of a leak, together with the quantity and duration of contaminant release. In this study it is assumed that any point in the landfill can be a potential source of leakage, taking place once, and resulting in an instantaneous ejection of contaminants into an aquifer.

Initial leakage from a landfill is usually due to holes and tears in geo-membranes because of poor waste deposition or membrane ageing, and resulting in embrittlement, stress cracking, and chemical erosion near welded seams (Lee & Jones-Lee, 1994; Allen, 2001). Most of these failures are distinct and usually of very small dimensions leading to one or multiple point sources of contamination. Thus, (Collucci et al., 1999) have reported that two holes, each 5cm×3cm, and a crack of 63cm×31cm were the source of leachate leakage from a municipal solid waste landfill in northern Italy, whereas (Laine et al., 1997) reported, through an electrical leak imaging method (ELIM), leakage from two 80mm-long cuts at an active landfill. In addition, at several waste disposal facilities with natural clay bottom barriers, leakages may be caused by deposition of fluid containers over cracks or failure zones of small areal extent. Consequently, we have assumed that the size of the leakage source is a single point inside the landfill area, representing a worst case scenario in terms of detection because the plume to be formed will be very narrow and difficult to detect (Meyer et al., 1994; Allen, 2001; Hudak, 2005).

The case of an instantaneous leak refers physically to a sudden discharge of leachate into the aquifer as a result of high hydraulic head, which might have built up on the liner due to continuous or localized leachate presence (Koerner & Soong, 2000), in conjunction with the development of a crack or tear at a weak area of the bottom liner. A high hydraulic head may develop due to clogging of the leachate collection and drainage pipeline system (Koerner & Koerner, 1995), or due to large precipitation fluctuations, which in turn may cause excessive water percolation through the wastes (Collucci et al., 1999; Fatta et al., 1999; Tatsi & Zouboulis, 2002). Numerically, instantaneous ejections can be considered leaks whose duration is less than the modeling time step Δt that is used in the transport of contaminants, set here equal to one day.

The contribution of the unsaturated zone in the contaminant's movement and dispersion was neglected. In the unsaturated zone, flows are gravity driven and thus are primarily vertical, with the saturated-zone transport presenting perhaps the greatest opportunity for a contaminant to travel large distances (Academies, 1994). Cases where ignoring the influence of the unsaturated zone may be a valid approximation include those when the water table is relatively close to the bottom of the facility and contaminants move vertically towards the aquifer (Meyer et al., 1994; Çelik et al., 2009); when there is a highly permeable vadose zone or non-stratified deposits between a point source and the aquifer (Hudak, 2005), or when there is fingered flow, which significantly increases the vertical pore water velocity leading to rapid discharge of contaminant into the saturated zone (Selker et al., 1996).

Seven linear configurations of monitoring installations were examined consisting of 1, 2, 3, 4, 6, 12 and 20 wells, equally spaced from each other. Wells that were located at the ends of each arrangement were placed half the distance from the landfill's top and bottom edges so that the efficiency of the monitoring system would be maximized (Yenigül et al., 2005). The distance, d, of the monitoring installations from the landfill's trailing edge was normalized with respect to the landfill's width, L.

The procedure for the Monte Carlo simulations was as follows:

2-D random hydraulic conductivity fields were created by STUBA (Mantoglou & Wilson, 1982) for a flow field 1,000m long and 400m wide. The variance of the log hydraulic conductivity varied from 0.0 (homogeneous aquifer) to 2.0 (strongly heterogeneous aquifer), while the mean of the log hydraulic conductivity was taken to be equal to 2.3. The correlation length, λ, was considered constant and equal to 20 m for both directions X and Y (isotropic medium).

Numerical calculations of steady state two-dimensional groundwater flow were based on a finite difference 7-point scheme (Sarris & Paleologos, 2004), with the velocity on each grid node calculated by Darcy's law. Continuous velocity values inside the domain were calculated using a bilinear interpolation scheme (Salamon et al., 2006b).

A rectangular landfill facility was located between x-coordinates of 10m and 60m, and y-coordinates of 140m and 260m (Figure 3.1). A point was selected randomly inside the landfill as the starting point of pollution. The total pollutant mass was equal to 1,000gr, simulated by 2,000 or 8,000 discrete particles (depending on the case investigated). The initial concentration of the point source, $C_0 = M_0 / (nV_0)$, was 4,000mgr/lt, where M_0 the initial mass, $n = 0.25$ the effective porosity, and $V_0 = 1\,\mathrm{m}^3$. The threshold concentration C_{TH}, which was detectable from the monitoring wells, was set at 0.35% of the initial concentration. This corresponds to a level of critical contamination from nitrate, cyclohexanon, or diethyleneglycol, which would require remedial procedures (Yenigül et al., 2005).

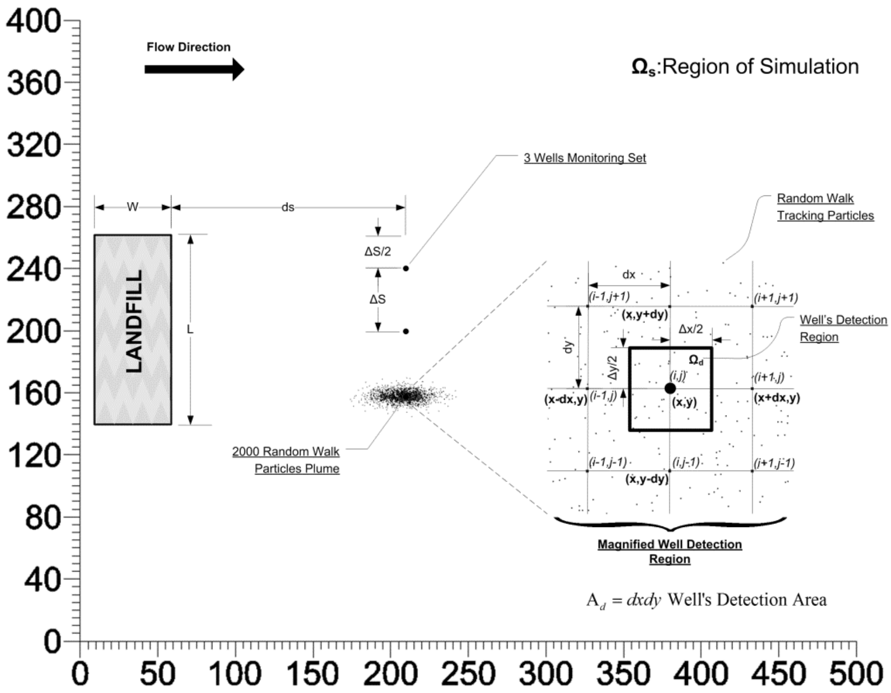

Figure 3.1 : Section of simulated flow field with a rectangular landfill $\boldsymbol{W} \times \boldsymbol{L}$, a 2000 particles plume, and a magnified well-detection area

Evolution of the plume was simulated via the random walk particle tracking algorithm. A brief overview of particle displacement equations can be found in the work of (Salamon et al., 2006b) and in the more extensive work of (Tompson et al., 1987a). For each geologic field reproduced by STUBA different transverse dispersion coefficients, a_T, were examined, varying between 0.001*m* and 0.5*m*. The longitudinal dispersion coefficient, a_L, was calculated by the relation $a_L = 10a_T$ (Spitz & Moreno, 1996; Cirpka & Kitanidis, 2001).

For each dispersion case different linear arrangements of monitoring wells were examined, each time step utilizing various frequency sampling policies: on-line (every day), once every two, three, four, six and twelve months. If the contaminant's concentration at any monitoring well of a specific well arrangement was found equal to, or greater than the threshold concentration, then detection was considered to have been achieved. Because the random walk particle method provides discrete particle displacements and not the concentration values themselves, the particle density found in each computational cell was converted to a concentration value with the use of a mesh similar to the one used for the solution of groundwater flow equation. The average concentration in a grid cell (i, j) with dimensions $\Delta x = \Delta y = 2$ m in the x- and y-directions, respectively, is given by

$$C_{ij}(t) = \frac{M_0 n_{ij}(t)}{Nnb\Delta x\Delta y} \tag{3.1}$$

Here $C_{ij}(t)$ is the volume averaged concentration in a grid cell (i, j) at time t, M_0 is the total initial mass of the contaminants, $n_{ij}(t)$ is the number of particles found inside a cell (i, j), N is the total number of particles, n is the porosity, and b is the depth of the aquifer taken equal to unit. If a value of concentration was found, in any one of the wells of a specific arrangement, to equal or exceed the threshold value C_{TH} at any time step, during the 30-year monitoring period, then, successful detection was considered to have been attained and was given in any simulation i the value $I_{\text{det}}^{(i)} = 1$, otherwise it took the value of 0.

The detection probability of a specific arrangement of monitoring wells was calculated as the ratio of simulations where successful detection was attained over the total number of simulations, N_{MC}, and was expressed as

$$\mathrm{P_d} = \frac{1}{N_{MC}} \sum_{i=1}^{N_{MC}} I_{det}^{(i)} \tag{3.2}$$

If contamination was detected, then the total polluted area was calculated at the moment of detection. This calculation was repeated again 3, 6, 12, 24 and 36 months after the initial detection, in order to record the evolution of the plume. In case where no successful detection was accomplished the total contaminated area was calculated at the end of the 30-year monitoring period.

3.3 Number of Simulations and Tracking Particles

One of the computational shortcomings of Monte Carlo stochastic simulations is that the accuracy of the results depends on the number of realizations utilized. Although many stochastic numerical studies have shown (Storck et al., 1997; Sarris & Paleologos, 2004; Yenigül et al., 2005) that, in many cases, approximately 500 simulations may be sufficient for results to converge to a constant value, the calculations to estimate detection probabilities of monitoring systems have practical use as entries in decision-making analyses. There, the detection probability is multiplied by remediation costs, and hence an error in the value of P_d, from the constant value that is attained at a higher number of simulations, may affect the outcome of a decision.

Figure 3.2 plots the dependence of the detection probability on the number of Monte Carlo simulations for three different cases of well arrangements, levels of heterogeneity, and dispersion of the plume. This figure indicates that convergence of P_d is attained at about 3,000 simulations, with the average difference from the value of P_d returned from 500 simulations being approximately 4%. In all subsequent calculations of our study the number of 3,000 realizations was used for all cases of hydro-geologic investigation. Alternatively, one could consider that the flow and transport calculations could be performed with a smaller number of simulations and at the decision level a sensitivity analysis could be conducted on the effect on the results by small perturbations of the value of the detection probability.

Our study investigated numerically the effect of the number of particles, used to simulate a plume of total mass M, on the detection probability. The particle tracking method assigns the solute mass of the contaminants to a group of N particles having identical, unchanging amounts of mass, and free to move independently in time. A particle in each time step is displaced in two ways: the first motion involves movement along a streamline, while the second is a random displacement, whose direction and magnitude are chosen so that the overall distribution of the cloud of particles reproduces the desired concentration. Because of the need to use a large number of particles in order to obtain consistent and reliable results of contaminant concentration there exists a strong dependence of the calculated values of P_d on the total number of particles used in the simulations. On the other hand, the computational effort, per time step, is proportional to the number of particles used, making the optimization of N necessary.

Contaminant concentration by the method of particle tracking is calculated by measuring the number of particles found in each grid cell of area A_d (Figure 3.1) and applying Equation (3.1). Consequently, contrary to the space-and-time continuous concentrations that are provided by analytical methods, the particle tracking method provides discrete values of concentrations $C(A_d t)$ - in the form of step functions - to adjacent grid cells. The discrepancy between the concentration distribution obtained via the random walk tracking particle and the analytical solution, averaged over cell area A_d, can be quantified through the total square error of the concentration over the flow domain Ω_S (Figure 3.1), given by (Ahlstrom et al., 1977; Kinzelbach, 1987; Tompson et al., 1987a)

$$\varepsilon^2 = \frac{(\mathrm{M}/\mathrm{n})^2}{\mathrm{N}A_d} \tag{3.3}$$

This result is a global measure of the error in concentration over Ω_S and shows that a factor of two reduction in the global error can be accomplished either by a four-fold increase in the number of particles N or an equivalent increase in the sampling region Ω_d from which concentrations are estimated (Tompson et al., 1987a). Since in our case Ω_d was set equal to A_d (Figure 3.1), which was derived from the finite difference mess, improvement in ε^2 is conditioned on an increase in the number of tracking particles. (Kinzelbach, 1987) has reported that in his numerical experiments an increase in the number of particle N did not lead to an improvement in ε^2 as described by Eq. (3.3).

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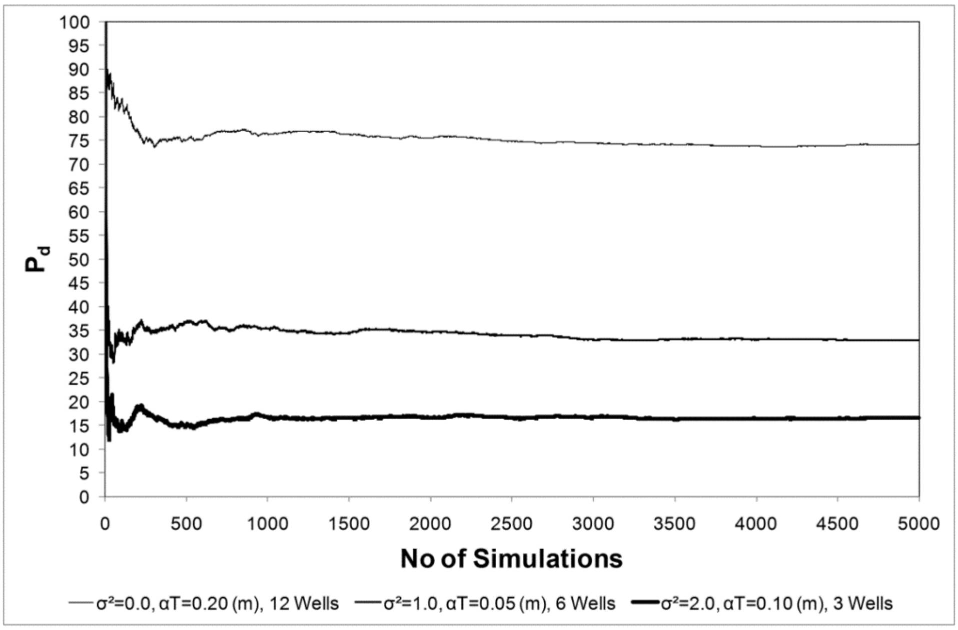


Figure 3.2: Detection probability P_d versus number of Monte Carlo simulations for 3 cases of well arrangement, heterogeneity, and dispersion

Yenigül et al. (2011) defined the theoretical detection probability $P_{d(TH)}$ for a single well, in a homogeneous medium and for an instantaneous release, as the ratio of the maximum width $2l$ of the plume at time t to the width of a landfill L. These authors found that,

$$P_{d(TH)} = \frac{2l}{L}, \; when \; y_W - l > y_C - \frac{L}{2} \; or \; y_W + l < y_C + \frac{L}{2}, \tag{3.4}$$

where y_c is the *y*-coordinate of the landfill's center line, and y_w is the y-coordinate of the well. When the well is close to the upper or lower boundary of the landfill $P_{d(TH)}$ is given by

$$P_{d(TH)} = \frac{l + L/2 - y_W + y_C}{L}, \; if \; y_W + l > y_C + \frac{L}{2}, \tag{3.5}$$

or

$$P_{d(TH)} = \frac{l + L/2 - y_C + y_W}{L}, \; if \; y_W - l < y_C - \frac{L}{2} \tag{3.6}$$

respectively.

Based on the above equations the total $P_{d(TH)}$ for the case of multiple, equally spaced, wells, arranged linearly was formulated by us as the sum of the detection probability of each individual well. When the maximum width of the plume extended over more than half the distance d between the wells the total width of the landfill was covered, yielding $P_{d(TH)} = 1$. In every other case $(2l < d)$ $P_{d(TH)}$ was calculated to be

$$P_{d(TH)} = n\frac{2l}{L} \tag{3.7}$$

Figure 3.3 depicts the theoretical $P_{d(TH)}$ and the numerical P_d for five different wells arrangements (1, 3, 6, 12 and 20 wells) against the $\log_{10} N$, where the number of tracking particles N took the values of 500, 1000, 2000, 4000, 8000, 16000, 32000, 64000, 128000, 256000, and 512000. The results were obtained for a homogeneous field with $a_T = 0.10a_L$; the monitoring set was located at a distance $d = 0.125L = 15$ m (where maximum detection was attained), and the maximum plume's half width was calculated to be $l = 3.085$ m (Yenigül et al., 2011). The threshold number of particles inside a well, in order to attain detection, was adjusted so that the detection concentration limit remained constant at $0.35\% \cdot C_0$. Figure 3.3 indicates that as the number of particles increases, the numerical detection probability P_d converges to the theoretical value $P_{d(TH)}$, with P_d becoming almost equal to the theoretical value when 64,000 or more particles are used. When only one well is considered then even 8,000 particles appear to be sufficient for P_d to converge to $P_{d(TH)}$.

Yenigul et al. (2011) performed a sensitivity analysis of the approximation provided by particles ranging from 500 to 8,000 to the analytical plume's concentrations in a homogeneous and heterogeneous field. This author concluded that 2,000 particles provide a satisfactory tradeoff between accuracy and computational cost for the calculation of concentration in these flow fields. For the detection probability, however, she concluded that this number of particles resulted in values greater than the analytical ones.

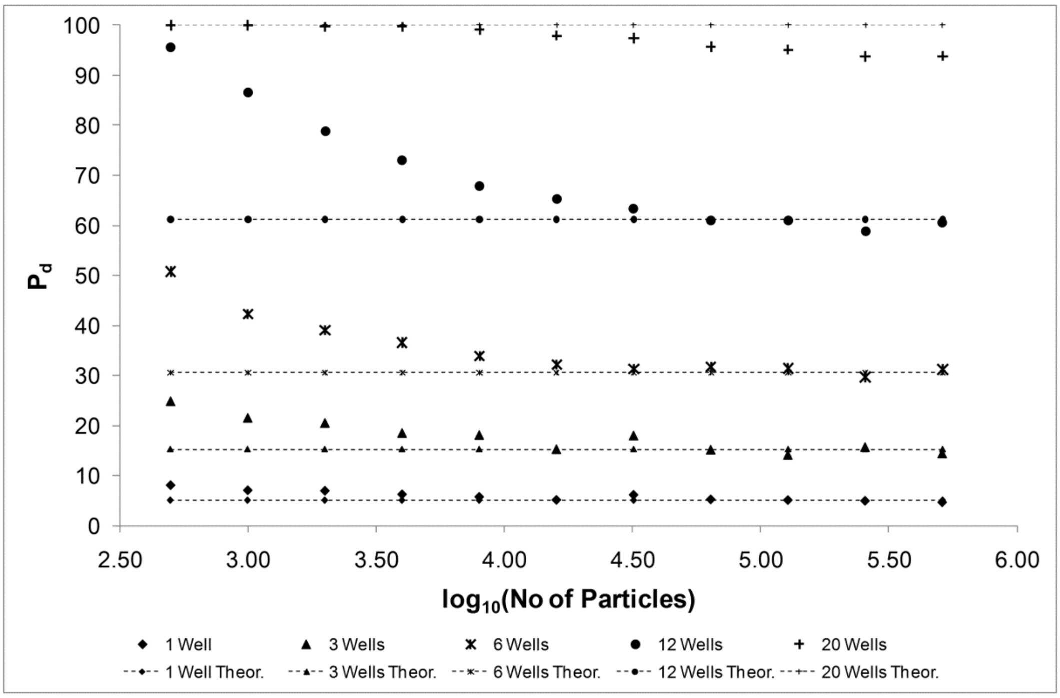


Figure 3.3: Comparison between numerical and theoretical P_d versus log_{10} of number of tracking particles *N*, *N*=500, 1,000, 2,000, 4,000, 8,000, 16,000, 32,000, 64,000, 128,000, 256,000, and 512,000

It is apparent from Figure 3.3 that, independently from the number of monitoring wells, the detection probability decreases as the number of particles increases. This occurs because an increase in the number of tracking particles would make the concentration variations between sequential cells smoother, since a larger number of smaller particles are distributed into various cells. As a result the contamination plume is described better, reducing some erroneous detection cases, which occur when the concentration at a monitoring numerical cell is found to be marginally above or below the detection threshold limit. This may explain the discrepancy between analytical and numerical results for the detection probability, which was observed by *Yenigul et al.* (2006) by using 2,000 particles for calculations.

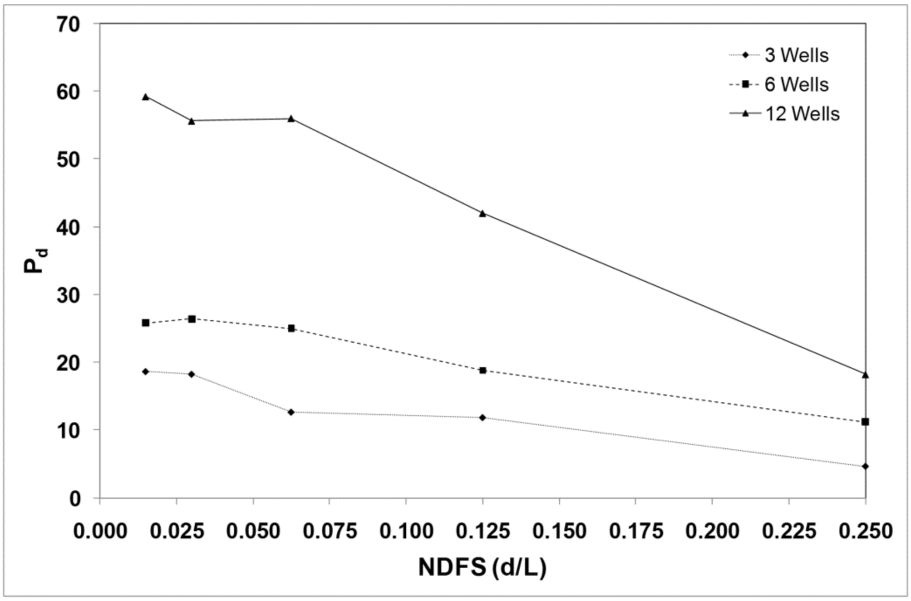
3.4 Results and Discussion

3.4.1 Effect of Number and Distance of Wells on Detection Probability

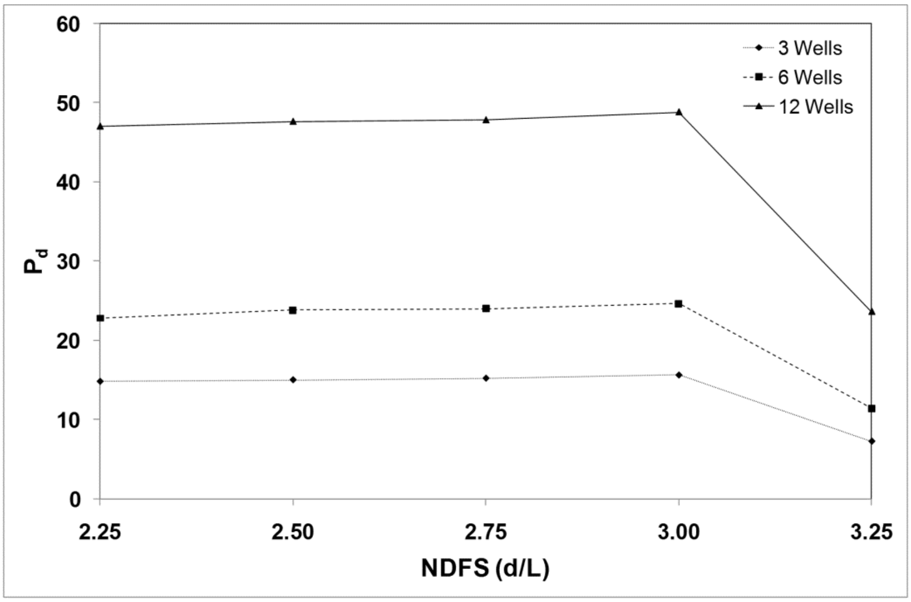
The number of wells that are used in a monitoring arrangement has a great influence on the likelihood of detecting or not potential contamination events from a landfill facility. Table 1 presents the results of our simulations for different levels of heterogeneity, values of transverse dispersion coefficients $a_T = 0.001$, 0.01, 0.02, 0.05, 0.1, 0.2, 0.5m or different number of monitoring wells, NOW=1, 2, 3, 4, 6, 12, and 20, and for two cases, the first utilizing 500 hydrogeological realizations and 2,000 tracking particles, and the second utilizing 3,000 realizations and 8,000 tracking particles. The detection probabilities shown in this table refer to the optimum distance d from the contamination source, normalized by the width L of the landfill. The normalized optimum distance is designated as NDFS, and it refers to that distance from the landfill where the maximum detection probability was observed for each arrangement of wells.

Our numerical experiments showed that, in most cases, different monitoring wells, under the same conditions of heterogeneity and dispersion, perform better at slightly different distances. For example, Figure 3.4(b), 6 wells attain the maximum P_d at a normalized distance of 0.03, while 3 and 12 wells attain the maximum P_d at NDFS=0.015. On the other hand Figure 3.4(a) indicates that all 3, 6, and 12 wells attain their maximum P_d at the same distance. Because of the computational effort it was chosen that the values of P_d, shown in Table 4.1, would be calculated (in each α_T case) at the same NDFS for all arrangement of wells, with NDFS selected as the distance where the performance of the majority of the well arrangements was maximized.

The first observation from Table 4.1 refers to the variability of the values of P_d obtained by the numerical scheme utilizing 500 realizations and 2,000 particles, and that which uses 3,000 realizations and 8,000 particles. This is to be expected since Figure 2 indicates that at 500 Monte Carlo realizations P_d is well within the zone where significant fluctuations around its asymptotic value still occur, and in particular that depending on σ_{Y}^2 and α_{T} the value of P_d obtained by 500 realizations, for the case of 3 wells, may underestimate the asymptotic value obtained by 3,000 realizations, while for 6 and 12 wells the opposite result may hold true. This variability in P_d from the two numerical schemes becomes more pronounced when the number of wells exceeds 3, in agreement with the results of Figure 3.3, which indicate that the choice of the number of tracking particles influences P_d more when the number of wells increases.



(a)



(b)

Figure 3.4: Optimum detection distance for 3, 6, and 12 wells. Top: Heterogeneous (σ^2_{lnK}=2.00, a_T=0.20m) flow field. Bottom: homogeneous flow field with a_T=0.001m.

It is evident from the results at Table 4.1 that in all cases of hydrogeological heterogeneity and dispersion the more wells utilized for detection purposes the greater the detection probability. It is notable that the use of 20 monitoring wells provides extremely high detection probabilities, which in some cases, at least at the numerical level, may reach full detection. In terms of the minimum requirement of the 3 monitoring wells stipulated in the 1999/31/EU directive "on the landfill of waste" we found that, in agreement with (Yenigül et al., 2005), the detection probability from this well arrangement remained very low, not exceeding 19%. The implication of this result is that approximately four out of five cases of leakage from a landfill will remain undetected if such a well arrangement is to be used.

3.4.2 Effect of Field's Heterogeneity and Dispersion

For a given geologic field the dispersion coefficient determines the form that a contaminant's plume takes (Meyer et al., 1994; Yenigül et al., 2005). The longitudinal dispersion causes elongation of the plume in the direction of groundwater flow, while the transverse dispersion causes it to widen. This means that the farther a plume travels, the more it spreads and dilutes into the aquifer.

The dispersion of pollutants as they travel into an aquifer results in two opposing situations with regards to monitoring. As the plume evolves the contaminated area increases, making it more likely for a plume to be detected by a monitoring system. On the other hand though, as the plume evolves the concentration drops, making it more difficult to obtain high concentration samples, and hence to detect at a distance from the source. For a fixed heterogeneity level Table 4.1 shows that for each specific arrangement of wells the maximum detection probability increases with increasing dispersion coefficient up to a certain value of α_T and then P_d decreases. For the homogenous case this saddle point occurs at about the value of $\alpha_{\mathrm{T}} = 0.1m$ to $0.2m$, while the effect of increasing heterogeneity appears to be the appearance of the saddle point at lower α_{T} values.

The heterogeneity of the subsurface environment also influences the detection probability of a particular installation of monitoring wells. Analysis of the results in Table 4.1 shows that in general the efficiency of contaminant detection from a specific well arrangement decreases as the variance of $Y = \ln K$ increases. This conclusion holds consistently for the system of 6, 12, and 20 wells, but it appears to be more tentative for the lower number of wells. This may be attributed to the fact that arrangements of 1, 2, 3, and 4 wells return relative small detection probabilities and hence numerical errors from the limited number of realizations and tracking particles have the potential to make this trend less apparent. Indeed, the greater the heterogeneity the closer the monitoring wells must be to the contaminant source in order for detection to occur.

3.4.3 Effect of Sampling Frequency

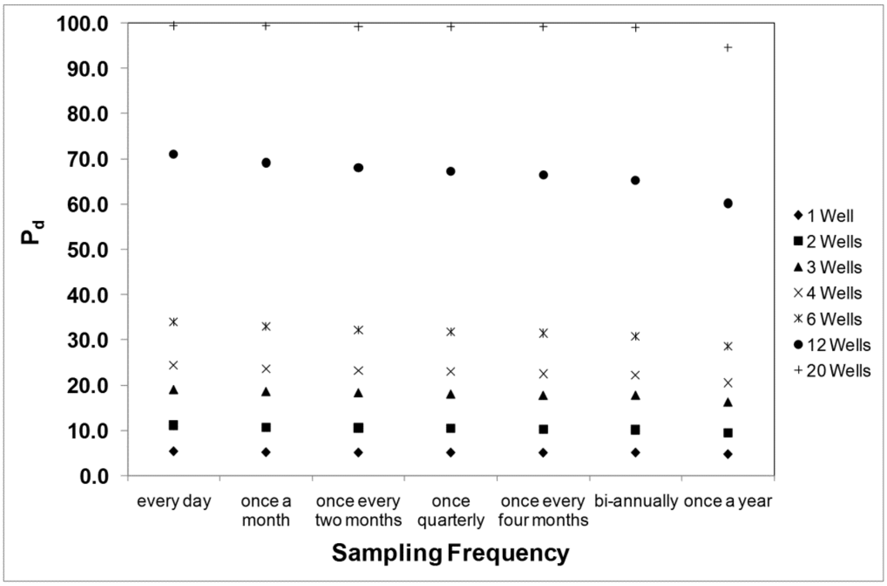
According to the EU directive 1999/31/EU on "*the landfill of waste*" sampling for monitoring purposes should be conducted "*…At a frequency to be determined by the competent authority, and in any event at least once a year…*" Annex III of the same directive specifies that for the protection of groundwater, monitoring of its chemical composition should follow a site-specific sampling frequency, which would be based on the velocity of groundwater flow, in order to allow for the "*...possibility for remedial actions between two samplings if a trigger level is reached...*"

Yenigul et al. (2006) examined the way that sampling frequency affects the detection probability of a contaminant plume, which emanates from a continuous leak of constant flow rate. These authors concluded that in the continuous leak case the detection probability of all the monitoring systems they considered remained insensitive to the sampling frequency, in contrast to the contaminated area, which increased as the sampling frequency decreased.

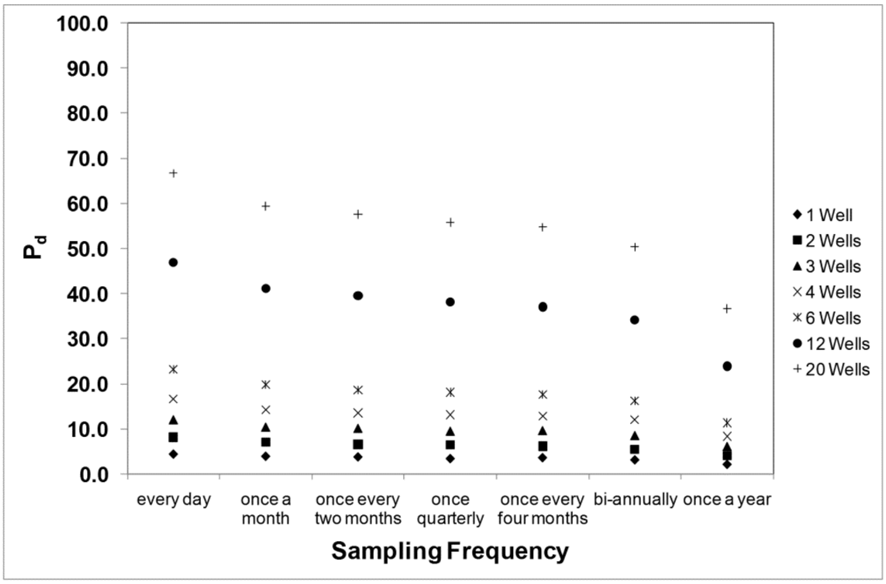
In the present study the dependence of the detection probability on the sampling frequency was investigated for the case where the contaminant's mass got released instantaneously into an aquifer. Figure 3.5 shows the results of our numerical experiments (3,000 realizations and 8,000 tracking particles) for two cases: the first is a homogeneous aquifer with $a_T = 0.01$ m, and the second is a heterogeneous one with $\sigma_Y^2 = 1.0$ and $a_T = 0.20\,m$. For both cases the sampling frequencies considered were: once a day, once a month, once every two months, once quarterly, once every four months, bi-annually, and once a year.

Figure 3.5(a) indicates that for the case of instantaneous release, if monitoring of a homogeneous and of low dispersion aquifer is performed with up to three wells, no higher detection of the contamination is obtained by sampling done more frequently than once a year. If 4, 6, or 12 monitoring wells are used then conducting bi-annual sampling increases the probability of detection by about 8% and sampling once a month improves P_d by 15% relative to the detection obtained if sampling is done annually. The case of 20 monitoring wells indicates that full detection can be accomplished with this arrangement if bi-annual sampling takes place.

The effect of sampling frequency on the detection probability is more pronounced when the aquifer is heterogeneous and dispersion is increased (Figure 3.5(b)). When 3 wells are used it is worth to proceed to bi-annual sampling, which will provide a 40% improvement on the detection probability, or else proceed directly to daily sampling that will improve detection by over 90%, relative to the P_d determined by annual sampling. For the cases of 4 and 6 monitoring wells bi-annual sampling improves P_d by 43%, and once a month increases P_d about 70%, again relative to the P_d determined by annual sampling. Finally, 12 and 20 monitoring wells show a substantial improvement in the P_d which approaches 40% simply by sampling twice instead of once a year, and much higher improvements if a more frequent sampling schedule is performed.



(a)



(b)

Figure 3.5: Dependence of the probability of detection on sampling frequency (5a: homogeneous, a_T=0.01m, and 5b: heterogeneous aquifer, σ^2_{lnK}=1.0, a_T=0.20m)

As a general rule it appears that under all conditions at least bi-annual sampling should occur at a monitoring system. If one wants a higher detection probability then sampling at a frequency of once a month appears to be the optimum choice for most well arrangements, considering both the effort involved if one were to proceed with a much more intense sampling and the improvements on detection attained at this level. It is interesting to note that in heterogeneous aquifers a large number of monitoring wells (such as the case of 12 wells considered here) if sampled infrequently (for example, once a year) does not perform much better in terms of detection than arrangements having a lower number of wells, but which are sampled more regularly.

3.5 Remedial Action Response Delay

Decision analyses that evaluate the economic worth of different arrangements of monitoring wells are performed by defining a risk term R, which is associated with the probability of detection P_d (and the probability of failure to detect, $P_f = 1 - P_d$), and the associated cost of remediating the detected volume of contaminated groundwater, C_d (correspondingly, of the remediation cost C_f of a much larger contaminated volume, due to a plume's failure to be detected by a monitoring system, and becoming apparent only by reaching, for example, the drinking wells of a community). This risk term R is defined for every monitoring system, whose economic worth is investigated, as (Bedford & Cooke, 2003; Yenigul et al., 2006):

$$R = P_d \, C_d + P_f \, C_f \tag{3.8}$$

The remediation costs in both cases can be obtained by multiplying the contaminated volume, which is evaluated during the stochastic groundwater flow and contaminant transport numerical analysis, by the remediation cost per unit contaminated water volume. The decision analysis then proceeds by determining that particular well arrangement that optimizes the risk factor R, i.e., determining this monitoring system that maximizes the detection probability while minimizing the contaminated area, or equivalently minimizing the remediation cost.

Implicit in the decision analysis framework described above is the assumption that remediation takes place immediately after detection occurs, in other words that the contaminated groundwater volume (contaminated area, equivalently, in our case of two-dimensional investigation), which is remediated, is the same with the volume observed and calculated at the time of detection. In reality, there is always a delay in the response, from the time when the exceedance of a threshold value of a chemical is observed until the time when remediation measures commence. This remedial action delay has as a result the increase of the contaminated volume, as the plume continues to evolve in time, and an increase of the remediation cost compared to that which would be calculated if the contaminated volume at detection were to be used.

One way to address this issue is to use the ratio of A_t / A_{t+dt}, where A_t is the contaminated area in the two-dimensional case (correspondingly, contaminated volume in 3-D) at time t of detection, and A_{t+dt} is the contaminated area at time $t+dt$ when remediation might take place, to correct for this remedial action delay. Of course the time interval dt between detection and remediation is not known a priori, and a sensitivity analysis can be performed, as is done here, to determine the influence of dt on the risk factor R. Multiplying this ratio by P_d results in a reduced detection probability P_d^{cor}, i.e., an increased delay in the response to remediate can be considered, in terms of economic outcome, as equivalent to a monitoring arrangement with a decreased efficiency to detect. While P_d contains information about the degree of our knowledge of the event detection, P_d^{cor} can be considered as a measure of the degree P_d is utilized. For example, if 20 monitoring wells were used and full detection were to take place, P_d =1.0, then Equation (3.8) would calculate R considering the second (failure) term equal to zero, irrespectively of the fact that in some cases remediation might take place only when the plume has reached a critical stage, for example threatening community drinking wells. Therefore, P_d^{cor} is a way to measure the economic impact of different remedial action delays as a divergence, from the maximum economic outcome (which takes place at detection) occurs for a specific monitoring installation.

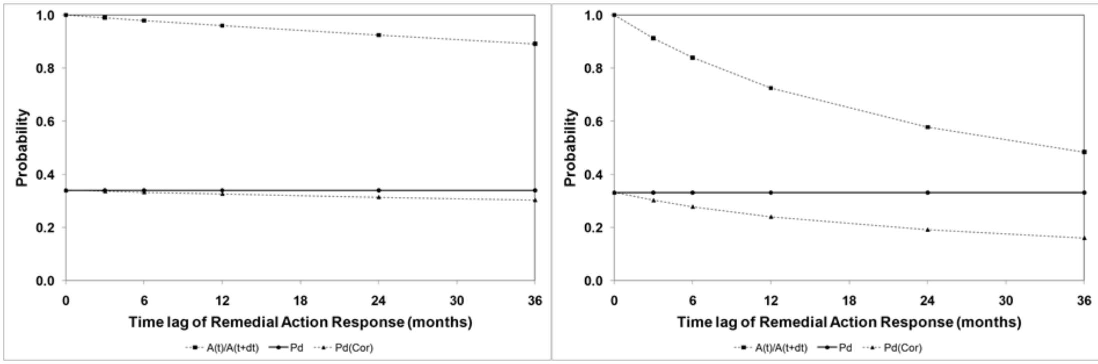
This approach provides also a corrected probability of failure P_d^{cor}, which will increase as the time to respond increases resulting in an increase of the weighted cost of failure that enters into expression (3.8) of the risk factor R. In essence the above procedure downgrades the importance of the first term in R, which provides the weighted remediation cost due to detection, and upgrades the significance of the second term, which provides the weighted cost due to failure to detect, in order to account in the calculation of R for a delay in the remedial response after detection. This procedure is summarized in the following equation yielding a corrected risk R^{cor} that accounts for the remedial action response delay,

$$R^{cor} = P_d^{cor} C_d + P_f^{cor} C_f \tag{3.9}$$

where

$$P_d^{cor} = P_d \left(\frac{A_t}{A_{t+dt}} \right), \; and \;\; P_f^{cor} = 1 - P_d^{cor} \tag{3.10}$$

In our model it is assumed that the pollutant is conservative, and that a particle found within a grid cell at particular time step, classifies the cell as contaminated, even if the concentration is below the regulatory limit.



(a) (b)

Figure 3.6: Effect of remedial action response: Corrected detection probability P_d^{cor} for six monitoring wells, sampling once a day, in a homogeneous field (a: a_T=0.01*m*, and b: a_T=0.10*m*), as a function of remedial action delay

Table 4.2 provides the results for P_d^{cor} for 3, 6, 12 and 20 monitoring wells, in two cases of aquifer heterogeneity ($\sigma_Y^2 = 0.0$ and $\sigma_Y^2 = 1.0$), and for two sampling frequencies, every day and once every six months. The ratio A_t / A_{t+dt} was evaluated numerically through Monte Carlo simulations, with A_{t+dt} calculate at time lags of 3, 6, 12, 24, and 36 months beyond the detection time. Figure 3.6a shows that for six monitoring wells in a homogeneous field of low transverse dispersion, and hence of contaminant transport taking place at a slow rate, the use of expression (3.8) for the risk factor R provides a good approximation to an optimum decision. A delay in the deliberations on planning, cost, and technology application will not affect critically the contaminated groundwater volume and hence the remediation cost. On the other hand, if contamination takes place in a homogeneous environment, but of high dispersion, then (Figure 3.6b) indicates that the contaminated groundwater area will increase fast with time, and so any remediation delays of the order of 3 years and above beyond the time of detection, would be almost equivalent to a monitoring system providing detection with half its number of wells.

Figure 3.7 summarizes the results for the effect of remedial action delay in a heterogeneous field of $\sigma_Y^2 = 1.5$ and $a_T = 0.05m$, for twelve monitoring wells as a function of the sampling frequency as well. When sampling is performed every day a remediation delay of 36 months is equivalent to reducing the detection probability from 59% to 22%, or increasing the failure probability from 41% to 78%. This means that the larger of the two costs, the failure cost, which enters into expression (3.8) increases by 90% as a result of the delay. If sampling is performed every 6 months then P_d is reduced from 42% to 19%.

Table 3.1: Corrected detection probability P_d^{cor} for two aquifers with σ^2_{lnK} =0.0 and σ^2_{lnK} =1.0, and two different sampling frequencies, once a day and biannually

			σ^2_{lnK}=0.0													σ^2_{lnK}=1.0												
			RARTi P_{det}^{Cor} (Sampling Every Day)						RARTi P_{det}^{Cor} (Sampling Bi-annually)							RARTi P_{det}^{Cor} (Sampling Every Day)						RARTi P_{det}^{Cor} (Sampling Bi-annually)					
	NOW	**NDFS**	**0 M**	**3 M**	**6 M**	**12 M**	**24 M**	**36 M**	**0 M**	**3 M**	**6 M**	**12 M**	**24 M**	**36 M**	**NDFS**	**0 M**	**3 M**	**6 M**	**12 M**	**24 M**	**36 M**	**0 M**	**3 M**	**6 M**	**12 M**	**24 M**	**36 M**
a_T=0.001 m	**3**	**2.250**	19.0	18.8	18.6	18.3	17.6	16.9	17.7	17.6	17.4	17.1	16.4	15.8	**1.250**	14.2	13.8	13.4	12.7	11.4	10.4	12.2	11.9	11.6	11.0	9.9	9.1
	6	**2.250**	34.0	33.6	33.3	32.6	31.4	30.3	30.8	30.5	30.2	29.6	28.5	27.5	**1.250**	29.9	29.1	28.3	26.8	24.2	22.0	26.3	25.6	24.9	23.7	21.4	19.4
	12	**2.250**	71.1	70.3	69.6	68.3	65.7	63.3	65.2	64.5	63.9	62.6	60.2	58.2	**1.250**	51.1	49.7	48.3	45.8	41.3	37.6	46.4	45.2	44.0	41.8	37.8	34.3
	20	**2.250**	99.4	98.4	97.4	95.4	91.8	88.5	98.9	98.0	97.0	95.1	91.4	88.2	**1.250**	68.6	66.6	64.8	61.3	55.3	50.3	62.9	61.1	59.7	56.5	51.0	46.4
a_T=0.02 m	**3**	**1.500**	18.6	18.3	18.1	17.5	16.6	15.8	16.4	16.2	16.0	15.5	14.7	14.0	**0.500**	16.8	15.9	15.1	13.7	11.5	9.9	14.4	13.7	13.1	11.9	10.1	8.7
	6	**1.500**	33.4	32.9	32.4	31.5	29.9	28.4	28.8	28.3	27.9	27.2	25.8	24.5	**0.500**	30.2	28.6	27.1	24.6	20.7	17.9	26.5	25.2	24.0	21.9	18.5	16.0
	12	**1.500**	69.8	68.8	67.8	65.9	62.4	59.3	60.5	59.6	58.8	57.1	54.2	51.6	**0.500**	56.4	53.4	50.6	45.8	38.4	33.0	51.3	48.7	46.3	42.1	35.6	30.7
	20	**1.500**	99.3	97.8	96.4	93.7	88.7	84.3	96.7	95.2	93.9	91.3	86.6	82.3	**0.500**	78.0	73.6	69.6	62.8	52.5	45.1	72.7	68.8	65.4	59.2	49.9	43.1
a_T=0.05 m	**3**	**0.500**	18.6	17.9	17.3	16.1	14.3	12.9	15.9	15.4	14.8	13.9	12.3	11.1	**0.125**	16.6	14.9	13.5	11.3	8.6	6.9	15.0	13.6	12.5	10.6	8.2	6.7
	6	**0.500**	33.3	32.1	30.9	28.9	25.6	23.1	28.2	27.2	26.3	24.6	21.9	19.8	**0.125**	30.5	27.3	24.8	20.8	15.7	12.6	27.2	24.6	22.6	19.2	14.8	12.0
	12	**0.500**	69.6	67.0	64.7	60.3	53.5	48.1	59.5	57.4	55.4	51.8	46.1	41.6	**0.125**	60.1	53.8	48.8	40.9	30.9	24.8	54.4	49.4	45.1	38.3	29.5	23.8
	20	**0.500**	99.3	95.6	92.2	86.0	76.2	68.6	93.9	90.5	87.4	81.8	72.7	65.7	**0.125**	85.4	75.9	68.3	56.8	42.5	34.0	80.0	72.2	65.7	55.4	42.4	34.1
a_T=0.10 m	**3**	**0.125**	18.6	16.9	15.5	13.4	10.6	8.9	15.6	14.4	13.3	11.5	9.2	7.8	**0.063**	16.4	14.2	12.6	10.2	7.4	5.8	13.7	12.1	10.9	9.0	6.6	5.2
	6	**0.125**	33.1	30.2	27.8	24.0	19.1	16.0	27.4	25.1	23.2	20.2	16.2	13.7	**0.063**	30.3	26.3	23.2	18.8	13.7	10.7	25.3	22.2	19.9	16.3	12.1	9.6
	12	**0.125**	69.2	63.0	57.9	49.8	39.5	33.1	58.3	53.5	49.4	42.9	34.4	29.0	**0.063**	61.9	53.5	47.2	38.0	27.6	21.6	51.0	44.9	40.0	32.9	24.3	19.2
	20	**0.125**	98.9	90.0	82.7	71.2	56.5	47.3	92.0	84.4	78.0	67.8	54.4	45.9	**0.063**	86.5	74.4	65.3	52.3	37.7	29.4	76.0	66.7	59.4	48.5	35.7	28.1
a_T=0.20 m	**3**	**0.030**	14.5	11.9	10.2	8.0	5.8	4.6	10.4	8.6	7.4	5.8	4.2	3.3	**0.030**	12.1	9.5	7.9	5.9	4.0	3.0	8.6	6.9	5.9	4.4	3.0	2.3
	6	**0.030**	26.6	22.2	19.2	15.2	11.0	8.8	19.2	16.0	13.9	11.0	8.0	6.4	**0.030**	23.2	18.3	15.3	11.4	7.8	5.9	16.3	13.3	11.3	8.6	6.0	4.5
	12	**0.030**	55.4	45.7	39.3	30.9	22.3	17.7	40.3	33.5	28.9	22.8	16.5	13.1	**0.030**	46.9	37.0	30.8	23.2	15.7	11.9	34.1	28.0	23.8	18.2	12.6	9.6
	20	**0.030**	82.4	68.3	58.8	46.3	33.5	26.7	64.2	53.6	46.3	36.6	26.5	21.2	**0.030**	66.6	52.4	43.6	32.7	22.2	16.8	50.3	41.0	34.7	26.5	18.2	13.9
a_T=0.50 m	**3**	**0.015**	8.2	4.8	3.5	2.3	1.5	1.1	5.3	3.8	3.0	2.2	1.5	1.1	**0.015**	7.2	3.9	2.8	1.8	1.1	0.8	4.3	3.1	2.4	1.7	1.1	0.8
	6	**0.015**	13.1	7.6	5.6	3.7	2.4	1.8	8.9	6.5	5.2	3.7	2.5	1.9	**0.015**	13.8	7.6	5.4	3.5	2.2	1.6	7.5	5.5	4.4	3.1	2.0	1.5
	12	**0.015**	29.2	17.0	12.4	8.3	5.3	4.0	19.5	14.1	11.3	8.1	5.5	4.2	**0.015**	26.4	14.5	10.4	6.8	4.1	3.0	15.4	11.2	8.9	6.3	4.1	3.0
	20	**0.015**	42.2	24.0	17.4	11.5	7.3	5.5	30.7	22.3	17.7	12.8	8.6	6.7	**0.015**	37.4	19.7	14.0	9.0	5.5	4.0	23.8	17.3	13.7	9.7	6.3	4.7

α_T(m) transverse dispersion coefficient, NOW: number of monitoring wells, NDFS: normalized distance from source d/L (max P_d), RARTi P_{det}^{Cor} : Corrected detection probability P_d for Remedial Action Response Time (RARTi) of 0 (instantly), 3, 4, 6, 12, 24, and 36 months (M

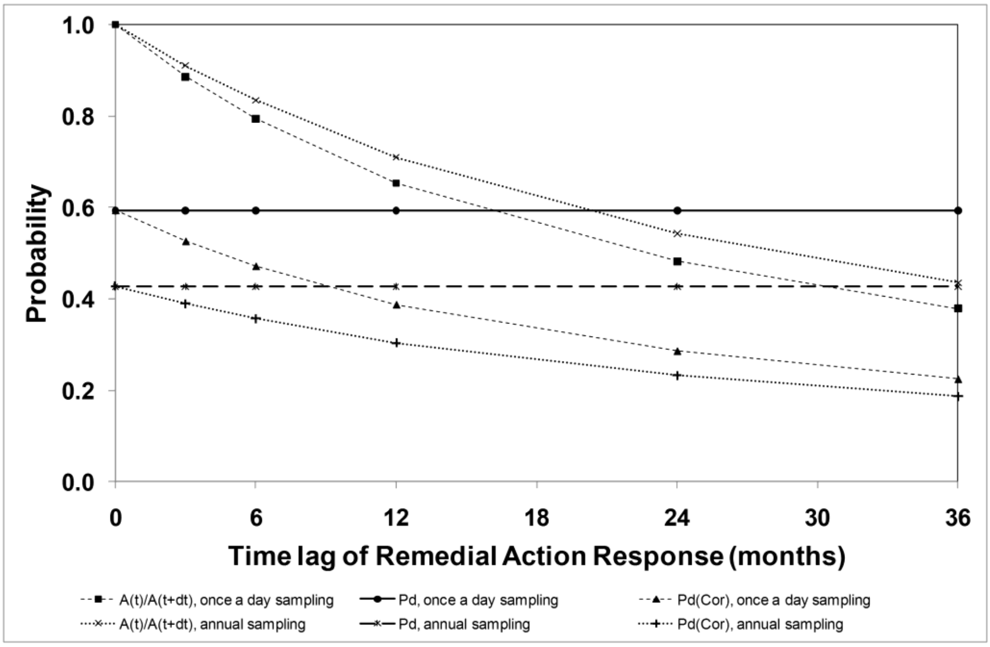


Figure 3.7: Corrected detection probability P_d^{cor} for a heterogeneous field σ^2_{lnK}=1.5, α_T=0.05*m* for twelve monitoring wells as a function of remedial action delay and sampling frequency

3.6 Conclusions

A Monte Carlo stochastic model was developed to simulate contaminant transport into heterogeneous, two-dimensional aquifers. Pollution originated from a random, instantaneous point source within a landfill facility. Different arrangements and distances of monitoring wells from a landfill were considered, and the corresponding detection probabilities P_d and contaminated groundwater areas, at different time periods, were calculated. The following major conclusions can be drawn from the current study.

1. Convergence of the probability of detection P_d to a constant value was attained at about 3,000 Monte Carlo simulations, with the average difference, from all cases, from the value of P_d returned by 500 simulations being approximately 4%. The number of tracking particles used to simulate contaminant transport had a strong influence on the values of P_d calculated through numerical experiments. For arrangements of 12 and 20 wells convergence of the P_d to a stable value was attained at very high particle numbers. Cases of 1, 2, 3, 4, and 6 wells require at least 8,000 tracking particles in order to define a stable probability of detection.

2. Our results showed that in all cases of hydrogeological heterogeneity and dispersion the more wells utilized for detection purposes the greater the P_d. The use of 20 monitoring wells provides extremely high detection probabilities, which in some cases, at least at the numerical level, reach full detection. In terms of the minimum requirement of the 3 monitoring wells stipulated in the 1999/31/EU directive "*on the landfill of waste*" it was found, in agreement with (Yenigül et al., 2005), that the detection probability from this well arrangement remained very low, not exceeding 19%. The implication of this result is that approximately four out of five cases of leakage from a landfill will remain undetected if only 3 monitoring wells are used.

3. For a fixed heterogeneity level, for each specific arrangement of wells, the maximum detection probability increases with increasing dispersion coefficient up to a certain value of α_T and then P_d decreases. For the homogenous case this saddle point occurs at about the value of $a_T = 0.1$ to $0.2m$, while the effect of increasing heterogeneity appears to be the appearance of the saddle point at lower α_T values. For transverse dispersion greater than $0.2m$ maximum detection is attained very close to the trailing edge of landfill. As a general rule the efficiency of contaminant detection from a specific well arrangement decreases as the variance of Y increases.

4. The frequency of sampling is critical in heterogeneous aquifers of high dispersion. Bi-annual sampling improves the detection probability, for almost all well arrangements, by about 40%, whereas once a month sampling improves P_d by about 70%, relative to the detection determined by annual sampling. As a general rule it appears that under all conditions at least bi-annual sampling should occur at a monitoring system. If one wants a higher detection probability then sampling at a frequency of once a month appears to be the optimum choice for most well arrangements, considering both the effort involved, if one were to proceed with a much more intense sampling, and the improvements on detection attained at this level. It is interesting to note that in heterogeneous aquifers a large number of monitoring wells if sampled infrequently does not perform much better in terms of detection than arrangements having a lower number of wells, but which are sampled more regularly.

5. Finally, decision-making analyses that evaluate the economic worth of different arrangements of wells calculate remediation costs based on contaminated

groundwater volumes that are estimated at the time of detection. In practice there is always a remedial action response delay, and contaminated volumes and hence remedial costs surpass those calculated at detection time. To correct for this situation we propose here an expression for a corrected risk factor R^{cor} that accounts for remedial action response delay,

$$R^{cor} = P_d^{cor} C_d + P_f^{cor} C_f \tag{3.11}$$

$$P_d^{cor} = P_d \left(\frac{A_t}{A_{t+dt}} \right), \; and \;\; P_f^{cor} = 1 - P_d^{cor} \tag{3.12}$$

A_t corresponds to the contaminated area (volume) at detection time t, and A_{t+dt} is the contaminated area (volume) at a later time due to delays in remediation procedures. Our approach can be viewed as a way to downgrade the importance of early detection, if not followed by quick remedial response, in risk analysis calculations.

Our expression allows us to estimate for a heterogeneous field, where twelve monitoring wells are operating and sampled every day, that a remediation delay of 36 months is equivalent to reducing the detection probability from 59% to 22%, or increasing the failure probability from 41% to 78%, almost doubling the failure cost entering risk calculations. If sampling is performed every 6 months then P_d is reduced from 42% to 19%, i.e., a delay of 36 months is equivalent to reducing the performance of 12 wells to that of only 3 wells.

CHAPTER 4

Sampling frequency of groundwater monitoring system and remediation delay at contaminated sites

4.1 Introduction

Geologic disposal of municipal wastes has been the dominant waste disposal practice and still remains the most profitable option in terms of exploitation and capital costs (Renou et al., 2008). On the other hand, disposal sites, whether old abandoned dumping grounds or sanitary landfills, have been responsible for soil and groundwater contamination as the aqueous effluent generated from rainwater, percolating through the wastes, or from bio-chemical processes, has leaked into the subsurface environment (Collucci et al., 1999; Koerner & Soong, 2000; Tsanis, 2006). Hence, early detection of aquifer contamination from a pollution source and quick remedial response is critical for plume minimization, reduction of remedial and legal costs, and decrease of the environmental and health impacts.

The duration of a leak may vary from a sudden to a continuous discharge of steady or variable rate. Sudden discharges into an aquifer can occur as high hydraulic head may develop as a result of continuous or localized leachate presence on the soil surface, or the bottom liner of unlined or lined landfills, respectively (Koerner & Soong, 2000); precipitation fluctuations leading to excessive percolation through the wastes (Fatta et al., 1999; Tatsi & Zouboulis, 2002), or, in the case of a landfill, clogging of the leachate collection and drainage pipeline system (Koerner & Koerner, 1995).

Even in lined landfills leakages can occur due to tears and holes in the geo-membranes caused by poor waste disposal practices and/or failure near welded membrane seams (Lee &

Jones-Lee, 1994; Allen, 2001). Synthetic materials used as bottom liners are prone to failure due to ageing, embrittlement, stress cracking, chemical corrosion, from extended leachate exposure, and elevated temperatures, from exothermic processes taking place in a landfill (Allen, 2001). Most locations of failure are of small dimension in relation to a landfill's cell area, constituting point sources of contamination (Collucci et al., 1999). Similar failure concerns refer to landfills with clay bottom barriers, where fracturing, due to differential waste deposition, chemical degradation, or ageing, can lead to contaminant leaks into the subsurface environment.

In practice it is very difficult to distinguish between instantaneous and continuous releases of contaminants. Instantaneous contaminant releases are more difficult to detect because they translate to narrow plumes and hence the characteristics of the geologic environment, the density of the monitoring well network, and the frequency of sampling become determining factors on whether detection can be achieved. Furthermore, instantaneous contamination releases may be followed by continuous leaks as landfill failure zones become more generalized. Continuous leaks are more probable to detect as the area with contaminant concentrations greater that the threshold detection limits increases, but in that case the effect of the initial instantaneous release becomes difficult to differentiate.

Detection of aquifer contamination is performed with the use of monitoring wells that are sampled according to a frequency schedule. Effective monitoring, and hence early remediation action, constitutes a complicated problem with many uncertainties involved, arising from the heterogeneity of the geologic medium, the aquifer's depth and the hydraulic gradient, the quantity and nature of the contaminants, all affecting the number, location, and frequency of sampling of a monitoring network.

Yenigül et al., (2005*)* conducted numerical experiments of the influence of aquifer heterogeneity and dispersion, and well density on the probability of plume detection, P_d, resulting from landfill contaminant releases. These authors concluded that the number of wells and aquifer dispersion are the dominant factors affecting detection probability. (Papapetridis & Paleologos, 2011a) demonstrated that the frequency of sampling is critical in heterogeneous aquifers, with bi-annual or monthly sampling improving P_d by 40 %, and 70 %, respectively, relative to that by annual sampling. They recommended that sampling should take place twice a year, at a minimum, with once- in-a-month appearing the optimum choice, considering the effort involved and the improvements in detection. These authors also introduced the notion of remedial action delay and provided a correction to decision analyses to account for the cost of delays in remedial actions.

The present study utilizes the stochastic Monte Carlo framework to investigate contaminant transport in heterogeneous aquifers (Hudak & Loaiciga, 1992; Meyer et al., 1994; Storck et al., 1997; Yenigül et al., 2005; Bierkens, 2006; Yenigul et al., 2006; Papapetridis & Paleologos, 2011a, 2011b; Yenigül et al., 2011) in order to evaluate the effect of sampling frequency on the detection probability of a linear monitoring arrangement of wells. Although our study considers for illustration purposes that an instantaneous contaminant release has emanated from a random point within a landfill's area, our analysis is also relevant for other cases as well, such as when contamination can be considered to have emanated from a small area of waste deposition, and from an unknown point of contamination within that area *(Højberg et al., 2007)*. The change in P_d for various sampling schedules, degree of heterogeneity and dispersion is quantified, together with the average time needed for detection depending on the sampling performed. In addition, the concept of the remedial action delay is further expounded for specific well arrangements and sampling schedules in geologic environments of differing heterogeneity and dispersion. Our study aims to define the critical factors that determine an optimal groundwater monitoring sampling strategy and to quantify how the contaminated area, and hence the cost of remediation is affected by delays in remedial actions.

4.2 Model Description

Our study employed the Monte Carlo numerical framework to simulate groundwater flow and contaminant transport in 2-D heterogeneous aquifers with the use of the Spectral Turning Bands Method (STUBA) (Tompson et al., 1987a; Ababou et al., 1989; McLaughlin et al., 1993; Elfeki, 1996; Paleologos & Sarris, 2011). The range of the log hydraulic conductivity variance varied from 0.0 (homogeneous aquifer) to 2.0 (strongly heterogeneous aquifer), and the mean of the log hydraulic conductivity was set equal to 2.3. The correlation length, λ, was considered constant and equal to 20m for both $x-$ and $y-$ directions. Contaminant transport into the subsurface heterogeneous environment was simulated using the particle tracking method based on the 'random walk' approach (Ahlstrom et al., 1977; Prickett et al., 1981; Tompson & Gelhar, 1990a; Uffink, 1990; Zimmermann et al., 2001; Hassan & Mohamed, 2003; Delay et al., 2005b; Yenigül et al., 2005; Salamon et al., 2006b; Yenigül et al., 2011). For each case of heterogeneous field 3,000 Monte Carlo realizations and 8,000 particles were utilized to calculate the groundwater velocity and the contaminant's movement into the subsurface environment. Transverse dispersion coefficients, α_T, were set equal to $\alpha_T = 0.01$, 0.02, 0.05, 0.10, 0.20, 0.50m, corresponding to values observed in field experiments (Gelhar, 1986), and the longitudinal dispersion coefficient, α_L, was calculated by the relation $a_L = 0.10a_T$.

Steady state groundwater flow in an isotropic, heterogeneous porous medium, with a fixed depth of aquifer was considered with a constant hydraulic gradient of 0.001m, between the nodes lying perpendicular to the direction of flow, and no-flow conditions at the lower and upper boundaries of the flow domain. Although hydraulic gradient variations or other hydrogeological considerations, such as the existence of fast pathways or of "hot" spots, where contaminants may be sorbed and slowly released at a later time have been seen to occur, our analysis did not extend on these aspects that are difficult to address, without detailed field investigations (Mahar & Datta, 2000). The simulated region was 1,000 m long and 400 m wide (Figure 4.1), and it was discretized in cells of area $dx \cdot dy = 2 \cdot 2\ \mathrm{m}^2$, creating a 500×200 grid. A rectangular area simulating a contaminant potential source area (CPSA), for example a section of a landfill, or the area of a waste storage facility, was situated between $x-$coordinates 10m and 60m, and $y-$coordinates of 140m and 260m (Figure 4.1). At a random

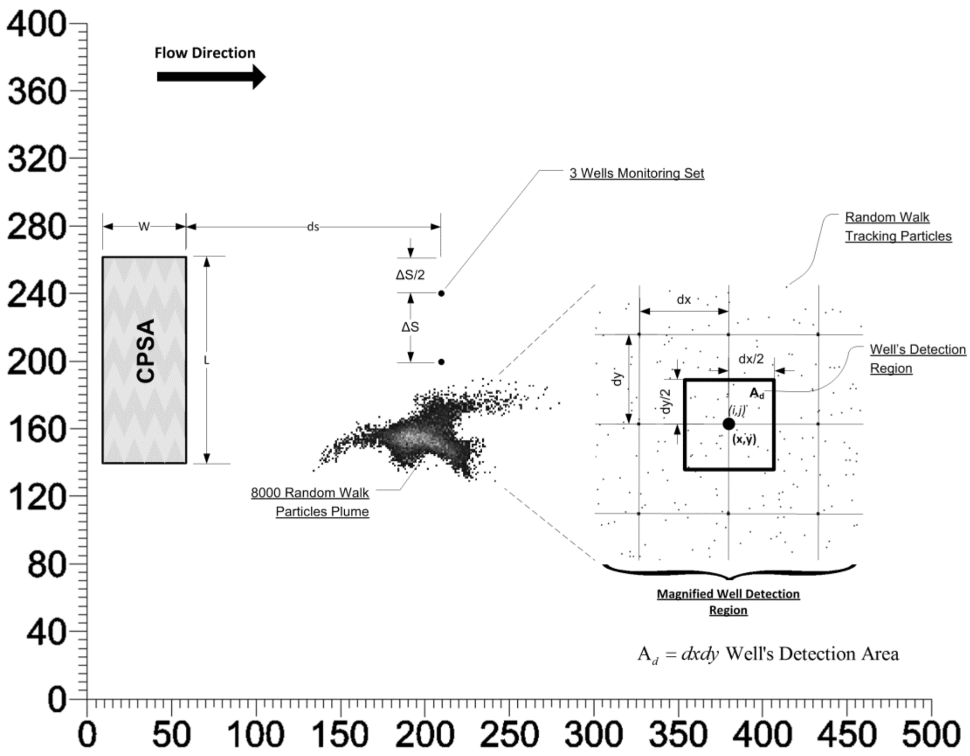


Figure 4.1: Half section of simulated flow field illustrating the rectangular CPSA, an 8000 particles plume evolved for 10 years, and a magnified well-detection area (wells are deliberately placed further away for illustration purposes)

point within these boundaries a contamination event was initiated that polluted the aquifer. The total contaminant mass was equal to 1,000 gr, and was assumed conservative and fully water soluble. The initial concentration of the point source, $C_0 = M_0/(nV_0)$, was 4,000mgr/lt, where M_0 the initial mass, $n = 0.25$ the effective porosity, and the volume $V_0 = 1\text{m}^3$. The threshold concentration C_{TH}, detectable by the monitoring wells was set at 0.35 % of the initial concentration, corresponding to C_{TH} =14mgr/lt or 112 particles in a single cell. The uncertainty regarding the potential location within a cell of a landfill, where a leak might have developed, stems from the lack of information on potential failure locations at a landfill's bottom liner. In case pollution from a different facility is assumed, such as from an industrial plant or a military facility, uncertainty about the contamination's point source may stem from our inability to detect leaks from waste carrying pipelines, or underground storage areas of liquid waste, or even accidental spills during operations. In either case, it was assumed that any point within the rectangular CPSA is an equal-probable source of leakage, taking place once as a single failure event at zero time (when the simulation begun) and resulting in an instantaneous ejection of contaminants into the aquifer. Monitoring wells were assumed to fully penetrate the aquifer resulting in vertically-averaged concentration measurements. Six linear configurations were examined consisting of 1, 3, 6, 8, 12 and 20 wells, equally spaced from each other. Wells that were located at the ends of each arrangement were placed half the distance from the cell's top and bottom edges so that the efficiency of the monitoring system would be maximized (Yenigül et al., 2005). Monitoring of the aquifer and plume evolution was simulated for a 30-year period.

4.3 Sampling Frequency of Groundwater Monitoring

Table 4.1 and Table 4.2 present the results for the detection probability P_d (%) achieved for different number of wells (NOW), where NOW=1, 3, 6, 8, 12, 20, for various levels of heterogeneity, $\sigma^2_{\ln K}$ =0.0, 0.5, 1.0, 2.0 and values of transverse dispersion coefficients, a_T = 0.01, 0.02, 0.05, 0.10, 0.20, 0.50m. The values for the detection probability are given at NDFS, which was the distance from the trailing edge of the CPSA where P_d was maximized, normalized by the width ($L_o = 120$m) of the facility. (Papapetridis & Paleologos, 2011a) have shown that, in most cases, different monitoring wells, under the same conditions of heterogeneity and dispersion, performed better, in terms of P_d, at slightly different distances. However, because of the computational effort it was chosen that the values of P_d, shown in Table 4.1 and Table 4.2, would be calculated (in each a_T case) at the same NDFS for all

Table 4.1: Detection Probability P_d (%)

NOW	σ^2_{lnK}=0.0								σ^2_{lnK}=0.5							
	NDFS	**D**	**1M**	**2M**	**3M**	**4M**	**6M**	**A**	**NDFS**	**D**	**1M**	**2M**	**3M**	**4M**	**6M**	**A**
				a_T=0.01 m								**a_T=0.01 m**				
1	**2.25**	6.0	5.7	5.6	5.5	5.4	5.4	4.9	**1.50**	5.4	5.2	5.2	5.2	5.1	5.0	4.5
3	**2.25**	18.9	18.2	17.8	17.5	17.1	16.9	15.9	**1.50**	15.1	14.5	14.3	14.1	13.9	13.6	11.8
6	**2.25**	35.4	34.3	33.6	33.4	32.7	32.3	29.8	**1.50**	30.7	29.5	29.0	28.6	28.2	27.5	24.1
8	**2.25**	47.2	45.5	44.8	44.2	43.3	42.8	39.9	**1.50**	41.5	39.7	38.9	38.3	37.9	37.1	32.7
12	**2.25**	70.5	68.5	67.4	66.7	65.8	64.8	59.5	**1.50**	57.0	55.5	54.5	53.5	53.1	51.8	46.7
20	**2.25**	99.6	99.5	99.4	99.4	99.3	99.3	95.1	**1.50**	77.2	75.9	75.0	74.2	73.5	72.7	66.8
				a_T=0.02 m								**a_T=0.02 m**				
1	**1.50**	5.8	5.6	5.5	5.4	5.3	5.2	4.5	**0.50**	5.9	5.9	5.9	5.7	5.7	5.6	4.5
3	**1.50**	18.2	17.5	17.0	16.7	16.3	15.9	14.0	**0.50**	16.9	16.6	16.4	15.9	16.0	15.5	12.8
6	**1.50**	34.6	32.9	31.8	31.2	31.0	30.2	27.4	**0.50**	33.2	32.4	32.0	31.7	31.2	30.8	25.8
8	**1.50**	46.3	43.9	43.0	42.1	41.5	40.2	36.5	**0.50**	43.6	42.0	41.5	40.9	40.7	39.5	33.8
12	**1.50**	69.0	65.6	64.5	63.2	62.4	60.3	55.0	**0.50**	61.9	60.0	59.2	58.7	58.0	57.0	48.6
20	**1.50**	99.4	99.3	99.0	98.7	98.5	97.1	89.4	**0.50**	84.4	83.0	82.2	81.9	81.6	80.8	71.8
				a_T=0.05 m								**a_T=0.05 m**				
1	**0.50**	5.8	5.5	5.2	5.3	5.1	4.9	4.4	**0.50**	5.6	5.0	4.7	4.5	4.2	4.0	3.0
3	**0.50**	18.2	17.3	16.7	16.3	16.3	15.6	13.9	**0.50**	14.9	13.6	12.9	12.6	12.0	11.5	8.9
6	**0.50**	34.1	31.9	31.0	30.6	30.2	29.0	25.3	**0.50**	29.9	27.0	25.5	24.7	24.0	22.8	17.0
8	**0.50**	45.8	43.2	42.2	41.3	40.5	39.4	34.7	**0.50**	39.1	35.1	33.7	33.0	31.5	29.7	23.4
12	**0.50**	69.0	65.1	63.0	61.9	60.7	59.0	52.3	**0.50**	55.7	50.2	48.0	46.2	44.4	41.8	33.2
20	**0.50**	99.4	98.9	98.1	97.4	96.5	94.9	84.7	**0.50**	78.2	73.4	70.9	69.2	67.4	64.5	51.7
				a_T=0.10 m								**a_T=0.10 m**				
1	**0.125**	5.7	5.3	5.1	4.9	5.0	4.7	4.4	**0.125**	6.4	5.9	5.6	5.3	5.2	4.8	4.0
3	**0.125**	18.1	16.9	16.4	15.9	16.0	15.3	13.9	**0.125**	16.2	14.9	14.4	13.9	13.5	12.9	10.3
6	**0.125**	33.9	31.8	30.9	30.0	29.5	28.6	25.1	**0.125**	30.3	28.0	27.1	26.0	25.7	24.3	19.9
8	**0.125**	45.8	42.6	41.4	40.7	39.9	38.8	34.1	**0.125**	42.2	38.4	37.1	35.9	36.0	33.8	27.6
12	**0.125**	67.9	63.7	62.0	60.5	59.8	57.5	51.1	**0.125**	62.2	56.4	54.6	52.3	51.8	48.7	39.8
20	**0.125**	99.1	97.3	96.0	95.1	93.9	92.3	83.6	**0.125**	87.0	81.9	79.9	77.9	76.5	73.2	60.7
				a_T=0.20 m								**a_T=0.20 m**				
1	**0.030**	4.7	4.1	3.8	3.6	3.6	3.3	2.7	**0.030**	4.8	4.2	4.1	4.0	3.9	3.7	2.7
3	**0.030**	14.3	12.3	11.6	10.9	11.0	10.1	8.1	**0.030**	12.9	11.2	10.9	10.6	10.4	9.8	7.2
6	**0.030**	26.1	22.5	21.2	20.5	19.5	19.2	14.6	**0.030**	24.1	20.2	19.2	18.6	17.9	16.7	11.7
8	**0.030**	36.1	30.7	29.1	27.9	27.5	26.1	20.0	**0.030**	32.5	28.5	27.1	25.9	25.4	23.2	16.2
12	**0.030**	53.9	46.0	44.3	42.1	42.0	39.1	30.2	**0.030**	48.3	42.3	40.5	39.2	37.9	35.9	25.3
20	**0.030**	80.8	70.9	68.2	65.9	64.8	62.1	47.7	**0.030**	69.6	61.7	59.7	58.0	56.6	53.3	37.4
				a_T=0.50 m								**a_T=0.50 m**				
1	**0.015**	2.4	2.2	1.9	1.9	1.9	1.7	0.1	**0.015**	3.0	2.6	2.4	2.2	2.1	1.8	0.9
3	**0.015**	7.3	6.2	5.8	5.6	5.5	5.0	0.4	**0.015**	7.8	6.9	6.6	6.2	5.9	4.9	1.8
6	**0.015**	13.7	11.5	11.1	10.7	10.5	9.8	0.8	**0.015**	13.5	10.9	10.5	10.0	9.3	7.8	2.8
8	**0.015**	18.2	15.1	14.4	13.7	13.5	12.5	1.3	**0.015**	18.0	15.1	14.4	13.7	13.0	10.6	3.4
12	**0.015**	27.6	23.9	22.5	22.2	21.3	19.8	2.4	**0.015**	27.5	22.6	21.3	20.5	19.5	16.1	5.6
20	**0.015**	40.5	36.7	35.0	34.2	33.4	31.0	3.1	**0.015**	38.2	34.0	32.8	31.7	30.0	25.4	8.7

NOW: No of Wells, NDFS: Normalized Distance from Source, D: Daily, 1M: Every Month, 2M: Once every two months, 3M: Once every three months, 4M: Once every four months, 6M: Bi-Annually, A: Annually

Table 4.2: Detection Probability P_d (%)

NOW	σ^2_{lnK}=1.0								σ^2_{lnK}=2.0							
	NDFS	**D**	**1M**	**2M**	**3M**	**4M**	**6M**	**A**	**NDFS**	**D**	**1M**	**2M**	**3M**	**4M**	**6M**	**A**
	a_T=0.01 m								**a_T=0.01 m**							
1	**1.25**	5.7	5.3	5.2	5.2	5.1	5.0	4.0	**0.50**	5.3	5.1	5.1	5.1	4.8	4.7	3.3
3	**1.25**	14.7	14.0	13.6	13.4	13.2	12.8	10.4	**0.50**	14.2	13.9	13.8	13.6	13.1	12.4	9.7
6	**1.25**	27.4	26.3	25.6	25.0	24.5	23.8	19.9	**0.50**	23.8	23.2	22.7	22.5	22.1	20.9	16.9
8	**1.25**	35.7	34.4	33.6	32.9	32.6	31.3	25.6	**0.50**	32.3	31.6	31.1	30.7	30.0	28.4	22.8
12	**1.25**	50.4	48.4	47.8	46.7	46.2	45.2	37.5	**0.50**	46.8	45.8	45.2	44.4	43.6	40.9	33.6
20	**1.25**	68.8	66.7	65.7	64.7	64.3	62.4	53.6	**0.50**	64.7	63.4	62.7	62.1	61.1	58.2	47.5
	a_T=0.02 m								**a_T=0.02 m**							
1	**0.50**	6.3	5.9	5.7	5.7	5.6	5.3	4.5	**0.25**	5.0	4.9	4.8	4.7	4.7	4.6	3.8
3	**0.50**	17.0	16.2	15.9	15.7	15.5	14.8	12.0	**0.25**	13.5	13.0	12.9	12.7	12.4	12.0	9.7
6	**0.50**	28.5	27.5	26.9	26.6	26.0	25.0	20.7	**0.25**	28.0	27.1	26.7	26.0	25.7	24.4	19.8
8	**0.50**	42.1	40.8	39.9	39.3	38.6	37.0	29.9	**0.25**	36.7	35.3	34.5	34.3	33.3	31.6	25.4
12	**0.50**	57.5	55.6	54.7	53.9	53.5	52.2	44.1	**0.25**	50.6	49.1	48.1	47.6	46.2	44.0	35.5
20	**0.50**	77.0	75.5	74.6	74.2	73.5	72.0	61.9	**0.25**	71.7	70.2	69.0	68.6	67.0	64.6	54.4
	a_T=0.05 m								**a_T=0.05 m**							
1	**0.125**	5.7	5.6	5.5	5.4	5.1	5.0	3.7	**0.125**	5.1	4.9	4.7	4.6	4.4	4.1	3.0
3	**0.125**	17.0	16.5	16.2	16.0	15.4	14.8	11.9	**0.125**	14.0	13.4	13.0	12.6	12.4	11.5	9.0
6	**0.125**	33.3	31.9	31.2	30.8	30.2	29.2	23.7	**0.125**	29.8	28.3	27.8	27.0	26.5	24.7	20.3
8	**0.125**	43.5	42.1	41.5	40.9	40.3	39.0	32.7	**0.125**	40.4	38.3	37.5	37.1	36.1	34.3	27.0
12	**0.125**	61.8	59.7	59.1	58.3	57.5	55.8	47.1	**0.125**	56.4	54.2	53.1	52.2	51.2	48.2	39.1
20	**0.125**	86.3	84.7	84.2	83.1	82.9	80.6	68.7	**0.125**	76.9	74.8	73.9	73.1	71.7	68.9	56.9
	a_T=0.10 m								**a_T=0.10 m**							
1	**0.0625**	5.4	5.1	5.1	4.8	4.8	4.6	3.7	**0.0625**	4.9	4.6	4.4	4.1	4.1	3.9	3.1
3	**0.0625**	17.1	15.9	15.8	15.2	14.9	14.1	10.9	**0.0625**	14.7	13.7	13.0	12.4	12.2	11.5	8.4
6	**0.0625**	31.6	29.4	28.5	27.6	27.1	25.5	19.7	**0.0625**	28.9	26.6	25.7	25.0	24.0	22.7	17.2
8	**0.0625**	43.2	40.0	38.6	37.8	36.8	34.8	27.6	**0.0625**	37.5	34.7	33.2	32.4	31.2	29.2	22.7
12	**0.0625**	60.8	56.5	54.8	53.7	52.5	49.5	38.8	**0.0625**	54.5	50.4	48.9	47.1	45.6	42.7	32.5
20	**0.0625**	86.2	82.7	81.0	79.5	78.5	74.9	59.3	**0.0625**	74.7	71.1	69.4	67.8	65.9	61.9	47.9
	a_T=0.20 m								**a_T=0.20 m**							
1	**0.030**	4.0	3.4	3.2	3.0	3.0	2.7	1.7	**0.015**	3.8	3.5	3.4	3.2	3.0	2.7	1.9
3	**0.030**	12.8	11.2	10.6	10.3	10.0	9.2	5.9	**0.015**	12.2	10.4	10.0	9.4	8.9	7.9	5.1
6	**0.030**	22.0	19.2	18.0	17.8	16.7	15.6	10.0	**0.015**	22.0	19.0	17.8	16.6	15.8	14.3	9.7
8	**0.030**	31.1	26.6	25.3	24.5	23.2	21.3	14.7	**0.015**	29.2	24.8	23.4	22.2	21.2	18.6	12.6
12	**0.030**	44.7	38.6	37.0	35.8	34.3	31.7	21.0	**0.015**	44.0	38.2	36.2	34.8	33.0	29.4	18.6
20	**0.030**	64.6	57.8	55.6	53.6	52.7	48.0	32.8	**0.015**	62.3	55.6	53.0	50.9	48.6	43.4	29.9
	a_T=0.50 m								**a_T=0.50 m**							
1	**0.015**	2.2	2.0	1.9	1.6	1.5	1.2	0.4	**0.015**	2.1	1.8	1.7	1.5	1.4	1.0	0.7
3	**0.015**	7.7	6.7	6.4	5.8	5.4	4.1	1.6	**0.015**	6.8	5.4	4.9	4.4	4.0	3.1	1.8
6	**0.015**	12.7	10.9	10.4	9.7	9.3	7.2	2.7	**0.015**	12.0	10.0	8.9	8.0	7.3	5.6	3.4
8	**0.015**	18.1	15.6	14.4	13.4	12.2	9.5	4.0	**0.015**	16.6	13.9	12.5	11.8	10.6	8.4	4.6
12	**0.015**	25.3	21.6	20.5	19.0	17.8	14.0	5.7	**0.015**	25.4	22.1	20.5	19.2	17.5	13.5	6.0
20	**0.015**	36.9	32.9	31.5	29.8	28.0	22.3	9.2	**0.015**	34.7	30.6	28.9	26.8	24.6	19.3	9.9

NOW: No of Wells, NDFS: Normalized Distance from Source, D: Daily, 1M: Every Month, 2M: Once every two months, 3M: Once every three months, 4M: Once every four months, 6M: Bi-Annually, A: Annually arrangement of wells, with NDFS selected as the distance where the performance of the majority of the wells was maximized. (Mahar & Datta, 2000) have concluded that, with the exception of low transverse dispersive subsurface environments, observation wells should be located downstream, in close proximity to contamination sources. All numerical experiments were based on 3,000 Monte Carlo flow simulations and 8,000 tracking particles. Sampling frequencies that were considered were as follows: daily (D), once every month (1 M), once every 2 months (2 M), once every 3 months (3 M), once every 4 months (4 M), bi-annually (6 M), and annually (A).

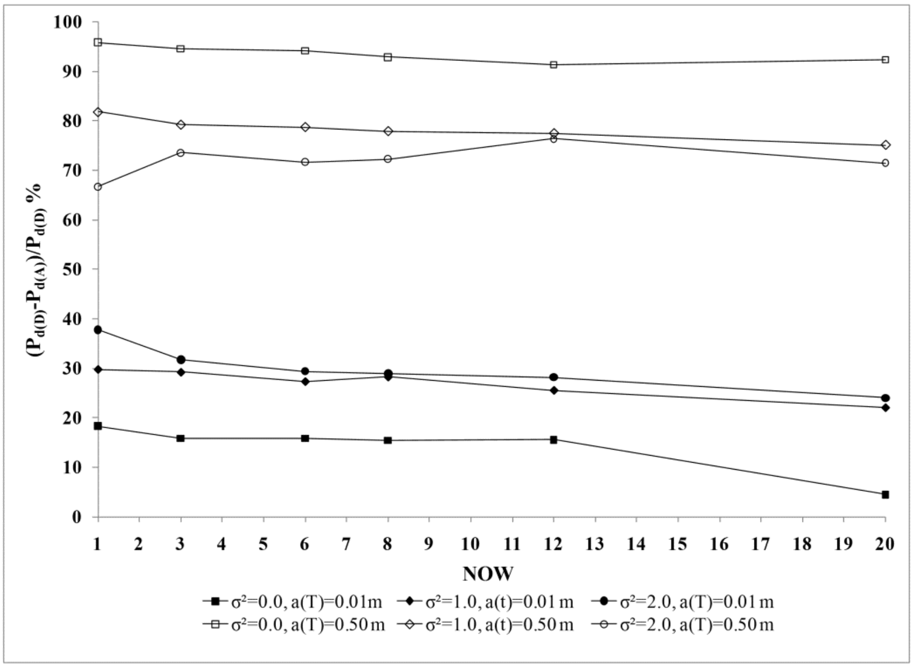


Figure 4.2: Percent detection change between daily and annual sampling for different well arrangements and types of soil

Several conclusions can be drawn from these tables. Monitoring networks with up to 6 wells have, at best, a 35% chance to detect subsurface contamination, which quickly deteriorates even further if sampling becomes less frequent than once-a-day and the geologic environment departs from ideal homogeneous conditions. The addition of two more wells, i.e., a network of 8 wells with sampling only twice per year performs practically at least as well, for all types of soils considered here, with 6 wells, where samples are collected and analyzed every day. It appears therefore that networks of 6 wells do not accomplish the goal of successful monitoring, considering both their low probability of detection and the fact that an intense, daily, sampling effort, and corresponding expenditure, is required in order to maintain such low performance. Furthermore, for all types of soils and dispersions analyzed, networks of 8 wells, even if sampled daily, have a maximum detection probability that does not exceed 50%. This means that under the best conditions, at least at the numerical level, one out of two contamination events would remain undetected, if monitored by 8 wells. If a higher confidence is needed in the performance of a monitoring network to detect contaminant plumes then 20 wells are required in order to at least, with a monthly sampling, in the majority of situations ($a_T \leq 0.20$ m) have a probability of detection that is greater than the probability of failure to detect.

Figure 4.2 plots the percent change of P_d between daily and annual sampling for all combinations of monitoring wells and different types of soils. When the subsurface environment is homogeneous and of low dispersion (α_T=0.01 m) arrangements that consist of up to 12 wells have a deterioration of about 20% in their respective P_d, whereas 20 wells have a decrease in detection of about 5%. A potential explanation of this result, in conjunction with the values in Table 1 that show almost full detection for 20 wells, is that in homogeneous media of low dispersion a large number of wells, such as 20 wells, provide such a dense coverage of the area downstream a landfill that a plume cannot remain undetected and even a single observation is sufficient to verify a contamination event. In contrast homogeneous soils of high dispersion ($a_T = 0.5$m) indicate an almost doubling of the detection capability if sampling is performed daily compared to that of annually. This result indicates that, irrespective of the density of the monitoring network, because contaminants disperse strongly concentrations at the monitoring points can quickly drop below the threshold detection limits, and hence the detection capability of a monitoring network in such an environment can become extremely low, unless a rigorous sampling schedule is followed. A similar situation holds for heterogeneous soils of high dispersion, with the heterogeneity appearing to ameliorate slightly the dispersion effects, but not sufficiently, in practical terms in order to alter our conclusion about the criticality of the sampling schedule. Finally, heterogeneous soils of low dispersion appear to increase the discrepancy between the sampling schedules with most notable the influence on 20-well arrangements. In this type of soils full detection is no longer possible with 20 wells and only the combination of a dense network and frequent sampling can retain a credibly high level of detection (Table 4.1 and Table 4.2).

The effect of dispersion on the detection probability attained through various sampling frequencies is illustrated in Figure 4.3. This figure utilizes 12 wells and plots the ratio of $P_d / P_{d(D)}$ as a function of the $\log_{10}(a_T)$ for homogeneous soils ($\sigma^2_{\ln k} = 0.0$). Here P_d corresponds to the detection probability of a sampling schedule, and $P_{d(D)}$ to that of daily sampling. For a homogeneous field as transverse dispersion increases the ratio of $P_d / P_{d(D)}$ decreases. For all sampling schedules (with the exception of annual sampling) it appears that for a_T in the range of 0.01m to 0.10m the departure of detection achieved by any sampling frequency to that by daily sampling, $P_{d(D)}$, appears to remain approximately constant and smaller than 10%. At $a_T = 0.20$m an additional 10% decline in detection is observed relative to that at $a_T = 0.10$m, and subsequently the ratio $P_d / P_{d(D)}$ remained constant, until $a_T =$ 0.50m. If annual sampling is considered then the ratio $P_d / P_{d(D)}$ continuously declines, and when $a_T > 0.10$m the rate of decline becomes very sharp. This figure in conjunction with Table 4.1 indicate that in homogeneous soils and for dispersions up to $a_T \leq 0.20$m monthly sampling at 12 wells retains a probability of detection that is greater than 60%, which in practical terms does not differ significantly from that attained by daily sampling. For greater dispersion coefficients this particular well arrangement returns a probability of detection that is equal to or lower to the probability of failure to detect, deteriorating very rapidly the moment sampling departs from a daily schedule. For 12 wells in heterogeneous soils a similar analysis did not provide any additional insight to the pattern of behavior observed in Figure 4.3 and Figure 4.4.

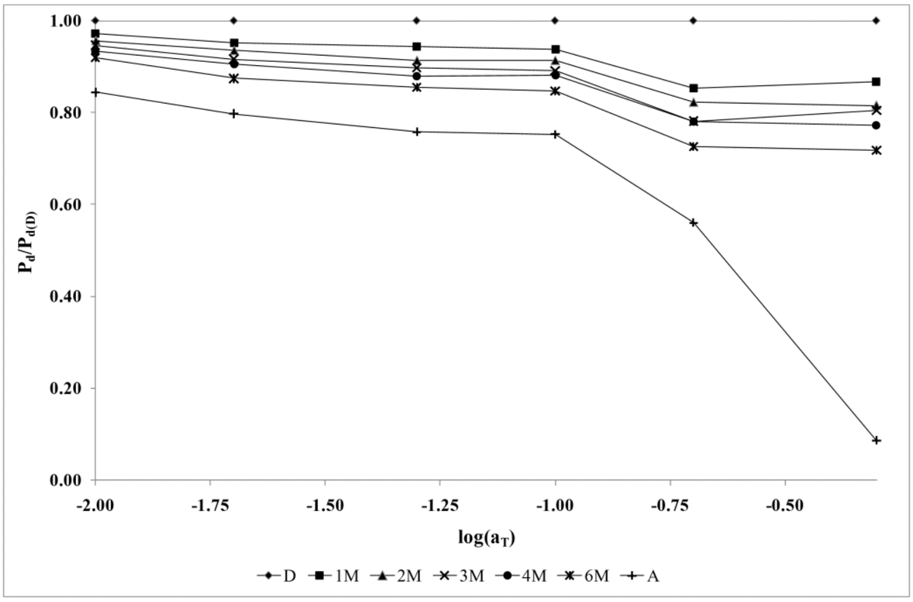


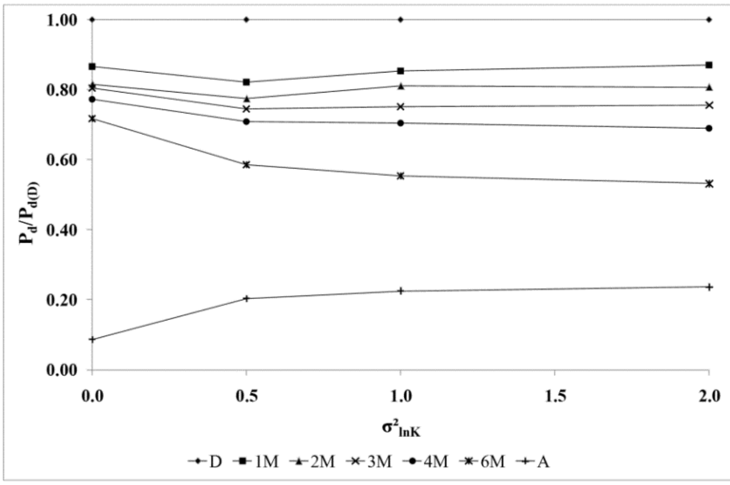
Figure 4.3: 12 monitoring wells: P_d /$P_{d(D)}$ versus $\log_{10}(\boldsymbol{\alpha_T})$ for homogeneous soils $\left(\boldsymbol{\sigma^2_{lnK} = 0.0}\right)$

Field heterogeneity did not appear to affect contaminant detection probability as strongly as transverse dispersion did. Figure 4a indicates that when the transverse dispersion coefficient was equal to or less than 0.20m and for sampling performed at least three times a year the ratio $P_d / P_{d(D)}$ remained approximately constant (with minor fluctuations, which are on the average less than 2%) as the variance of $\ln K$ ln*K*, $\sigma^2_{\ln K}$, increased. If sampling became more sparse then a decrease of $P_d / P_{d(D)}$ on the average of 5%, and 20% for the bi-annual and annual schedules, respectively, relative to daily sampling was observed.

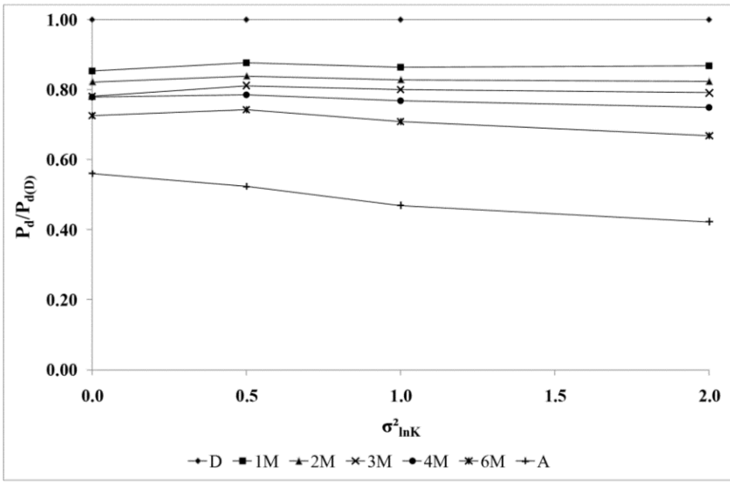
When the transverse dispersion coefficient a_T equaled 0.50m it appeared that in certain situations an increase in the heterogeneity ameliorated the effects of large transverse dispersion. This can been seen in Figure 4.4(b) for all types of sampling, up to bi-annual, where initially, the detection probability declined by approximately 6%, relative to that by daily sampling, as the field became mildly heterogeneous ($\sigma^2_{\ln K} = 0.5$), and then increased by the same amount when $\sigma^2_{\ln K} = 1.0$ to remain constant and equal to the detection achieved by daily sampling, for higher heterogeneities. For bi-annual sampling the initial decrease in $P_d / P_{d(D)}$ was 18% at $\sigma^2_{\ln K} = 0.5$ and continued to decrease by an additional 10% as heterogeneity increased. In contrast when sampling took place only once a year the ratio $P_d / P_{d(D)}$ improved with increased field heterogeneity. This improvement was of the order of 120% from $\sigma^2_{\ln K} = 0.0$ to $\sigma^2_{\ln K} = 0.5$, and by another 20% as $\sigma^2_{\ln K}$ reached the value of 2.0.

An explanation for this behavior may be that while high transverse dispersion leads to greater dilution and lower concentrations at set monitoring points after a time interval, which would not be possible to detect if sampling is not frequent, high heterogeneity through the presence of low permeability regions may impede the lateral spread of contaminants, thus counteracting the effects of transverse dispersion. Irrespective of the above, at this level of dispersion the use of 12 wells achieved a maximum detection of 27% (Table 4.1), if sampled daily and any other sampling schedule corresponded to a monitoring of plume migration of an even lower efficiency. The frequency of sampling is of interest in order to minimize the time lag between the time that concentrations above a threshold limit first appear at the locations of a monitoring network and the time that these concentrations are actually observed through sampling. The effort of course is to identify the extent of the contaminated area as soon as contaminants become observable and to initiate remediation efforts as soon as possible.

In order to investigate these aspects in each Monte Carlo realization, for each $\sigma^2_{\ln K}$ and a_T hydrogeological case analyzed, the time of contaminant release from the landfill facility was set to zero. The time step of our numerical calculations was 1 day and the number of days (T_{ar}) required for concentrations above a threshold limit to arrive at an, at least, one well of an 8-well arrangement was recorded for each realization. Then, if one were to utilize, for example, a monthly monitoring schedule the concentrations at the well monitoring locations would be checked 30-days after the initial contaminant release to observe whether they exceeded or not the threshold limit. If no exceedance of the limit was detected then the next checking period at the wells would be 30-days later and so on. The number of days (T_{obs}) for observation of contamination to be achieved at the monitoring points, based on a specific sampling schedule, would be recorded. The ratio of average observation time, $<T_{obs}>$, to average arrival time of contaminants at the monitoring points, $<T_{ar}>$, over 3,000 simulations for each $\sigma^2_{\ln K}$ and a_T case is plotted on the $y-$axis of Figure 4.5. Of course a daily sampling with our numerical time step set equal to 1 day would return a ratio equal to unity for all hydrogeological cases.



(a)



(b)

Figure 4.4: P_d /$P_{d(D)}$ versus $\boldsymbol{\sigma^2_{lnK}}$: (a) $\boldsymbol{\alpha_T = 0.20m}$, and (b) $\boldsymbol{\alpha_T = 0.50m}$ for 12 monitoring wells

Figure 4.5 shows that when dispersion is low ($a_T = 0.05$m) the average observation time does not differ from the average arrival time if groundwater is sampled no later than every 4 months. The frequency of sampling starts to affect the ratio $< T_{obs} > / < T_{ar} >$ only when the variance of $\ln K$ becomes greater than one and sampling is performed bi-annually or annually. When $a_T = 0.05$m and $\sigma^2_{\ln K}$ =2.0 then annual sampling returned a $< T_{obs} >$ that is 20% higher than $< T_{ar} >$.

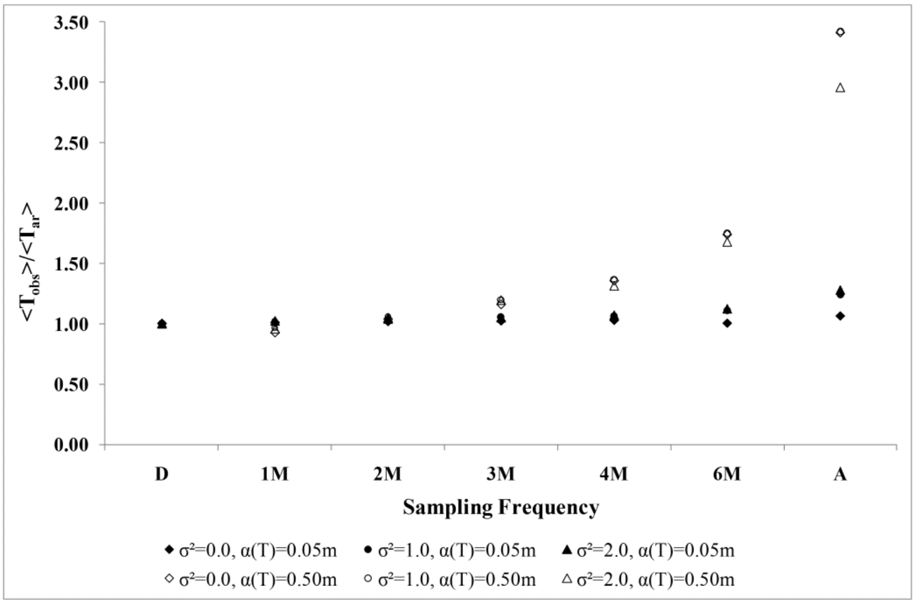


Figure 4.5: $<T_{obs}>/<T_{ar}>$ versus sampling frequency for an 8-well monitoring arrangement in different hydrogeological environments

The average observation time starts to diverge from the average arrival time when dispersion is high ($a_T = 0.50$m) and sampling is performed less frequent than every 3 months. Then there is a 25% difference between the times of observation and first arrival of the contaminants at the monitoring locations, which increases to 240% in the case of annual sampling. Therefore, it appears that if one wishes, under the specific conditions of the hydraulic gradient considered in this study, to detect contaminants as soon as they reach monitoring check-points collection of samples every 2 months appears to be a safe sampling strategy for a wide range of hydrogeological environments. When the hydraulic gradient is one order of magnitude smaller than the one considered here it was calculated through numerical experiments that the average P_d differs by about 15% from that of our base hydraulic gradient case, leading to approximately the same sampling strategy. On the other hand, when the hydraulic gradient is one order of magnitude greater than our base hydraulic gradient case the average P_d from all monitoring cases differs by about 60% from the results presented here, and the sampling strategy to be developed would differ from that of the base case discussed here.

The discrepancy between average observation and arrival times translates into differences between the average area of the plume that exists when the first above-the-threshold concentrations have reached the monitoring points, $< A_{ar} >$, and the extent of that area when observation of the subsurface contamination is made, $< A_{obs} >$. The extent to which a contaminated area has grown as a result of infrequent observation has of course consequences in the volume of groundwater needed to be treated, and correspondingly, in the cost of remediation.

Figure 4.6 shows that when groundwater samples are obtained at least once a month, then no change in the contaminated area occurs as a result of the monthly delay in sampling compared to that by a daily schedule, irrespective of hydrogeological conditions. When dispersion is low ($a_T = 0.05$m) it appears that the movement of contaminants in the subsurface environment is so slow that the contaminated area does not increase by more than 10% from the area that an optimum daily sampling would discern. In this case even sparse information on the state of groundwater, even of the order of once a year, would not lead to significantly more costly remediation efforts.

For high dispersion ($a_T = 0.50$m) an initial observation from Figure 4.6 is that with the exception of monthly sampling all other less frequent sampling schedules result in significant delays in detecting contaminant concentrations at the monitoring points, which allow the plume area to enlarge and hence result in more costly remediation efforts. The less frequent the sampling the more the plume has time to enlarge, with for example, in the case of sampling that is performed every 4 months, the plume to have grown, in some subsurface environments, by at least 50% relative to its size at the time of the plume's first arrival at the monitoring wells. The second observation is that when dispersion is high, stronger heterogeneities (the existence of high and low permeability zones) appear to mitigate a plume's evolution and not allowing it to spread as much as in environments of low heterogeneity.

Thus, Figure 4.6 shows that for all sampling schedules in high dispersion environments strong heterogeneities $\sigma^2_{\ln K} \geq 1.0$ result in smaller $< A_{obs} > / < A_{ar} >$ ratios than those that correspond to $\sigma^2_{\ln K} \leq 0.5$. The fact that infrequent sampling in strongly heterogeneous environments provides plume areas that do not diverge as strongly, from the plume areas existing at the time of monitoring-point arrival, as in mild or homogeneous environments seems to support the notion that the existence of high and low permeability zones appear to impede a plume's spread and the effects of high dispersion.

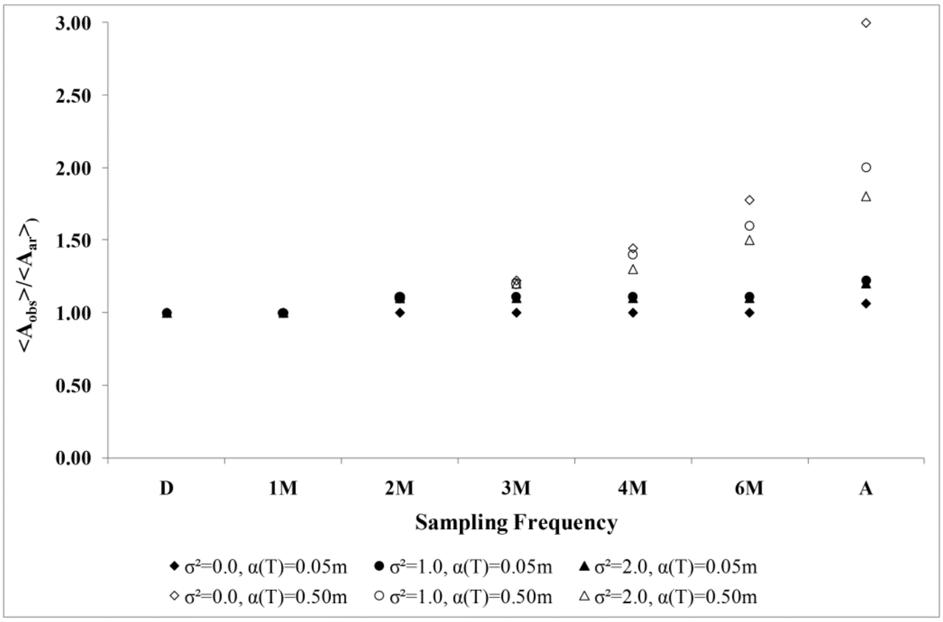


Figure 4.6: $<A_{obs}>/<A_{ar}>$ versus sampling frequency for an 8-well monitoring arrangement in different hydrogeological environments

4.4 Remediation Delay

Decision analyses of remediation actions define a risk term R, which associates the cost of remediation of a contaminated volume of groundwater, C_d, and the cost C_f of a much larger volume, due to failure of the monitoring system to detect with the probability of detection P_d, and the probability of failure $P_f = 1 - P_d$. Thus, R measures the performance of various monitoring systems via the impact that different levels of detection have on remediation costs (Freeze et al., 1990; Yenigul et al., 2006):

$$R = P_d C_d + P_f C_f \tag{4.1}$$

This description assumes that remediation takes place immediately after detection, i.e., that the groundwater volume to be remediated coincides with the contaminated volume at detection time. (Papapetridis & Paleologos, 2011a) provided a correction for the delay in response, which results in an increase of the contaminated volume, as the plume continues to evolve, and correspondingly to an increase of the remediation cost compared to that if the contaminated volume at detection were to be used. *Papapetridis and Paleologos* (2011a)

(Papapetridis & Paleologos, 2011a) defined a corrected risk R^{cor} that accounts for the remedial action response delay as follows:

$$R^{cor} = P_d^{cor} C_d + P_f^{cor} C_f \tag{4.2}$$

where

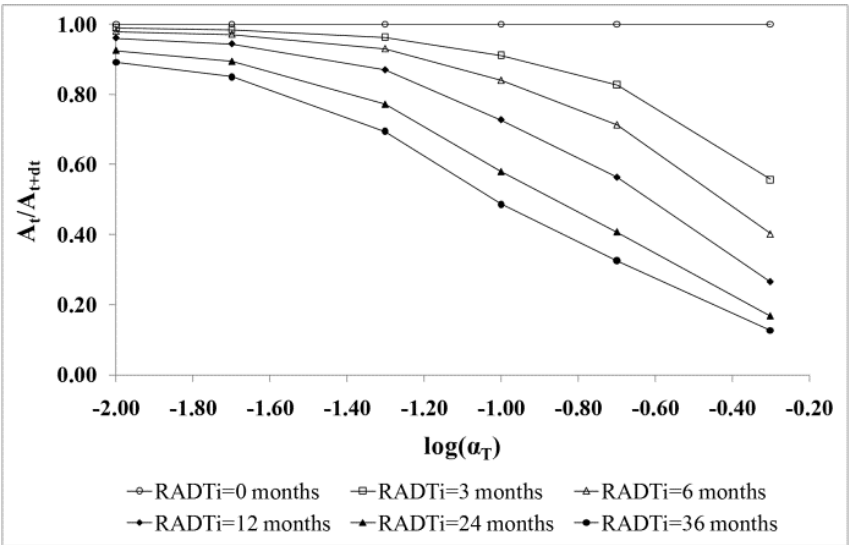
$$P_d^{cor} = P_d \left(\frac{A_t}{A_{t+dt}} \right) \tag{4.3}$$

and

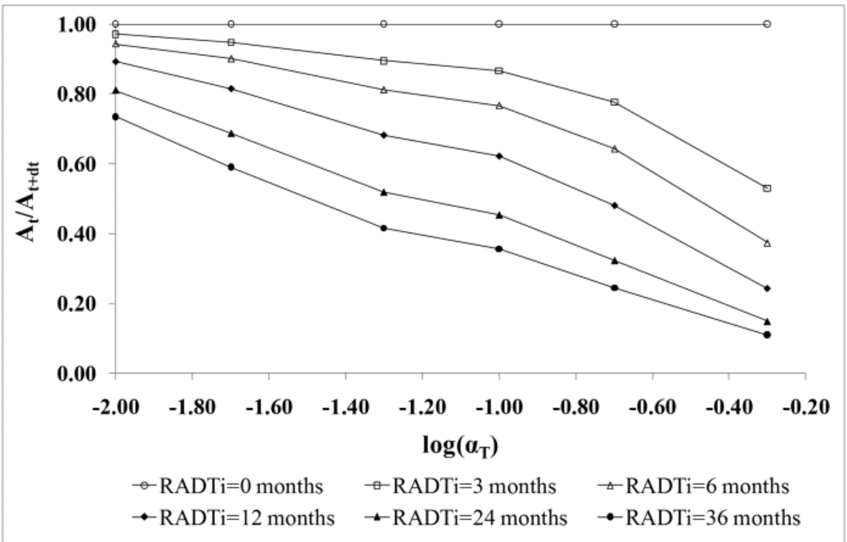
$$P_f^{cor} = 1 - P_d^{cor} \tag{4.4}$$

The corrected detection probability P_d^{cor} is a measure of the economic impact of a remedial action delay, when the contaminated area has extended to A_{t+dt}, as a divergence from the maximum economic outcome that would take place at detection time, when the contaminated area is A_t. This procedure results in increasing the failure probability and weighted cost of failure in the calculation of the risk factor as the time interval dt increases. Sensitivity analyses can then illustrate to decision-makers the influence of remedial delays on the cost of remediation.

Figure 4. demonstrates the influence of dispersion on the first term, the weighted cost due to detection, and correspondingly, the increase of the much larger failure term in Equation (4.1), through the ratio A_t / A_{t+dt}, in homogeneous and heterogeneous soils for different Remedial Action Delay Times (RADTi). In homogeneous soils (Figure 4.a) delays of even 6 months at $a_T = 0.10$m result in a 20% downgrading of the first term of equation (4.1), and at $a_T = 0.50$m this reduction reaches about 60%. At 2 or 3-year time delays for $a_T = 0.10$m an almost 45% reduction of the weight of the first term in the calculation of the risk has occurred, which for highly dispersive environments of $a_T = 0.50$m this reaches almost 80%. The difference between homogeneous and heterogeneous soils (Figure 4.b) is that in heterogeneous soils the impact of consecutive delays on the ratio A_t / A_{t+dt} tends to be greater than that in homogeneous soils of similar dispersion. It appears that in highly dispersive environments not only sampling must be very frequent, in order not to allow the contaminated area to grow as a result of lack of observation, but in addition the remediation response must be of the order of a few months if one does not wish the remediation costs to grow significantly.



(a)



(b)

Figure 4.7: $\boldsymbol{A_t/A_{t+dt}}$ versus log($\boldsymbol{\alpha_T}$) for 6 monitoring wells and different Remedial Action Delay Times (RADTi): (a) homogeneous, and (b) heterogeneous soils with $\boldsymbol{\sigma_Y^2 = 1.0}$

The heterogeneity of the subsurface environment influences the ratio A_t/A_{t+dt} but not to the same extent as dispersion. Figure 4.8 illustrates that in low dispersion environments ($a_T = 0.02$m) delays of up to 6 months would decrease the ratio A_t/A_{t+dt} by less than 20% in highly heterogeneous soils, an equivalent result to that obtained previously for $a_T = 0.10$m and homogeneous soils. A five-fold increase in the dispersion coefficient produces an

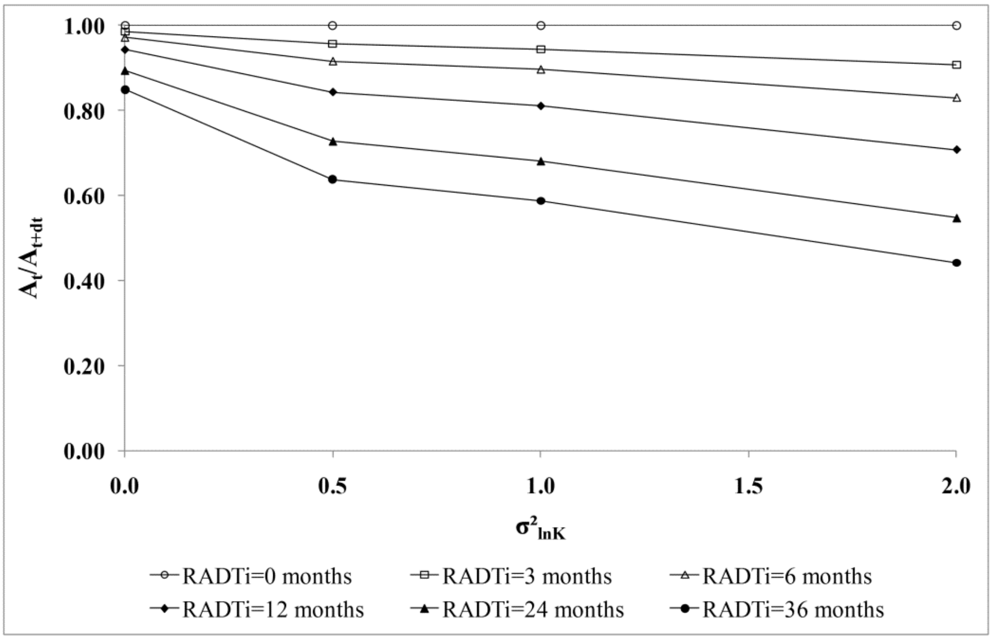


Figure 4.8: $\boldsymbol{A_t/A_{t+dt}}$ versus heterogeneity $\boldsymbol{\sigma^2_Y}$ for fixed dispersion $\boldsymbol{\alpha_T = 0.02\ m}$ for different Remedial Action Delay Times (RADTi) and 3 monitoring wells

equivalent spread in the contamination to that by several orders of magnitude increase in the heterogeneity of a field. At 2 or 3-year time delays again for ($a_T = 0.02$m an almost 45% reduction of the weight of the first term in the calculation of the risk has occurred at $\sigma^2_{\ln K} = 2.0$, an equivalent result to that of homogeneous soils with a five times higher dispersion. Results in high dispersion environments ($a_T = 0.20$m) exhibited a similar pattern to that of Figure 4. with the main difference being that the impact of consecutive delays on the ratio A_t/A_{t+dt} tended to be greater at the same $\sigma^2_{\ln K}$ than that presented in this figure. Both Figure 4. and Figure 4.8 calculate the areas A_t considering immediate detection, i.e., of sampling that is performed daily.

4.5 Conclusions

This work investigates the impact of sampling frequency on the probability to detect groundwater contamination in various subsurface environments, as well as the effects that sampling schedules and remediation delays have on the growth of contaminated subsurface areas and remediation costs. High-resolution numerical Monte Carlo realizations were utilized to simulate contaminant movement in heterogeneous, two-dimensional aquifers and to calculate the probabilities of detection P_d, and contaminated areas by various monitoring well arrangements. Networks of 8 wells, even if sampled daily, had a maximum detection probability that under the best conditions allowed one out of two contamination events to remain undetected. If a higher confidence in the performance of a monitoring network was needed then 20 wells sampled monthly returned a probability of detection greater than the probability of failure even in highly dispersive environments. In homogeneous media of low dispersion a large number of wells provide such density of coverage of the area downstream a landfill that a plume cannot remain undetected even with few observations. In contrast in homogeneous soils of high dispersion, irrespective of the density of monitoring network, because contaminants disperse strongly and concentrations at the monitoring points drop below the threshold limits quickly a rigorous sampling schedule must be followed in order to retain a network's performance. A similar situation holds for heterogeneous soils of high dispersion, with the existence of low permeability zones appearing to ameliorate the dispersion effects, but not sufficiently in order to alter our conclusion about the criticality of the sampling schedule. The frequency of sampling is also of interest in order to minimize the time lag between the time that concentrations above a threshold limit first appear at monitoring locations and the time that these concentrations get to be observed through sampling. The objective of course is to delineate the extent of the contaminated area and to initiate remediation efforts as soon as possible. Analysis of the lag between the time that contaminants appeared at monitoring sites and the time they got to be observed led to the conclusion that, in terms of time delay, sampling every 2 months constitutes a safe strategy for a wide range of hydrogeological environments. In the case of aquifers that exhibit fast pathways of contaminant transport, through the existence of high permeability zones, farther investigation is required. However, in terms of growth of contaminated area with the exception of monthly sampling all other less frequent schedules resulted in significant enlargement of plume areas, thus leading to more costly remediation.

Traditional decision analyses assume that remediation takes place immediately after detection that is that the groundwater volume to be remediated coincides with the contaminated volume at detection time. Based on a correction presented by (Papapetridis & Paleologos, 2011a) for remedial response delays, which result in an increase of the contaminated volume as the plume continues to evolve, the current study demonstrates that in highly dispersive environments the remediation response must be of the order of a few months if one does not wish the contaminated areas and remediation costs to grow significantly.

CHAPTER 5

Parameters on stochastic simulation of contaminant detection probability

5.1 Introduction

Groundwater contamination plume detection is an important aspect of environmental protection, during landfill operation and after closure time. Groundwater monitoring network design and operation has become a subject of major concern mainly in the last three decades (Nunes et al., 2007). Successful detection of an underground pollutant transported into an aquifer is directly dependent on the information of a possible protective barrier failure and the possibility of calculating the movement and dispersion of the pollutant in an environment about which very few things are actually known. This lack of information is caused by the fact that there are difficulties of experimentally measuring, at any point in the geological field, its various hydraulic properties (hydraulic conductivity, hydraulic head, porosity etc.) so as to predict, or even approximate, the way a plume can propagate into the aquifer. Additional uncertainty factors of the problem are lack of information about the geometry and the number of sources from which pollution originates in a landfill waste, the quantity of pollution intruding into the aquifer as well as the duration of the leak.

In order to simulate hydro-geological as well as epistemic uncertainties, the latter arising through lack of knowledge of the landfill and monitoring installation system parameters, a stochastic model in a Monte Carlo context has been utilized. *Yenigul et al.* (2006) performed simulations studying in two dimensions the effect of a field's heterogeneity and dispersion on detection probability of groundwater pollution by a linear arrangement of a landfill's downgradient monitoring wells, originating from a random, single point source inside the vicinity of the installation. The effect of the number of wells, their distance from the landfill and the size of the source were studied too. *Papapetridis and Paleologos* (2011a) performed high resolution Monte Carlo numerical experiments studying more hydro-geological cases, in addition to the effect of monitoring wells sampling frequency.

In the present study we examine how the number of point sources, the size of the controlled area (landfill) and the quantity of an instantaneous aquifer injection pollution event affect groundwater pollution detection probability of a monitoring installation. For this purpose a two-dimensional stochastic model is utilized to perform numerical experiments. The monitoring installation was considered in different cases to be located in various distances from the landfill facility and perpendicular to the flow field. This work extends that of *Papapetridis and Paleologos* (2011a), thoroughly investigating additional uncertainty aspects of detecting instantaneous aquifer pollution. In each examined parameter it is considered that the rest of the factors affecting detection probability estimation remain constant. Simulations are performed in the context of uncertainty factors deriving from the environment itself, where the pollution is propagating, and from the lack of information about certain parameters, concerning the initial conditions of the leak.

5.2 Model description and simulation results

A 2-D steady groundwater flow in a heterogeneous, isotropic and confined aquifer was considered in this study. Our study employed the Monte Carlo numerical framework to simulate groundwater flow and contaminant transport in 2-D heterogeneous aquifers with the use of the Spectral Turning Bands Method (STUBA) (Mantoglou & Wilson, 1982) to stochastically simulate hydro-geological heterogeneity and the Random Walk Tracking Particles algorithm (Tompson et al., 1987a; Salamon et al., 2006b) to simulate the advection and dispersion of the pollution into the aquifer.

Hydro-geological heterogeneity was expressed through the natural logarithm of hydraulic conductivity variance $\sigma^2_{\ln K}$, which varied among 0.0 (homogeneous aquifer), 1.0 (medium heterogeneity) and 2.0 (strongly heterogeneous aquifer). The mean of the log hydraulic conductivity was set equal to 2.3. The correlation length, λ, was considered constant and equal to 20 m for both directions x and y. Transverse dispersion coefficients, α_T, were set equal to $\alpha_T = 0.01,\ 0.05, 0.10, 0.50\ \mathrm{m}$, corresponding to values observed in field experiments, and the longitudinal dispersion coefficient, α_L, was calculated by the relation $\alpha_L = 10\alpha_T$. Contaminant transport into the subsurface heterogeneous environment was simulated using the Particle Tracking method based on the ‘Random Walk’ approach.

The simulated region was 1000m long and 400m wide, discretized by $\Delta x = \Delta y = 2 \times 2m^2$ cells, creating a 500×200 grid. 3,000 Monte Carlo realizations were performed in order to calculate groundwater pollution detection probability by a linear arrangement of monitoring wells. Six linear configurations were examined, consisting of 1, 3, 4, 6, 8, 12 and 20 wells, equally spaced from one another. Wells that were located at the ends of each arrangement were placed half the distance from the cell's top and bottom edges, so that the efficiency of the monitoring system would be maximized. Monitoring of the aquifer and plume evolution was simulated for a 30-year period.

The simulation parameters of the control area where simulation originated, the quantity of pollution that entered the aquifer instantaneously at $t = 0$ and the number of sources were customized accordingly, so that their effect on monitoring efficiency could be examined. More details on the simulation model development are referred at *Papapetridis and Paleologos* (2012a).

5.2.1 Control Area Size

A rectangular control area of $120 \times 50 m^2$ – a landfill cell or other installation capable of causing groundwater pollution – was used as reference area L, situated between x-coordinates of 10 m and 60 m, and y-coordinates of 140 m and 260 m. This specific size was chosen in order to concur with the dimensions of the area used at the study of *Papapetridis and Paleologos* (2012a). Control area cases that were numerically studied were equal to $0.3L,\ 2L/3,\ L,\ 4L/3,\ 5L/3$ and $2L$. It was assumed that any point within a cell of the control area was an equally-probable source of leakage, taking place once as a single failure event at zero time (when the simulation began) and resulting in an instantaneous ejection of contaminants into the aquifer. The total contaminant mass was equal to 1,000 gr, and was assumed conservative and fully water soluble. The initial concentration of the point source, $C_0 = M_0/(nV_0)$ was 4,000 mgr/lt, where M_0 the initial pollution mass, $n = 0.25$ the effective porosity, and $V_0 = 1.0 m^3$ the volume. The threshold concentration C_{TH}, detectable by the monitoring wells, was set at 0.35% of the initial concentration, corresponding to $C_{TH} = 14 mgr/lt$.

Simulation results showed that when the size of the control area became larger than L, then detection probability P_d diminished. On the other hand, when the size became smaller than L, detection probability P_d increased or, if it had already achieved maximum value, it remained the same. At Figure 5.1 it is observed that in case of a homogeneous, low dispersion field (Figure 5.1.a) P_d drops fast as the control area is increased. Between reference sizes L and $2L$ there is a 60% reduction in P_d when 20 monitoring wells are used, while in the case of a dispersive homogeneous field (Figure 5.1b) the same reduction is only 43%. At monitoring installations with a smaller number of wells this reduction is even bigger, as in case of 3 wells, for example, where P_d reduction is 84%. When the control area becomes less that the reference area, then in the first case (Figure 5.1.a) we observe that P_d remains the same, as it has reached maximum, while at the dispersive case (Figure 5.1b) P_d continues to increase as the monitored area goes from L to $0.3L$.

When a heterogeneous field is considered, the same change in P_d occurs. The difference in P_d between the control area reference size L and $2L$ is 58%, in case of 20 monitoring wells in a low dispersion field (Figure 5.1c), and 54% when a higher dispersion field is simulated (Figure 5.1d). If an installation is made up of 3 wells, P_d percentage reduction is 85% and 84% respectively.

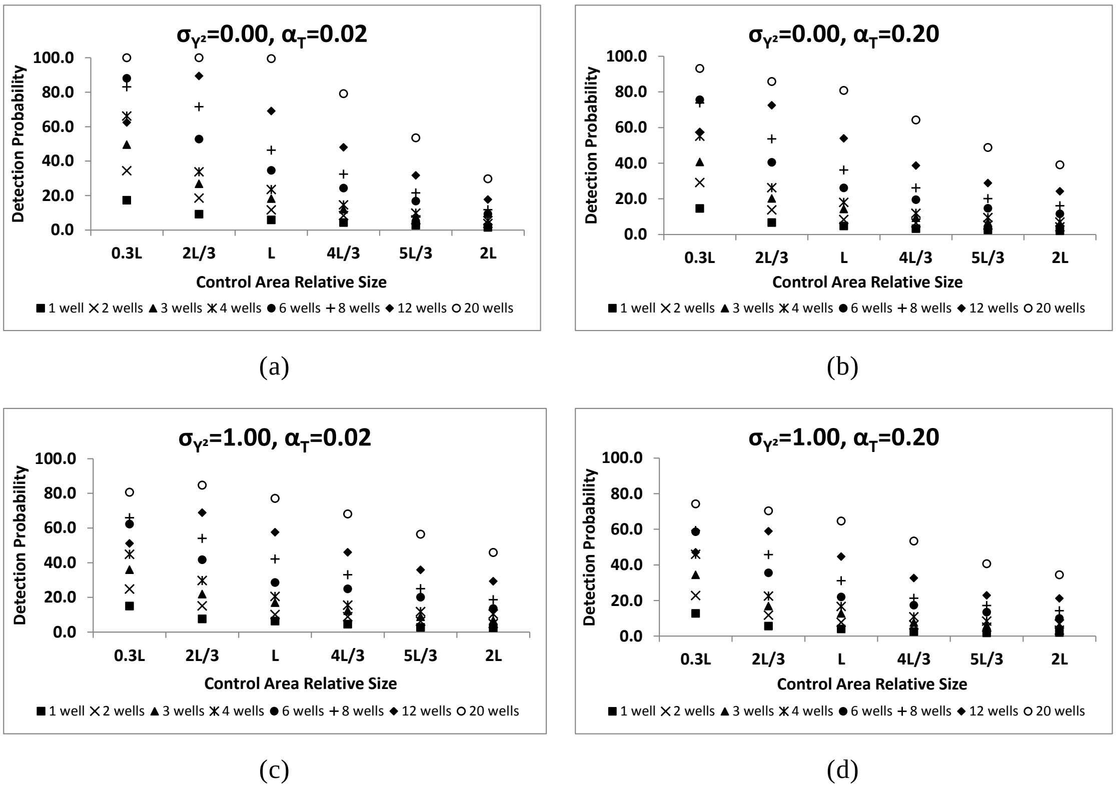


Figure 5.1: Detection Probability P_d change in relation to control area relative size, in a homogeneous low (a) and high (b) dispersion field, and in a heterogeneous low (c) and high (d) dispersion field.

At the heterogeneous case it is observed, though, that when the control area becomes smaller than the reference size L, then P_d increases. In a heterogeneous, low dispersion field a dropdown in P_d (Figure 5.1c) occurs when the control area becomes smaller than $2L/3$ and at least 12 wells are used, and this fact results from the way monitoring wells are located by the model itself on the grid nodes. During simulation the trailing edge of the control area is divided by the number of wells to be used. The integer part of the outcome is used as the space between two successive wells. In addition, the integer part of half the previous outcome is used as the starting point for No1 well. In cases where 12 and 20 wells are used, the starting point of the placement of the wells is at the beginning of the control area's trailing edge, leading to a portion of the trailing edge at the top end, equal to the distance between two wells, being unattended. This is why in these cases detection probability seems falsely to be reducing. When dispersion becomes higher, then the effect of monitoring wells placement faints, due to the fact that in higher dispersion aquifers pollution originating from an unattended portion of the control area can still be detected as it covers a larger area while it is transported. In conclusion, it can be said that as the control area's size becomes larger, detection probability P_d decreases. It has been numerically verified that the fewer the monitoring wells, the less the detection probability. When the control area becomes smaller, P_d increases until it reaches a maximum point.

Examining the case where monitoring wells density remains constant as the control area changes, then it has been observed (Figure 5.2) that detection probability changes very little. In Figure 5.2, as control area width increases from $0.3L$ (40 m) to $2L$ (240 m), the number of wells increases from 2 to 12, providing this way a constant density of wells equal to 0.005. Besides the case of low dispersion homogeneous field, where a P_d dropdown of 50% is observed between sizes $4L/3$ and $2L$, in the rest of the cases detection probability P_d changes less than 15%, meaning that monitoring installation efficiency practically remains the same. Consequently, if the width of a control area where possible groundwater pollution may originate is to be increased, so should the number of monitoring wells, maintaining at least the same density as for the initial size.

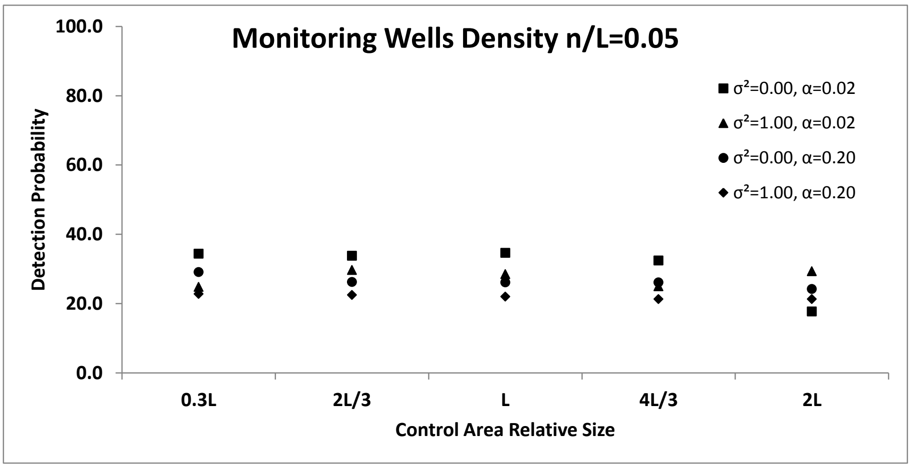


Figure 5.2: Detection probability P_d change shown as monitoring wells density in relation to control area width is kept constant and equal to 0.05.

5.2.2 Multiple Point Sources

Uncertainty regarding the potential location of a leak within a cell of a landfill stems from the lack of information on potential failure locations at a landfill's bottom liner. In all stochastic modeling so far, single pollution source has been the common case. It is not impossible, though, to have more than one pollution source at the same region, caused by the same or different reasons. At least in one case (Collucci et al., 1999), two different tears at a landfill's protective liner have been documented, providing this way two groundwater pollution sources charging the aquifer at the same time.

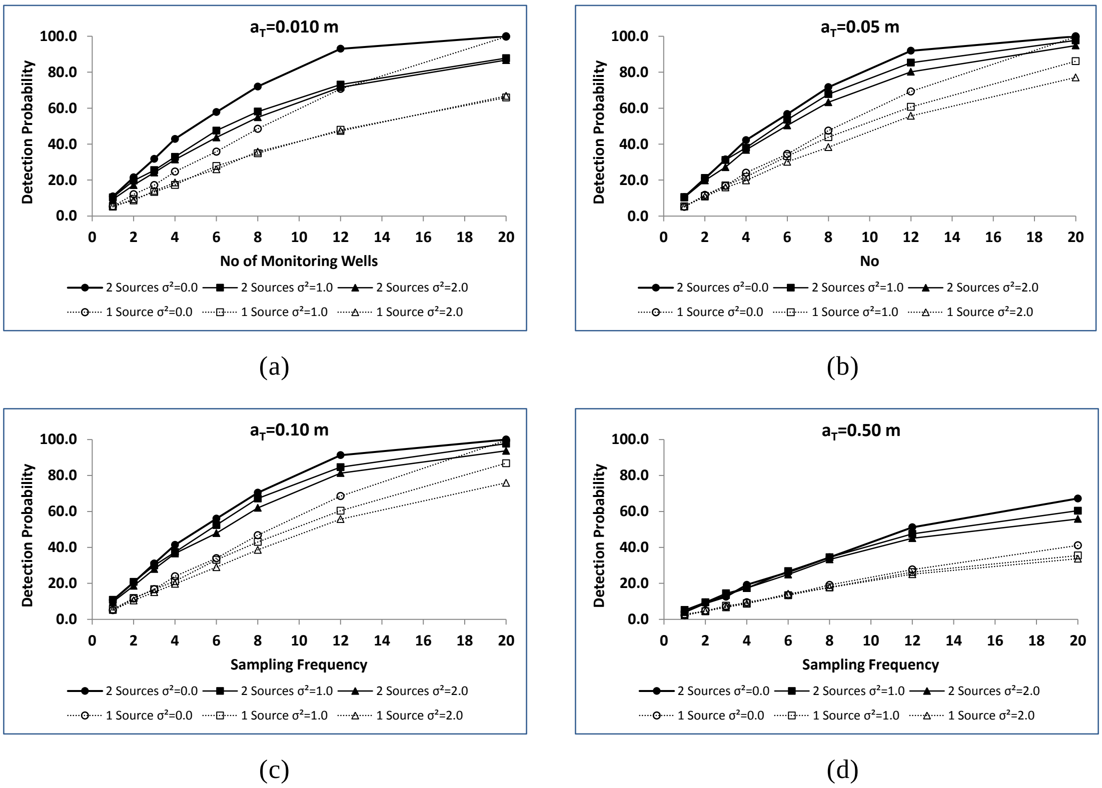


Figure 5.3: Change in detection probability P_d for a single source (dashed lines) and dual source (solid lines) pollution, as the number of wells is increased, for homogeneous $\left(\sigma^2_{\ln K}=0\right)$ and heterogeneous $\left(\sigma^2_{\ln K}=1,\ \sigma^2_{\ln K}=2\right)$ cases, considering four dispersion cases, $a_T=0.01\text{m}$ (a), $a_T=0.01\text{m}$ (b), $a_T=0.01\text{m}$ (c) and $a_T=0.01\text{m}$ (d) .

In the present study it was assumed that two point pollution sources act at the same time. Both of them inject the same quantity of pollution into the aquifer at, providing an initial concentration at the point of injection. Both plumes are transported independently, without any other interaction between them. Both sources are inside the control area vicinity (equal to reference size) and in each computational realization different sources are independently selected with equal probability. The objective is to study how dual pollution sources affect detection probability achieved by a groundwater linear monitoring arrangement

If pollution plumes originate from adjacent sources, they may be transported very closely, crossing each other, providing this way greater pollutant concentration at grid cells. On the other hand, it is possible for them to move to completely different regions, increasing the detection probability as there is more areal coverage. Simulation results showed that groundwater detection probability is increased when two sources are the case (Figure 5.3). In all cases of heterogeneity and transverse dispersion coefficient, it is observed (Figure 5.3a,b,c,d – Figure 5.4) that, as the number of monitoring wells is increased, the difference between P_d tends to decrease. More specifically, when dispersion is among $a_T = 0.01\text{ - }0.10\text{m}$, the average relative percentage difference between dual and single sources is 37% , while in the case of higher dispersion, where $a_T = 0.50\text{m}$, the same difference is 47%. In the case of a low dispersion homogeneous field there is no difference in P_d, something that results from the fact that 100% detection had already been achieved in the single source case.

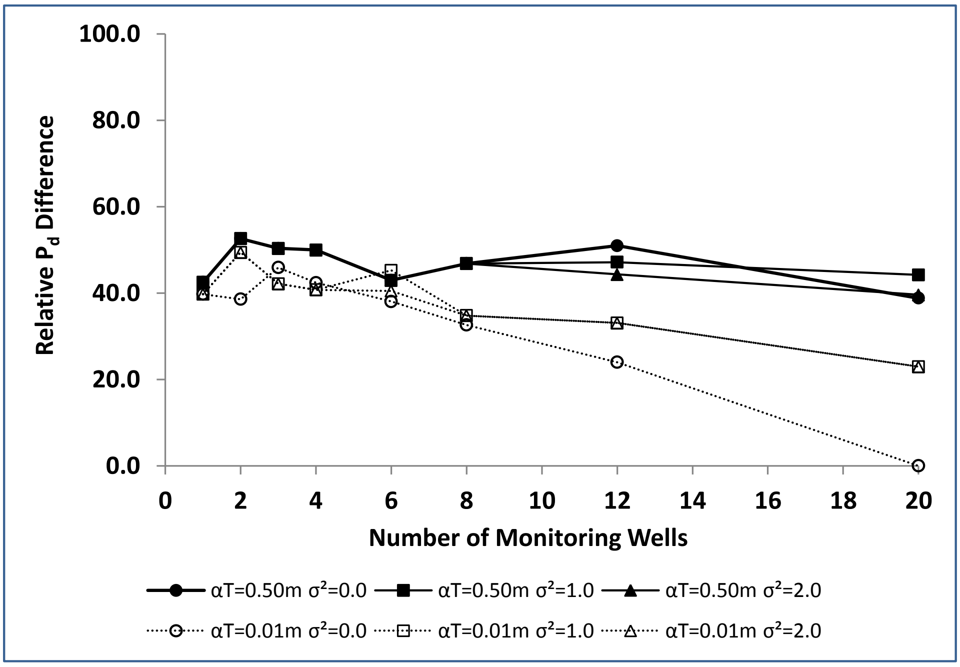
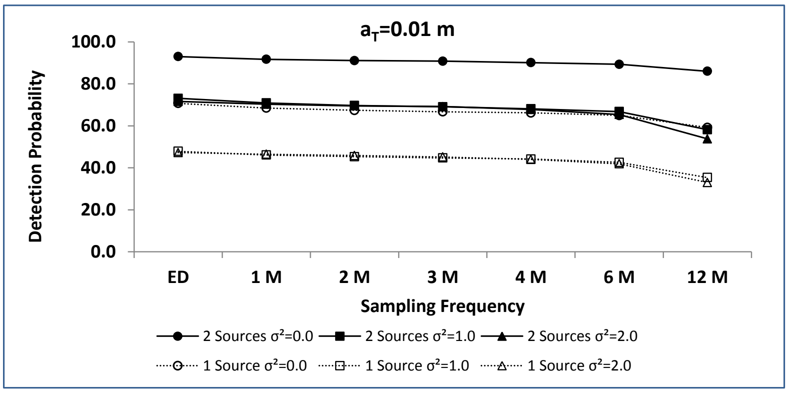


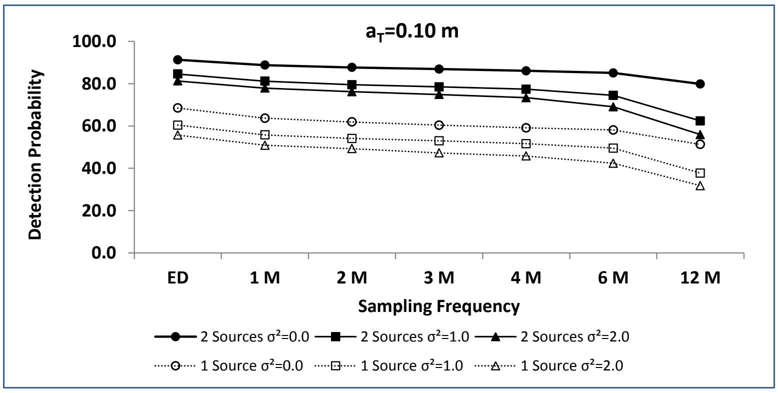
Figure 5.4: Detection probability P_d relative percentage difference between a dual and a single pollution source case in two different transverse dispersion coefficient cases.

In all simulated cases, the general observation (Figure 5.3) is that when two equivalent groundwater pollution sources are present their detection is easier, as the average P_d increase is among 35% – 55%, but for the cases where detection was already 100% successful due to the presence of a dense monitoring network (20 wells). It is obvious that if there were more than two instantaneous sources, injecting the same initial pollution concentration, as in the cases at hand, would make the P_d difference even greater, as it seems that plume superposition results in an average detection probability increase of 45%. This means that in any single pollution case where P_d is at least 50%, an average increase of 90% would be expected if at least three pollution sources were present, setting monitoring wells detection capabilities to a maximum of 100%.

Different sampling frequencies were studied in the case of two pollution sources. It was assumed that sampling was performed at the same time at every monitoring well. Time intervals were assumed to be daily (ED), monthly (1M), bimonthly (2M), quarterly (3M), every four months (4M), biannually (6M) and annually (12M). Studying P_d change in relation to sampling frequency in the case of two sources, the same trend is observed (Figure 5.5a,b,c) in every numerically studied case of field heterogeneity and pollutant dispersion coefficient. The same P_d increase relative to single source cases is observed, independently of the sampling frequency. Consequently, aquifer sampling more often does not alter monitoring efficiency in terms of the presence of more pollution sources.



(a)



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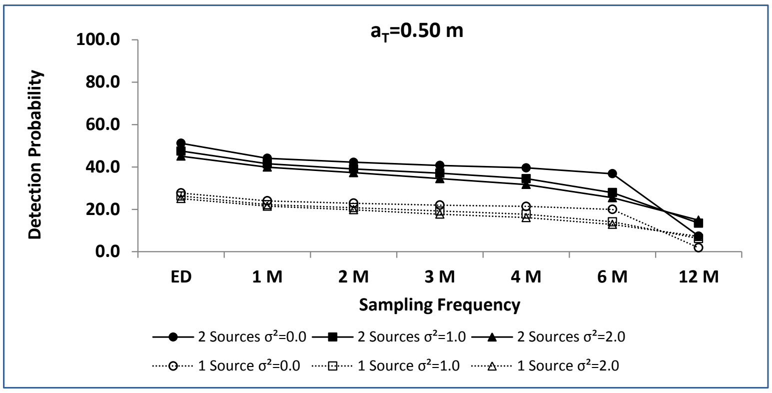


(c)

Figure 5.5: Change of detection probability P_d for a single source (dashed lines) and dual source (solid lines) pollution, as sampling frequency changes from daily (ED), monthly (1M), bimonthly (2M), quarterly (3M), every four months (4M), biannually (6M) and annually (12M)

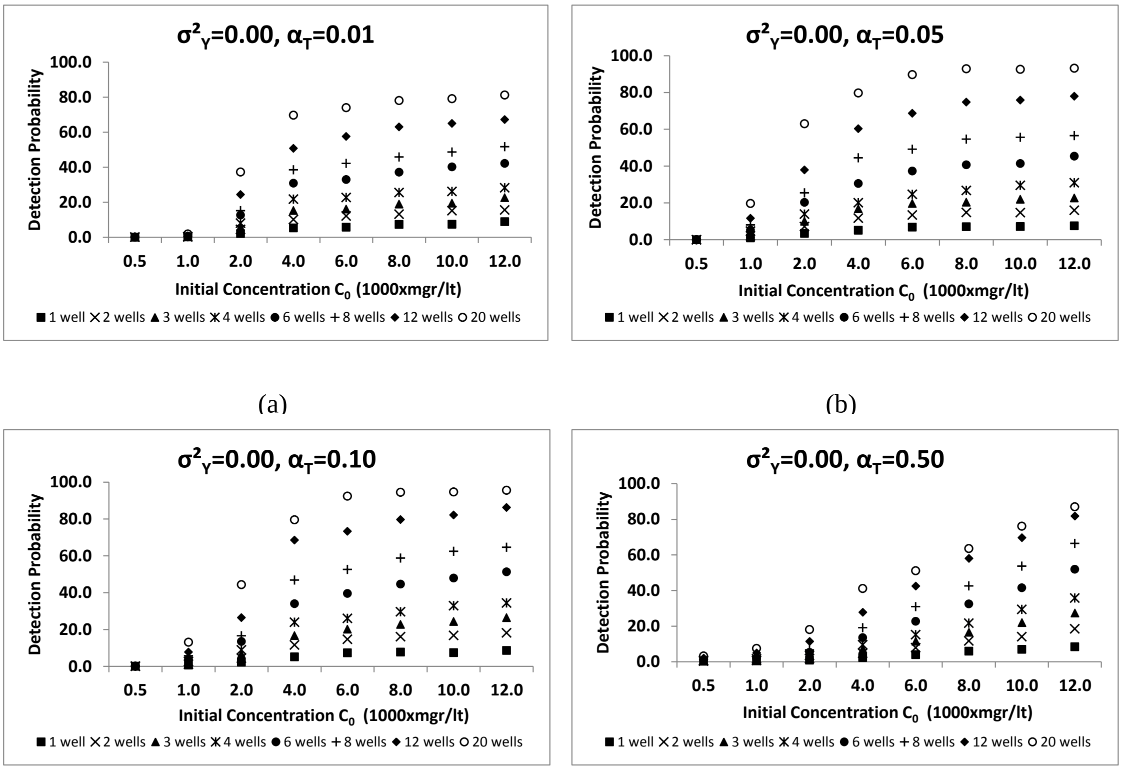
5.2.3 Quantity of Pollution

The sensitivity of groundwater pollution detection probability P_d to pollutant quantity, instantaneously injected into a 2-D aquifer through a randomly selected single point source, was examined during numerical experiments. A rectangular reference control area L was, in all simulations, the region where pollution could originate. Three heterogeneity cases were studied, as reflected in $\sigma^2_{\ln K}$ of hydraulic conductivity K, where $\sigma^2_{\ln K} = 0.0$ was the homogeneous one, $\sigma^2_{\ln K} = 1.0$ was the medium heterogeneous one and $\sigma^2_{\ln K} = 2.0$ was the strong heterogeneous one. Four different pollution dispersion cases were examined, corresponding to $a_T = 0.01m,\ 0.05m,\ 0.10m$ and $0.50m$.

Eight different initial pollution quantities were numerically studied, among 125gr, 250gr, 500gr, 1,000gr, 1,500gr, 2,000gr, 2,500gr, and 3,000gr, providing an initial pollution concentration C_0 of 500mgr/lt, 1,000 mgr/lt, 2,000mgr/lt, 4,000mgr/lt, 6,000mgr/lt, 8,000mgr/lt, 10,000mgr/lt, and 12,000mgr/lt respectively. Detection threshold concentration was set equal to $C_{TH} = 14mgr/lt$ in all cases. Each different initial pollution quantity was simulated in all hydro-geological cases, as previously described.

Simulation results indicated that when the initial concentration of pollution is below 1,000mgr/lt then its detection is very hard, as P_d is below 20% even for a 20-well setting, in every hydro-geological configuration (Figure 5.6:, Figure 5.7, Figure 5.8:). As the initial concentration of pollution is increased, so does detection probability. In the case of a homogenous field, when initial concentration is bigger than 4000mgr/lt, there is little change in P_d achieved by every monitoring configuration when dispersion is less than $a_T = 0.50m$

(Figure 5.6:a,b,c). In the case dispersion is as large as $a_T = 0.50m$, it is observed (Figure 5.6:) that as C is increased so does P_d. For example, when $C = 6,000mgr/lt$, detection probability of a 12-well installation is $P_d = 42.4\%$, while when $C = 12,000mgr/lt$ probability is $P_d = 81.8\%$ respectively, which is almost twice as big as the pollution concentration.

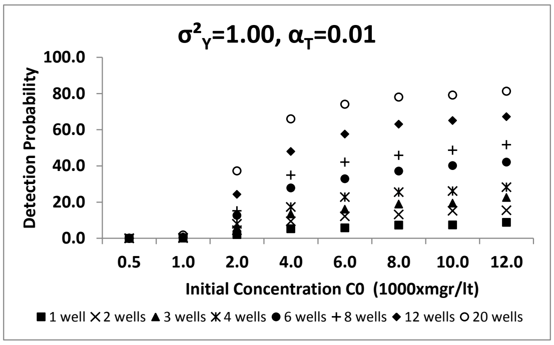


(a) (b)

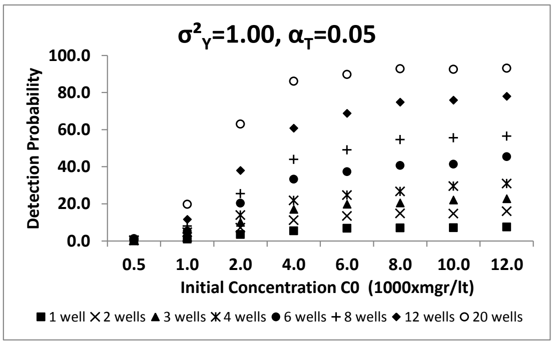
(c) (d)

Figure 5.6: Change of detection probability P_d of different monitoring wells installations, as the initial concentration of a single source instantaneous pollution increases at a homogeneous $\sigma^2_{\ln K} = 0.0$ aquifer

Another interesting observation is the fact that in high dispersion value (Figure 5.6:) P_d differences between different monitoring wells settings tend to decrease as the initial concentration of pollution increases. This effect is observed in all heterogeneity cases when transverse dispersion coefficient is as high as $a_T = 0.50m$ (Figure 5.6:, Figure 5.7d, Figure 5.8:). In all other lower dispersion cases it is observed that, as soon as initial concentration overcomes $C = 4,000mgr/lt$, then P_d changes very little (less than 5%), regardless of the number of wells, which means that further pollution injection into groundwater does not make its detection easier. This is very interesting, as it indicates that actually in low to medium dispersion aquifers monitoring wells efficiency reaches a maximum, which is independent of the initial mass of pollution intruding into groundwater (Figure 5.6: Figure 5.7a,b,c, Figure 5.8:). Only in high dispersion environment increase of pollution reflects to higher detection probability. The turning point for the concentration of initial pollution is $C = 8{,}000 mgr/lt$, which is the value where P_d starts to stabilize. Lower concentrations were harder to detect, dictating that in order for a monitoring setting to be sensitive, at least at simulation level, even in small amounts of pollution a large number of wells must be used.



(a)



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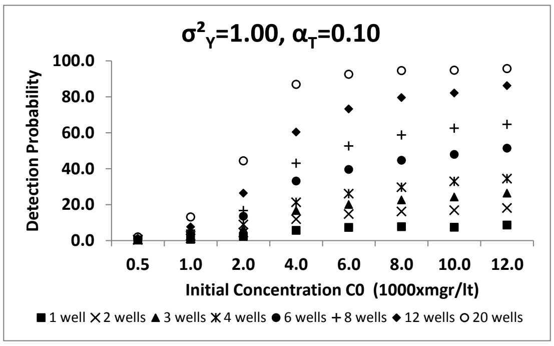
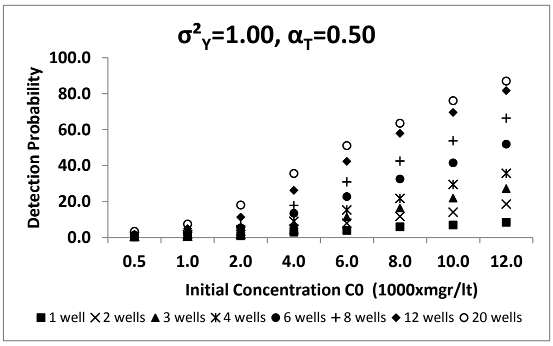


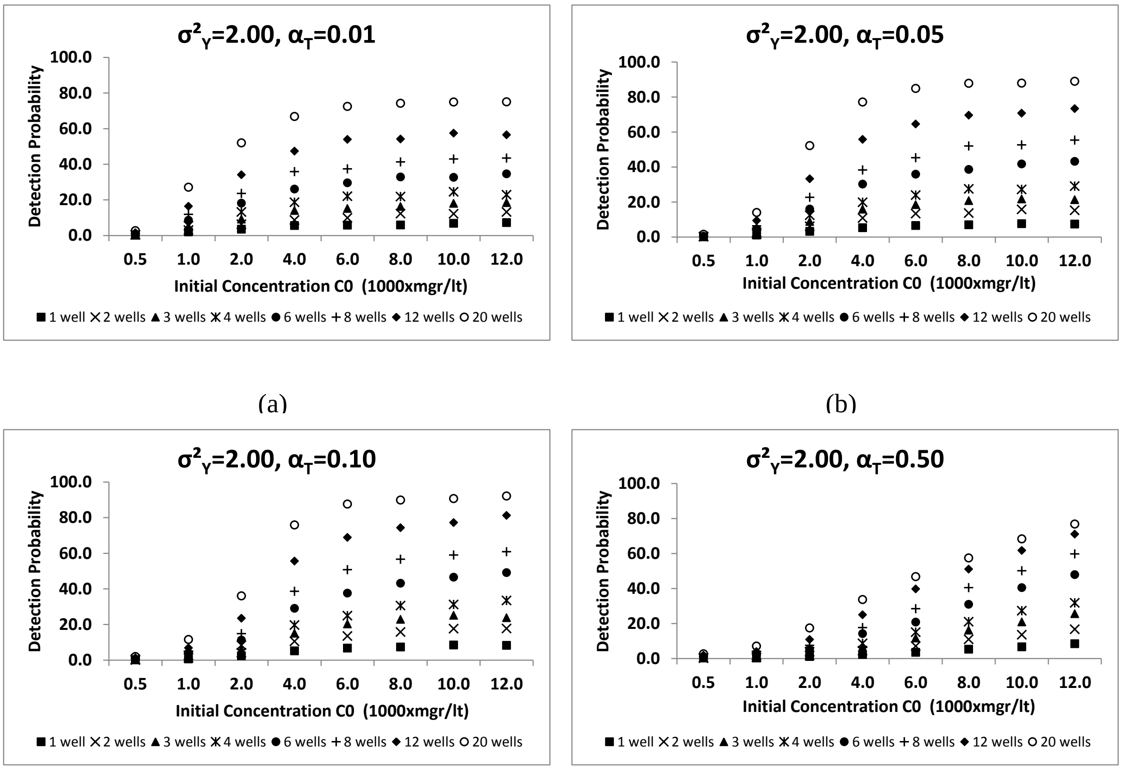
(c)



(d)

Figure 5.7: Change of detection probability P_d for different monitoring wells installations, as the initial concentration of a single source instantaneous pollution increases at a heterogeneous $\sigma^2_{\ln K} = 1.0$ aquifer

Simulations indicated that dispersion is the main hydro-geological parameter that affects plume detection in relation to the initial concentration of pollution. When dispersion increases as high as $a_T = 0.50m$, P_d increases almost linearly to initial concentration, because pollution disperses faster in a larger area and, in conjunction with the fact that a larger pollutant mass reserves greater detectable areal coverage, plume is detected more easily. On the contrary, in lower dispersion fields smaller plumes are produced and, even if a larger pollution mass is injected into groundwater, it leads to polluted regions of greater concentration and not in greater areal coverage, which is the main geometric attribute for a plume to be more easily detected (Yenigul et al., 2006; Papapetridis & Paleologos, 2011a, 2012), resulting in a P_d plateau.



(a) (b)

(c) (d)

Figure 5.8: Change of detection probability P_d for different monitoring wells installations, as the initial concentration of a single source instantaneous pollution increases at a heterogeneous $\sigma^2_{\ln K} = 2.0$ aquifer

5.3 Conclusions

In the present work a Monte Carlo approach of a stochastic model was used, simulating hydro-geological and epistemic uncertainties in groundwater pollution transport and detection by monitoring wells in order to study how the number of point sources, the size of the controlled area (e.g. a landfill facility) and the quantity of an instantaneous injected pollution affect plume detection. In each examined parameter it was considered that the rest of the factors affecting P_d estimation remain constant. Simulations were performed in the context of uncertainty factors deriving from the environment itself, reflected onto hydraulic conductivity K parameter and the lack of information about the initial conditions of a leak.

It was numerically verified in the cases examined in this work that as the size of the control area became larger and the number of wells remained constant, detection probability P_d decreased. In addition, the fewer the monitoring wells, the smaller the detection probability. However, when the control area became smaller, then P_d increased, until it reached the maximum value of 100% detection. Consequently, if the width of a control area was to be increased, so should the number of monitoring wells, maintaining at least the same density as that of the initial case.

In all simulated cases, the general observation is that when two equivalent groundwater pollution sources are present, then their detection is easier as the average P_d increase is among 35% – 55%, except for the cases where detection was already 100% successful due to the presence of a dense monitoring network (20 wells). The same trend in P_d increase relative to a single source case is observed, regardless of the sampling frequency. More frequent aquifer sampling does not alter monitoring efficiency in terms of the presence of more pollution sources.

Simulation results indicated that when the initial pollution concentration was below 1,000 mgr/lt , its detection was very hard, regardless of the aquifer's hydro-geological parameters. The efficiency of low to medium dispersion aquifers monitoring wells reaches a maximum, which is independent of the initial mass of pollution intruding into the aquifer. The turning point of the initial pollution concentration was $C = 8{,}000 mgr/lt$, which was the value where P_d reached a plateau. It has been observed, too, that only in high dispersion environment, where $a_T = 0.50m$, increase of pollution reflects higher detection probability. In every case, lower concentrations were harder to detect, dictating that in order for a monitoring setting to be sensitive, at least at simulation level, even in small amounts of pollution at least 12 wells must be used.

CHAPTER 6

Modeling of aquifer pollution detection probability triggered by precipitation

6.1 Introduction

Groundwater pollution is mainly caused by the presence of chemical compounds in concentrations for which, according to National and International regulations, water is considered harmful and unusable not only for human and animal consumption but even for irrigating purposes. Most of these substances, produced during various human activities, should be treated and disposed appropriately as soon as they are considered wastes by the end user, so as not to pose a threat on the environment and to public health.

There are some occasions, though, where these chemicals intrude into the aquifer accidentally, by reckless handling or even due to the lack of any administration provision. Cracks on underground petroleum tanks, chemical transportation accidents and uncontrolled waste disposal are some possible pollution sources. The current legislation system states that the polluter, whether proven to have polluted on purpose or by accident, pays not only for the damage caused to other properties but for the restoration of the environmental damage too. However, in the case of water pollution there is an accountable loss on its value, as *Paleologos* (2008) showed, through water's quality degradation after restoration, because Water Regulations state that initially potable water must be restored to that condition where it can be used at least for irrigation.

Aquifer pollution can be the result of an undiscovered condition, where infrastructure damage or failure may lead to uncontrolled liquid wastes disposal, first into the vadose zone and finally into the groundwater flow. Landfills may be an example of the situation described, as leachate concentrate at the lower level of the installation are pumped out using perforated tubing systems. There are cases, however, where leachate penetrate protective liner and clay barriers, usually through small cracks and holes (Laine et al., 1997; Collucci et al., 1999; Tatsi & Zouboulis, 2002; El-Zein, 2008), causing groundwater pollution. It is speculated that in the United States alone a 40% of active sanitary landfills suffer from leachate leakage problems (Paleologos, 2008). This is the main reason for installing downstream aquifer pollution monitoring wells, so that a case of leachate leak into groundwater can be detected and appropriate countermeasures can be taken.

Groundwater quality monitoring wells are also used at industrial sites (Bierkens, 2006), as it is possible for certain quantities of dangerous chemical compounds to escape and contaminate the aquifer due to waste handling or storage failure. The main objective is to detect pollution originating from the facility, at some distance from it, so that it can be cleaned up or controlled before contaminated groundwater reaches areas outside the site. In this case a bigger number of wells can be utilized, according to the magnitude of the facility and the danger that its waste may pose to public health.

Moreover, illegally dumped municipal or industrial wastes are another uncontrolled source of groundwater pollution. Waste may initially contain various dangerous chemical compounds, which may pose serious threats to local communities and ecosystems if they escape into the environment and especially into groundwater. Long term air exposure of organic matter contained into waste, as well as biological decay processes may cause toxic substances production (Fatta et al., 1999). These dangerous substances dissolve into, mix with or chemically react with precipitation water during raining periods, producing solutes which flow and finally infiltrate groundwater, where pollution is uncontrollably transported by the flow.

Waste dumps can be considered as point pollution sources triggered each time by precipitation to deliver pollutants into the aquifer. Although it is natural to assume that the chemical footprint of pollutants will not possibly be the same as time passes (Kulikowska & Klimiuk, 2008; Renou et al., 2008), that organic matter decomposes or other chemical processes take place, that concentrations will not remain constant as rainfall varies and that the quantity of the pollutant is not the same, precipitation is a mean that may cause or amplify the effects of a point pollution source. Pollutants mass transfer takes place by dissolving them into precipitation water, thus increasing their mobility, leading in protective barrier overflow or rapid infiltration into groundwater. Leachate flow rate from sanitary landfill sites varies both from site to site and seasonally at each site. In relatively warm climates the increase in leachate production after precipitation is quite rapid (Shinozuka & Jan, 1972). At least in one case it has been documented that, during a raining incident, groundwater's pollutant concentrations (COD, Cl, NH_{40}) originating from a small liner crack in the landfill increased temporarily and repeatedly according to the local precipitation event (Collucci et al., 1999) (Figure 6.1). As a first approximation, the quantity of leachate produced may be regarded as proportional to the volume of water percolating through waste (Shinozuka & Jan, 1972).

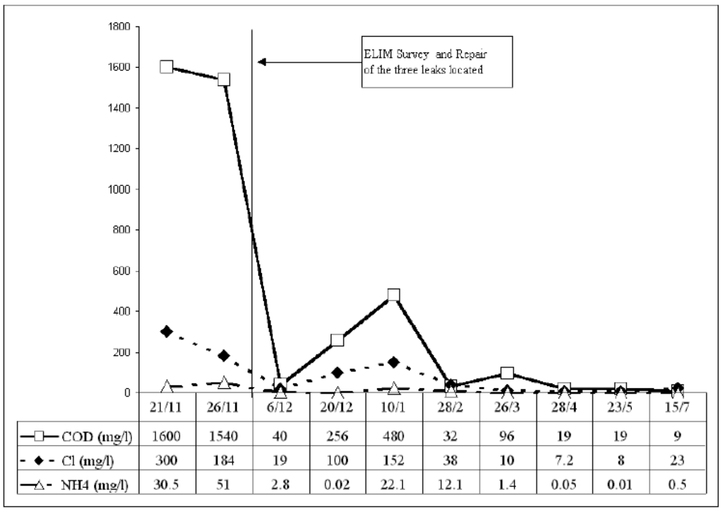


Figure 6.1: Plot of Groundwater Monitoring Data Indicating High COD and Cl Levels after a landfill leak case repair has taken place (vertical line), where the spikes are due to rain episodes on the area (Collucci et al., 1999).

In the real world however, there are many different ways for a pollution to happen. It may be spotted in a very small region or it may cover a large area. It may take place in a short period of time, as it usually happens during an accident, or it may be continuous if there is a permanent undiscovered leak, for example in a hydrocarbon pipeline transfer system. Moreover, it may be triggered by some other random event, such as rapture in a high pressure fuel transfer pipeline system or a precipitation event which augments solute infiltration into an aquifer. This means that not only does the event of pollution affect the way groundwater is contaminated, but also spatial and time characteristics contribute to the evolution and consequences of this event.

Considering a different way of a groundwater pollution incident in the context of triggering it according to local precipitation events, in the present study we have assumed that there is a point pollution source inside a controlled area of specific dimensions which injects a quantity of pollutant inside the aquifer, each time rain occurs. It can be assumed that this is a municipal waste sanitary landfill cell where a local liner failure has occurred or an area where uncontrolled industrial waste dumping has taken place and a local leak has commenced, causing pollutant exposure, flow and concentration at the lowest point of the area. Furthermore, it has now been recognized that the dominant mechanism of contaminant migration may be diffusion through the protective liner and not advection (Tompson et al., 1989; Allen, 2001; El-Zein, 2008). The pollutant has been assumed to dissolve into rainwater percolating through wastes, concentrating at the bottom of the facility, where the developed hydraulic head causes pollutant intrusion into groundwater. The quantity of the pollutant that infiltrates is considered linearly analogous to the recorded daily average precipitation height, for a specific location. While there are computational models to simulate or to forecast precipitation intensity as well as time events (Moustris et al., 2011), a 30-year time series rain data from Macedonia Airport in Thessaloniki was used in order to save computational time. The area, which in our study was simulated in two dimensions (2-D), is downstream controlled by a linearly arranged monitoring network, consisting of a different number of drilling wells arrangements in each study case. The ability of the monitoring installation is evaluated through the probability of successful pollution detection, and its performance is evaluated in different hydro-geological environments.

The pulsing ejection of different quantities of pollution into groundwater during every time step, represents a different concept of time dependence between the time of ejection and the quantity that is ejected, as it is different from the instantaneous or the continuous cases with a steady inflow rate. While in the case of instantaneous ejection of pollution a certain number of particles enters the aquifer at the beginning of the simulation (Yenigül et al., 2005; Papapetridis & Paleologos, 2011a) or in the case of continuous pollution a certain number of particles is ejected during each time step (Yenigul et al., 2006), in the case of pulsing pollution a relation between a natural phenomenon that augments pollution transportation and pollution quantity is established.

6.2 Model Description

Heterogeneous aquifer structural properties, such as size, position and amount of clay lenses, sand and gravel layers, as well as the resulting distribution of hydraulic conductivity, porosity and hydro-geochemical parameters significantly control groundwater flow and spread of solutes (Dagan, 1989; Ptak et al., 2004). In order to study the effects of pollution transport and dispersion into a heterogeneous subsurface environment in relation to its detection probability P_d by a monitoring wells network, the Monte Carlo numerical framework was used. Uncertainty due to contaminant subsurface heterogeneity is reflected by the spatial variability of hydraulic conductivity. Hence, hydraulic conductivity is treated as a random space function. The natural logarithm of the isotropic hydraulic conductivity [$Y = \ln(K)$] is modeled as a stationary Gaussian field with a geometric mean value of 2.30m/day. Variance ranged among 0.0 (homogeneous aquifer), 1.0 (medium heterogeneous aquifer) and

2.0 (strongly heterogeneous aquifer) and the isotropic covariance of *Y* is chosen to be of exponential form with correlation length $\lambda = 20m$.

In each different hydro-geological case that was examined, the Monte Carlo scheme consisted of 2,000 simulations. Heterogeneous aquifers in the model were simulated using the 2-D Spectral Turning Bands method (STUBA) (Mantoglou & Wilson, 1982; Ababou et al., 1989; Tompson & Gelhar, 1990a; McLaughlin et al., 1993; Emery, 2008; Paleologos & Sarris, 2011). The aquifer is assumed to be confined, with a given hydraulic head at its left and right boundaries, resulting in a macroscopically constant hydraulic gradient of 0.001m. Source location uncertainty was envisaged considering equally probable different points of pollution origin during each different simulation which belongs inside the control area.

Contaminant advection and dispersion were simulated using the Random Walk Tracking Particle approach, as described by *Tompson et al.* (1987b) and comprehensively reviewed by *Salomon et al.* (2006b). This choice is based on the algorithm's ease of implementation, its mass conservative nature and its computational effort economy, since it is independent of the control area we want to simulate. In each of the 2,000 Monte Carlo heterogeneous field realizations, pollution was simulated by a certain number of equal mass particles, which were ejected into the aquifer. In our study we considered that the number of particles entering the streamline flow of groundwater was related linearly with the total daily precipitation height at the simulation region. Precipitation events triggered pollution infiltration, resulting in a pulsing ejection, each time with different quantities, of pollution. In fact, precipitation increased pollution mobility, either by dissolving pollutants into the water or by simply mixing them with it and, in some cases, where chemical processes occurred, caused the increase of the pollutant quantity. Either way, this ended up with larger quantities of pollution that were transported along with rainwater through the vadose zone into the aquifer.

In this study we assumed that pollution enters directly into groundwater flow, neglecting transportation effects into the unsaturated zone. Even if the thickness of the vadose zone significantly affects the leakage of an installation's protective barrier, resulting in a substantial overestimation up to a factor of about 3.5 (Çelik et al., 2009), this holds true if the aquifer is very near at the source of pollution or if a fingering effect favors a specific direct path of pollution propagation into groundwater flow (Selker et al., 1996). In addition, the coupling of precipitation and pollution events focuses only on the pollution quantity infiltrated into the flow, considering mainly a mass diffusion transfer mechanism (Tsanis, 2006), and not on the recharge of the aquifer with polluted water due to precipitation. As a result, a steady state flow of groundwater without a free surface recharge is assumed. Even if aquifer recharge is not taken in mind, meaning that flow equation still satisfies Laplace equation (Harr, 1962; Bear & Buchlin, 1987), this computational simplification isolates and excels the effects on pollution dispersion and detection of a pulsing pollution source, which is related with an actual phenomenon.

It was considered that if during a simulation time step, equal to $dt = 1$ day, a precipitation event took place, then a certain quantity of pollution, proportional to the total rain height, would have infiltrated the aquifer and diffused into the flow, without disturbing groundwater flow. A proportionality factor between the total daily precipitation height and pollution mass infiltration was set in, so as to provide a detectable concentration of pollution at the point (cell) and time of ejection. Considering that the lowest recorded precipitation height data was 1mm, it was assumed that this quantity would provide detectable pollution. Threshold detection limit was set at $C_{Th} = 14$mgr/lt, which indicates the presence of chemicals into groundwater in such a degree that remediation actions should take place. This level of pollution is typical for chemicals such as nitrate, cyclohexanon and diethyneglycol (Yenigül et al., 2005). The threshold detection limit of pollution concentration in a 2×2 m cell (the depth is considered to be equal to 1m for unit consistency) is produced by 28 particles, which provide enough resolution to describe the plume's transportation and detection by monitoring wells (Yenigül et al., 2005; Papapetridis & Paleologos, 2010). Given that concentration in a cell equals $C = M/(nV)$, where n=0.25 is the effective porosity constant during all simulations, the pollution mass representing the detectable limit equals 14,000mgr or 500mgr per particle.

A thirty-year time series of daily average precipitation data from Macedonia airport in Thessaloniki was used. A total precipitation height for this period of time was recorded equal to 13,291.06mm. Considering that a 1mm precipitation height ejected pollution into the aquifer is represented by 28 particles, the total number of particles utilized to simulate the pollutant's advection and dispersion into the subsurface environment, at the end of the 30-year simulation, was 372,150. During each simulation time step, total precipitation height for that day was taken into account and linearly transformed into a number of pollutant particles. Then, this number of particles was added, through the same point source, to the total number of particles that were already transported into the aquifer. As a result of this kind of pollution inflow, a continuous plume of pollution was formed. If its concentration was larger than the threshold limit at the time of sampling at the grid cells where monitoring wells were located, then a successful detection was recorded. In every simulated case studied, detection time was recorded and the total contaminated area was calculated. In order for a 2×2 m cell to be considered polluted, concentration must be at least equal to C_{Th}, meaning that at least 28 particles must exist inside the grid's cell at the moment of sampling. At the end of the 2,000 simulations the average time of detection and the average contaminated area are calculated if daily (ED) sampling is assumed. Moreover, the average contaminated area is also calculated assuming different sampling frequencies, namely monthly (1 M), bimonthly (2 M), quarterly (3 M), every 4 months, biannual (6 M) and annual (A). The polluted area was additionally calculated 3 months, 6 months, 1 year, 2 years and 3 years after successful detection in order to evaluate the remedial action delay time (RADTi) as this was introduced by *Papapetridis and Paleologos* (2011a).

A computational model developed by *Papapetridis and Paleologos* (2011b) was used in order to perform the Monte Carlo simulations. The model was initially developed in order to simulate an instantaneous case of heterogeneous aquifer pollution. The practical meaning of instantaneous pollution is that the event itself takes place in a very short period of time in relation to the 1-day time step which the simulation uses. Consequently, a pressurized tank or a pipe system that is suddenly relieved due to some localized structural failure, an industrial accident or a landfill leak may potentially produce such kind of pollution. In order for the model to facilitate multiple pollution injections into the aquifer originating from the same point, during the 30-year monitoring period, certain modifications were made. Even if in the scenario of pulsing pollution the computational time needed was significantly increased, a contemporary workstation was able to provide results in a reasonable time span.

Five different cases of transverse dispersion coefficients, α_{T}, were investigated. These values varied among $\alpha_{\mathrm{T}} = 0.001$, 0.01, 0.05, 0.10, and 0.50m, corresponding to values observed in field experiments (Gelhar, 1986) which describe soils of low, medium and high dispersion. In each simulation, dispersion was considered to remain constant and the longitudinal dispersion coefficient, α_L, was calculated by the relation $a_L = 0.10a_T$ (Spitz & Moreno, 1996).

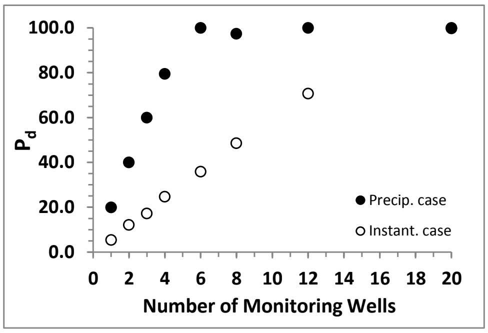
The simulated region was 1,000 m long, 400 m wide and, assuming a discretization of the area in cells of $dx \cdot dy = 2 \times 2\,\mathrm{m}^2$, a 500×200 grid was created. A rectangular area simulating a contaminant potential source area (CPSA), for example a section of a landfill, or the area of a waste storage facility, was situated between $x-$coordinates 10m and 60m, and $y-$coordinates of 140m and 260m. At a random point within these boundaries a contamination event was initiated, which polluted the aquifer every time a precipitation event occurred.

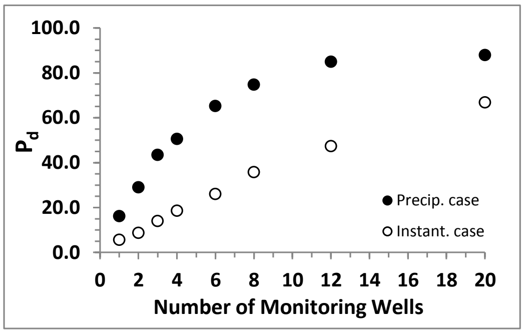
The contaminant mass was assumed conservative and fully water soluble. The uncertainty, regarding the potential location within a cell of a landfill where a leak might have developed, stems from the lack of information on potential failure locations at a landfill's bottom liner. In case pollution from a different facility is assumed, such as from an industrial plant or a military facility, uncertainty about the contamination's point source may stem from our inability to detect leaks from waste carrying pipelines, underground storage areas of liquid waste, or even accidental spills during operations. In either case, it was assumed that any point within the rectangular CPSA there was an equally probable source of leakage, taking place once as a single failure event at zero time (when the simulation began) and resulting in an instantaneous ejection of contaminants into the aquifer. Monitoring wells were assumed to fully penetrate the aquifer, resulting in vertically-averaged concentration measurements. Eight linear configurations were examined, consisting of 1, 2, 3, 4, 6, 8, 12 and 20 wells, equally spaced from one another. Wells that were located at the ends of each arrangement were placed half the distance from the cell's top and bottom edges so that the efficiency of the monitoring system would be maximized (*Yenigül et al.,* 2005). Monitoring of the aquifer and plume evolution was simulated for a 30-year period.

6.3 Simulation Results

6.3.1 Number of Wells

Considering the number of wells of the monitoring and detection arrangement of the installation, simulation results showed that even one of the smallest monitoring networks, that of 4 wells, in case of a homogeneous medium dispersive field, is capable of providing a 100% successful detection of pollution (Figure 6.2a). Even in a highly heterogeneity field where $\sigma^2_{\log K} = 2.0$ with as low dispersion as $a_T = 0.01m$, 4 wells will detect groundwater pollution half the time (Figure 6.2b). Comparing simulation results in relation to detection probability P_d between instantaneous pollution of the aquifer with a small quantity of pollution (1 kgr of a conservative pollutant, providing a 4,000mgr/lt initial concentration) and precipitation initiative pollution, for the latter it is clearly seen that P_d rapidly increases as the number of monitoring wells is increased, reaching a maximum of 100% detection when more than 3 wells are utilized, while for the former P_d presents an almost linear increment, succeeding maximum detection only with a dense monitoring arrangement. In case of a strongly heterogeneous field, P_d is always significantly less than the precipitation initiative case. In the precipitation initiative pollution case even a 3-well installation, which according to EU legislation is the minimum requirement for groundwater monitoring of an operational landfill, can detect aquifer pollution in more than 50%, depending on the field's hydrogeological properties.





(a) (b)

Figure 6.2: P_d change as the number of monitoring wells increases from 1 – 20, as well as comparison between an instantaneous case of pollution and a precipitation coupled case for a medium dispersion homogeneous field (a: $\sigma^2(\log K)=0.0$, $\alpha_T=0.10m$) and a low dispersion heterogeneous field, (b: $\sigma^2(\log K)=2.0$, $\alpha_T=0.010m$).

6.3.2 Field Heterogeneity

Subsurface heterogeneity, which in this study is reflected by the spatial variability of the hydraulic conductivity, has been examined for three different cases. When a small number of wells is used, as shown in Figure 6.3 where 3 wells are considered, at very low dispersion fields, P_d decreases by 23% when heterogeneity increases from 0.0 to 2.0. At low dispersion environment a 27% decrease is observed between homogeneous and strongly heterogeneous cases. At higher dispersion value, P_d remains practically constant as heterogeneity increases.

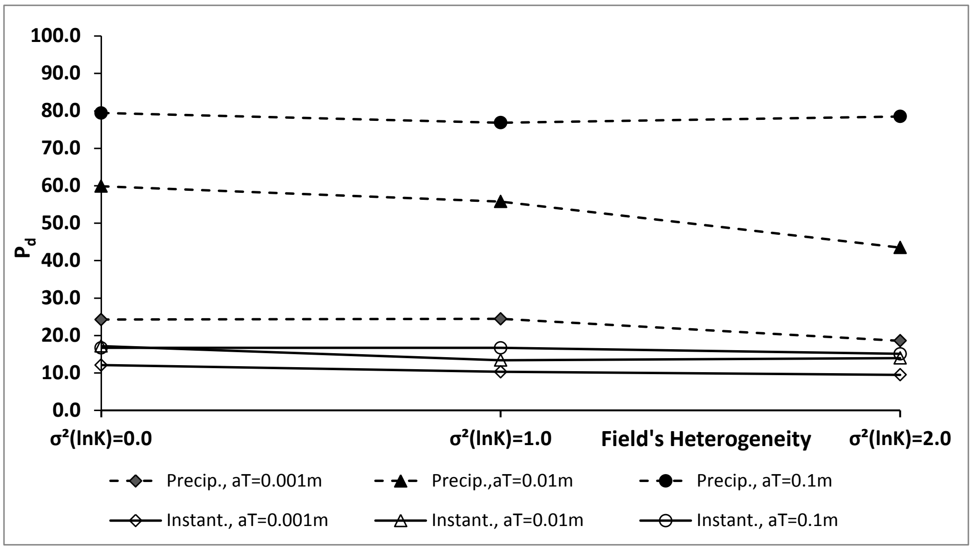


Figure 6.3: Groundwater pollution detection probability P_d of a 3-well arrangement in relation to the field's heterogeneity as this is reflected through variance of the natural logarithm of hydraulic conductivity $\left(\sigma^2_{\ln K}\right)$. Dashed lines are the precipitation triggered pollution (Precip.) and solid lines are for instantaneous cases (Instant.).

Examining an arrangement consisting of 12 wells (Figure 6.4), it is seen more patently that, as dispersion is increased, the effect of heterogeneity increase on P_d is languished. More specifically, at a very low dispersion field, where the transverse dispersion coefficient equals $a_T = 0.001m$, there is a significant 33.5% dropdown at the P_d between the homogeneous and the strong heterogeneous cases, while at $a_T = 0.01m$ the dropdown is 15%. At greater dispersion values, it is observed at the simulation results that there is no difference in detection probability, as it is 100% for every heterogeneous case that has been studied.

If an instantaneous pollution case is considered (Figure 6.4), then it is noted that P_d is decreased as heterogeneity is increased. At transverse dispersion coefficient $a_T = 0.001m$ a 29% decrease is observed, while at $a_T = 0.01m$ and at $a_T = 0.1m$ the decrease is 31% and 19% decrease respectively. Similarly, as the dispersion is increased, the effect of field heterogeneity on detection is lessened. This pattern holds true in both simulation scenarios, either instantaneous or precipitation caused pollution is computationally examined.

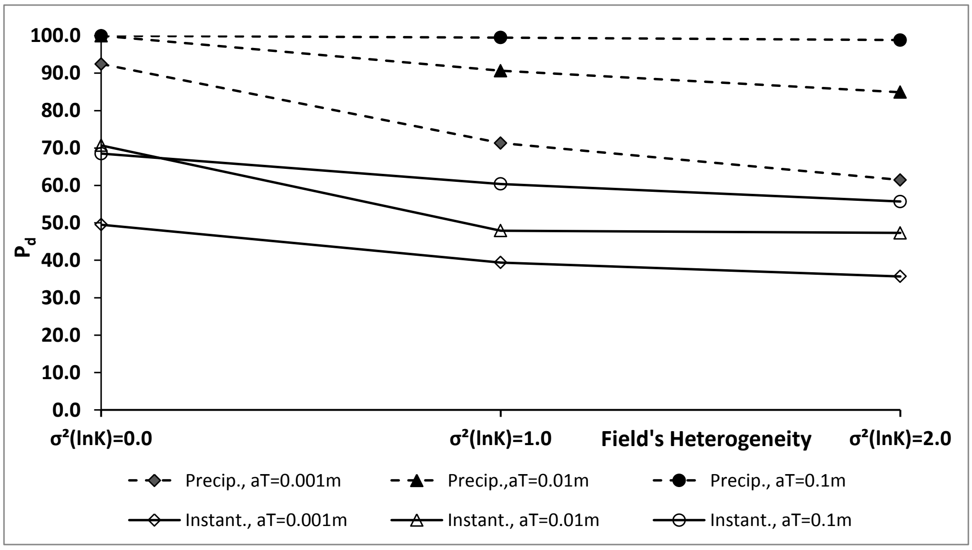


Figure 6.4: Groundwater pollution detection probability P_d of a 12-well arrangement in relation to the field's heterogeneity as this is reflected through variance of the natural logarithm of hydraulic conductivity $\left(\sigma^2_{\ln K}\right)$. Dashed lines are the precipitation triggered pollution (Precip.) and solid lines are for instantaneous cases (Instant.).

Hydraulic conductivity variation highly affects pollution plume propagation into the aquifer, as several tracer field experiments have shown (Freyberg, 1986; LeBlanc et al., 1991; Boggs et al., 1992). A solute plume in a given realization can be pictured as diffusing slowly, owing to local scale dispersion, and winding like a meandering stream because of large-scale regional heterogeneity (Dagan, 1984) (Figure 6.5). This solute behavior sometimes tends to separate a plume's formation into more than one branches, resulting in regions of smaller pollutant concentration and flow paths that bypass the monitoring arrangements. While in the case of instantaneous pollution fast deformation of pollution plume due to hydraulic conductivity variations may lead to areas of lower concentration than that of the detection threshold limit, which will result into a no detection situation, in the case of precipitation initiated pollution, because the pollutant keeps being added into the flow, it is more logical to assume that detectable preferential flow paths are formed through highly hydraulic conductivity paths, allowing for a significant portion of plume to escape detection (Figure 6.5).

However, as dispersion is increased, pollution dilutes faster and in a greater area (Figure 6.5). Considering the fact that a variable amount of pollutant mass is added throughout time, greater areal coverage is possible where concentration is above a detectable limit. This means that dilution of the plume below the detection limit, due to deformation along the propagation path, is not observed. The effect of plume deformation along with higher dispersion alleviates the influence of heterogeneity on P_d. The fact that the average P_d decrease is 16% in case of 12 wells, when at the same configuration for the instantaneous case the average decrease is 26%, indicates that preferential flow is possibly the main mechanism responsible for P_d decrease as the field gets more heterogeneous and dilution of the plume is hindered by pollutant injection

6.3.3 Dispersion

For a given structure of the simulated geological field, subsurface heterogeneity and dispersion are the main factors that directly determine the form that the developed contaminant plume will have. In the case of an instantaneous pollution event the longitudinal dispersion causes the elongation of pollution in the direction of movement of groundwater flow and is proportional to the total underground travel time of the pollutant and its speed in the subsoil. On the other hand, the transverse dispersion causes the widening of the plume and also depends on the total time running and the flow rate. This means that the farther a plume travels, the more it spreads and dilutes into the ground, rendering it non-detectable (Papapetridis & Paleologos, 2010). This behavior is reflected by the fact that as dispersion is increased (in this study all comparisons refer to different transverse dispersion coefficients) among $a_T = 0.05 - 0.10m$, as demonstrated in Figure 6.6, depending on heterogeneity and assuming all other parameters remain the same, detection probability of groundwater pollution P_d initially increases to a maximum, because of the plume dispersion leading to a larger area coverage where pollutant concentration is bigger than the threshold limit, resulting in more detectable cases. However, as dispersion continues to increase, it is observed that P_d

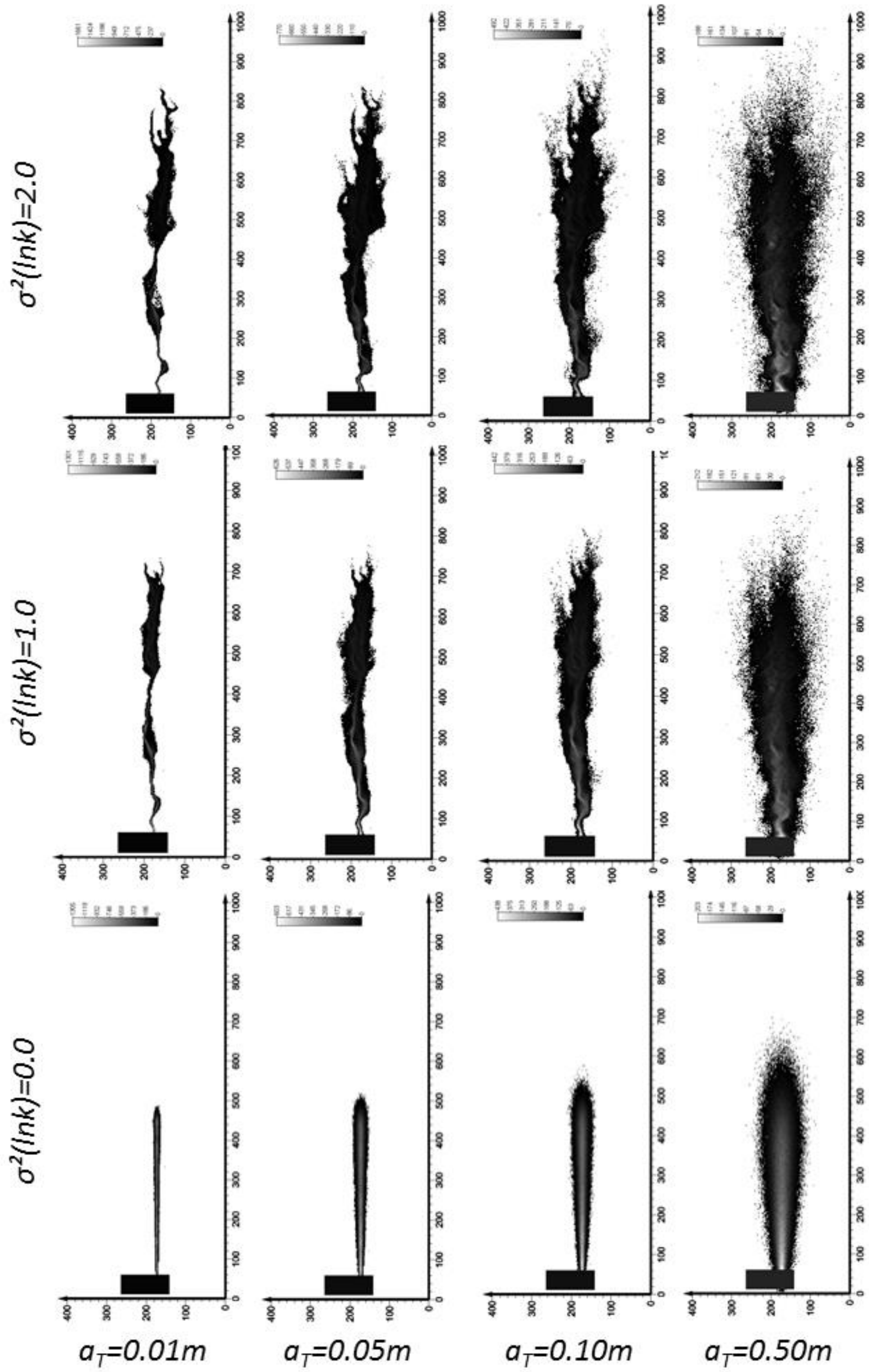


Figure 6.5 : Pollution dispersion and deformation as it is transported during a 30-year time span into aquifers, where on the vertical axis heterogeneity increases and on the horizontal axis transverse dispersion coefficient increases.

decreases again, reaching as low as 40% of the maximum value achieved (Figure 6.6). This happens because pollution dissolves so fast into groundwater that the concentration drops rapidly below the detectable limit, causing the plume's detection escape. This behavior is the same for every well configuration.

On the other hand, examining the results of precipitation related pollution, we notice that detection probability P_d tends to increase as the field's dispersion is increased. In case of a 3-well installation (Figure 6.6) the average difference between $a_T = 0.001m$ and $a_T = 0.50m$ is 78%, in all three cases of heterogeneity studied. It is noteworthy that even this configuration, which constitutes the least demand of monitoring for a sanitary landfill, may succeed detection in every case when dispersion is equal to or higher than $a_T = 0.50m$, while in the case of medium heterogeneity a successful detection of over 50% can be achieved in as low a dispersion as $a_T = 0.01m$. Of course, these results refer to the specific computational model and all of its initial assumptions made during the Monte Carlo simulations. Nevertheless, a behavior of the monitoring system is indicated, even if different assumptions may lead to different numbers.

It can also be seen that there is a small difference in P_d as field heterogeneity is increased. In homogeneous and low heterogeneity cases P_d at $a_T = 0.001m$ is 24%, while in the case of $\sigma^2_{\ln K} = 2.0$ the $P_d = 18.6\%$. P_d increases almost linearly and when dispersion gets larger than $a_T = 0.10m$ heterogeneity does not seem to affect the effectiveness of the monitoring network.

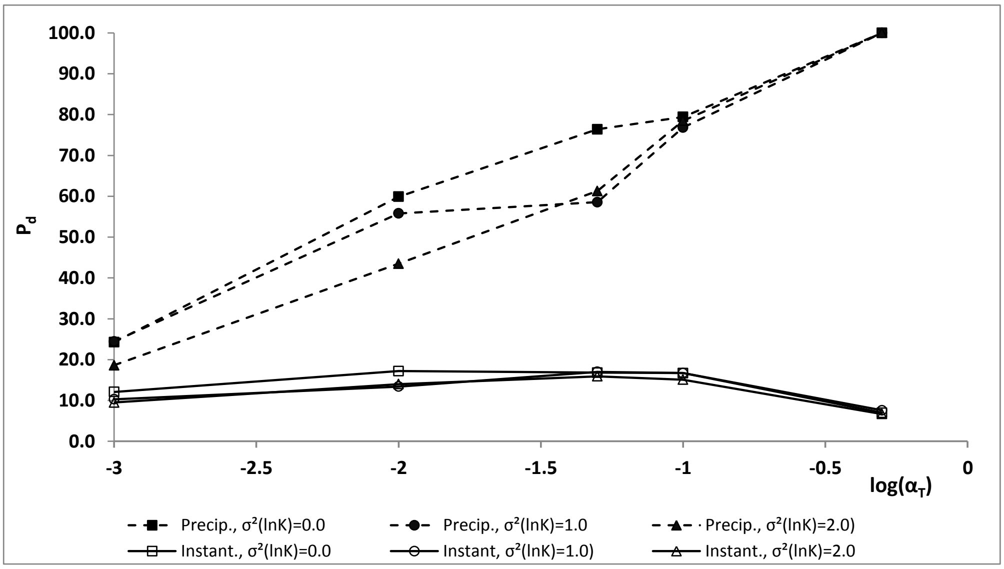


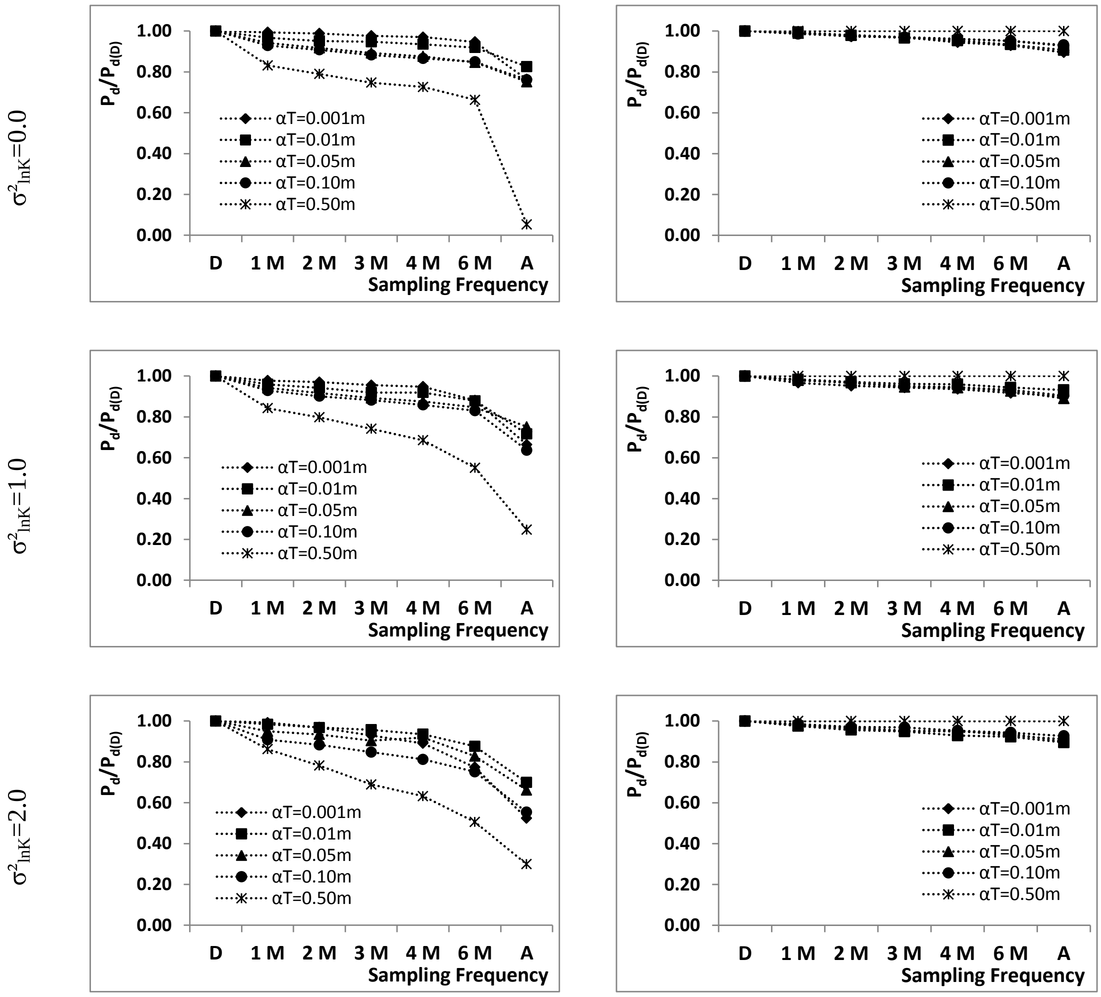
Figure 6.6: P_d change of a 3-well arrangement, in relation with transverse dispersion coefficient α_T increase, in three different heterogeneity cases, as well as comparison between precipitation related pollution cases (dashed lines) and instantaneous pollution cases (solid lines)

This behavior is mainly the result of the way heterogeneity and dispersion of the field affect the geometry of the plume and the areal coverage as plume is transported in groundwater. As it was explained in the previous paragraph, the plume's deformation due to heterogeneity causes a P_d decrease as $\sigma^2_{\ln K}$ is increased. This happens until a specific point of dispersion, as further dispersion increase results in no heterogeneity effect on the detection outcome (Figure 6.5). Contrary to instantaneous pollution, the fact that pollutant mass is constantly added to the aquifer, driven by precipitation through a mass diffusion mechanism, provides enough pollutant to larger portions of the plume's area, resulting in possible detection. This means that when pollution is added, thus preventing the plume's dissolution into the aquifer below a detectable limit, dispersion is the main factor that affects its detectability.

6.3.4 Sampling Frequency

Sampling frequency is an important factor that may significantly affect the effectiveness of a monitoring installation. For example, according to European Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste it is stated that "The frequency of (groundwater) sampling could be adapted on the basis of the morphology of the landfill waste. This has to be specified in the permit." In addition, a landfill operator is obliged to report all monitoring results to the competent authorities once a year. This obligation poses a maximum boundary on sampling frequency. Moreover, it is also stated that "the frequency must be based on possibility for remedial actions between two samplings if a trigger is reached". This dictates a minimum sampling strategy on groundwater sampling frequency, assuming that there is adequate knowledge of the hydro-geological environment, of the chemical footprint for all possible pollutants and, of course, of the fact that remedial actions should commence the moment the trigger event has occurred, which could be the detection of groundwater pollution by a monitoring well. In most of the cases, groundwater sampling frequency is determined by partial knowledge of the velocity of groundwater flow and the cost of the applied sampling policy.

Detection probability dependence on sampling frequency was investigated by *Papapetridis and Paleologos* (2011a, 2011b) in the case of an instantaneous pollution originating from a landfil. In that study it was assumed that the starting point of a leak comes from a single point in the control area and that all of the leachate's quantity enters instantly into the aquifer's field of flow. This type of failure is very difficult to detect, since the trace of the source is very small, as opposed to massive, multiple or continues leaks, where the trace is often large enough to be directly detected (Papapetridis & Paleologos, 2010). Seven different sampling frequencies were applied, which assumed sampling from every monitoring well of the installation at the same time daily (D), monthly (1 M), bimonthly (2 M), quarterly (3 M), every four months (4 M), biannually (6 M) and annually (A).



instantaneous pollution | precipitation related pollution

Figure 6.7: Percentage change of P_d as sampling frequency changes for a 4-well monitoring installation among daily (D), monthly (1 M), bimonthly (2 M), quarterly (3 M), every 4 months (4 M), biannual (6 M) and annual (A) sampling. The first column of the graphs reflects the results of an instantaneous case of pollution and the second column reflects a precipitation event related pollution, while horizontally heterogeneity changes, as is reflected through the variance of the *lnK*.

Simulation results by *Papapetridis and Paleologos* (2011b) showed that in case of instantaneous release, the effect of sampling frequency on detection probability is more pronounced when dispersion of pollution into the aquifer is increased. In the case of a 4-well installation (first column in Figure 6.7) it can be observed that when a homogeneous field is considered the decrease of detection probability P_d is almost 100%, which means that the monitoring installation is actually cancelled, as it is entirely ineffective. As heterogeneity is increased, from $\sigma^2_{\ln K} = 0.0$ to $\sigma^2_{\ln K} = 2.0$, the average improvement of P_d regarding a 4-well network, between biannual (6 M) and daily (D) sampling, excluding the case of high dispersion $\left(a_T = 0.50m\right)$, is 17% while the same gain of P_d between annual (A) and sampling daily (D) is 46%. If we consider the improvement between biannual (6 M) or annual (A) and monthly (1 M) sampling, then the P_d gain is 12% and 40% respectively.

It can be seen by simulation results that there is a significant difference when sampling once a year and once every 6 months. This difference becomes even bigger if a high dispersion geological environment is considered. As a general rule, it appears that under all conditions at least biannual sampling should occur at a monitoring system (Papapetridis & Paleologos, 2011b), which complies with EU Directive in case of a waste sanitary landfill. If one wants higher detection probability, then monthly sampling appears to be the optimum choice for most well arrangements, considering both the effort involved if one were to proceed with a much more intense sampling and the improvements on detection attained at this level. It is noteworthy that in heterogeneous aquifers a large number of monitoring wells (a setting larger than 8 wells) does not perform much better in terms of detection if sampled infrequently (for example, once a year) than arrangements having a lower number of wells but are sampled more regularly.

Detection probability P_d in relation to sampling frequency in case of a pulsing pollution triggered by a precipitation event presents a totally different behavior, as it is depicted in the second column of Figure 6.7, where P_d changes in relation to applicable sampling frequency. The striking observation is that pollution dispersion amplifies the effectiveness of the monitoring wells arrangement. Even in the case of 4 wells it can be seen that despite the field's heterogeneity a 100% detection is achieved at every sampling frequency applied, when transverse dispersion is as high as $a_T = 0.50m$. Even in lower dispersion fields it can be seen that there is practically no gain in detection if groundwater is sampled more frequently than once every three months, as the average gain in P_d is less than 3%. When sampling is performed biannually then the average improvement in relation to monthly sampling, regardless of the geological heterogeneity, is 5% and if we consider annual sampling then the improvement to monthly sampling is 8%. It can also be noted that as dispersion increases the importance of sampling frequency is diminished, which is the opposite in the case of an instantaneous ejection of pollution into the aquifer.

The fact that pollution infiltrates the aquifer due to precipitation triggered events and that groundwater is recharged with pollutant mass result in retaining a plume's pollutant concentration above a detectable limit in a larger area. In heterogeneous fields, as field experiments have shown (Boggs et al., 1992), pollution is transported in paths where hydraulic conductivity is higher in relation to the adjacent areas. As dispersion causes greater areal coverage by the plume, which in addition maintains detectable concentration values, detection is easier even if sampling is scarcer, as the paths of the plume remain basically the same, depending on hydraulic conductivity values.

It can be stated that in order for the operator of a controlled facility to succeed sufficient levels of possible groundwater pollution detection, they must focus on the problems that may come up from an instantaneous ejection rather than from a precipitation related one. It could safely be assumed that in the case of a continuous leak of pollutant into the aquifer the same results concerning sampling frequency policy would apply.

6.3.5 Time of detection and contaminated area

The average time needed until pollution is actually discovered from the monitoring was studied and compared to cases of instantaneous pollution. Assuming that $< T_{obs} >$ is the average number of days over 2,000 Monte Carlo simulations, in order for observation of contamination to be achieved at the monitoring points, based on a specific sampling schedule, and $\langle T_{ar} \rangle$ being the average time for the pollution to arrive at the detection network , then in Figure 6.8 the ratio of $< T_{obs} >/< T_{ar} >$ is plotted on the $y-$axis in relation to sampling frequency. Six different diagrams depict how time ratio changes for each three studied heterogeneities $\sigma^2_{\ln K}$ and two cases of transverse dispersion a_T, where the solid line describes the precipitation coupled pollution (PCP) events and the dashed line the instantaneous one (IP). A daily sampling with a 1-day numerical time step gives a ratio equal to one for all hydro-geological cases.

Diagrams depict, once more, that dispersion is the main contributing factor which influences the average detection time of groundwater pollution. The same behavior is observed in both cases of pollution origination, precipitation event started or instantaneous. In the case of a low dispersion environment, where $a_T = 0.01m$ or less (Figure 6.8, first column), $< T_{obs} >/< T_{ar} >$ ratio does not practically change when a homogeneous field is considered, while in the case of a heterogeneity field there is an average 10% increase in detection time ratio between daily and annual sampling, independently from the magnitude of heterogeneity, when pollution is coupled with precipitation, while in the case of instantaneous pollution the same difference is 8%. Practically, it can be said that there is no difference between instantaneous and pulsing pollution when the transverse dispersion coefficient is as low as $a_T = 0.05m$ or lower.

In cases of higher values of dispersion where $a_T = 0.1m$ or more (Figure 6.8, second column), $< T_{obs} >/< T_{ar} >$ ratio actually increases as heterogeneity is increased. Pollution dispersion functions as a background field attribute, which augments the influence of geological heterogeneity on the average time needed in order for pollution to be detected. It can be seen that in the case of PCP, when hydraulic conductivity variation is $\sigma^2_{\ln K} = 1.0$, then the $<T_{obs}>/<T_{ar}>$ ratio changes 15.5% between the monthly and bi-annual sampling and 22% between the monthly and annual sampling frequency, while for $\sigma^2_{\ln K} = 2.0$ the differences are 11% and 27% respectively. The same trend is observed in the cases of IP, but the time ratio difference in the case of $\sigma^2_{\ln K} = 1.0$ is 7% between the monthly and bi-annual sampling and 13% between the monthly and annual sampling frequency. In the case of $\sigma^2_{\ln K} = 2.0$ the difference is 5% and 18% respectively. Either way, heterogeneity increase in a high dispersion geological environment causes delayed pollution detection by the same monitoring wells network. As heterogeneity increases, differences in the average detection time between different sampling frequencies tend to decrease when sampling is performed at least twice a year or more. However, when sampling is performed once a year and heterogeneity increases, then the average needed detection time is increased, dictating that pollution is transported and dispersed for more time into the aquifer in order for detection to be accomplished.

It is also observed that when $\sigma^2_{\ln K} = 2.0$, the average change of the time ratio $<T_{obs}>/<T_{ar}>$ between bimonthly and every 4 months sampling frequency is less than 4%, while in the case of IP there is no practical difference even when the aquifer is sampled once every 4 months. In the corresponding diagram (Figure 6.8, $\sigma^2_{\ln K} = 2.0$, $a_T = 0.05m$) $<T_{obs}>/<T_{ar}>$ drops below one, meaning that groundwater detection is accomplished 1% faster when sampling is performed fewer times a year than daily. This is artificial due to numerical approximations during computational procedure.

However, it is a fact that, as far as the presented simulation results are concerned, under the same hydro-geological parameters and adopting the same sampling frequency, IP event of groundwater pollution seems to be detected faster than the PCP. Moreover, it is noted that as heterogeneity increases the influence of different sampling intervals on detection time ratio $<T_{obs}>/<T_{ar}>$ is more pronounced between precipitation events coupled pollution and instantaneous cases, as the average difference between them for the same sampling frequency is 8% in case of $\sigma^2_{\ln K} = 1.0$ and 12% in case of $\sigma^2_{\ln K} = 2.0$. Aquifer pulsing pollution is detected later because more time is needed until the necessary pollutant mass accumulates into the aquifer, so that the plume's concentration exceeds concentration detection threshold limit. As heterogeneity is increased and plume is distorted and separated into smaller regions

(Figure 6.5), more mass diffusion is required to reach a detectable limit, meaning more precipitation events and, consequently, delayed pollution detection.

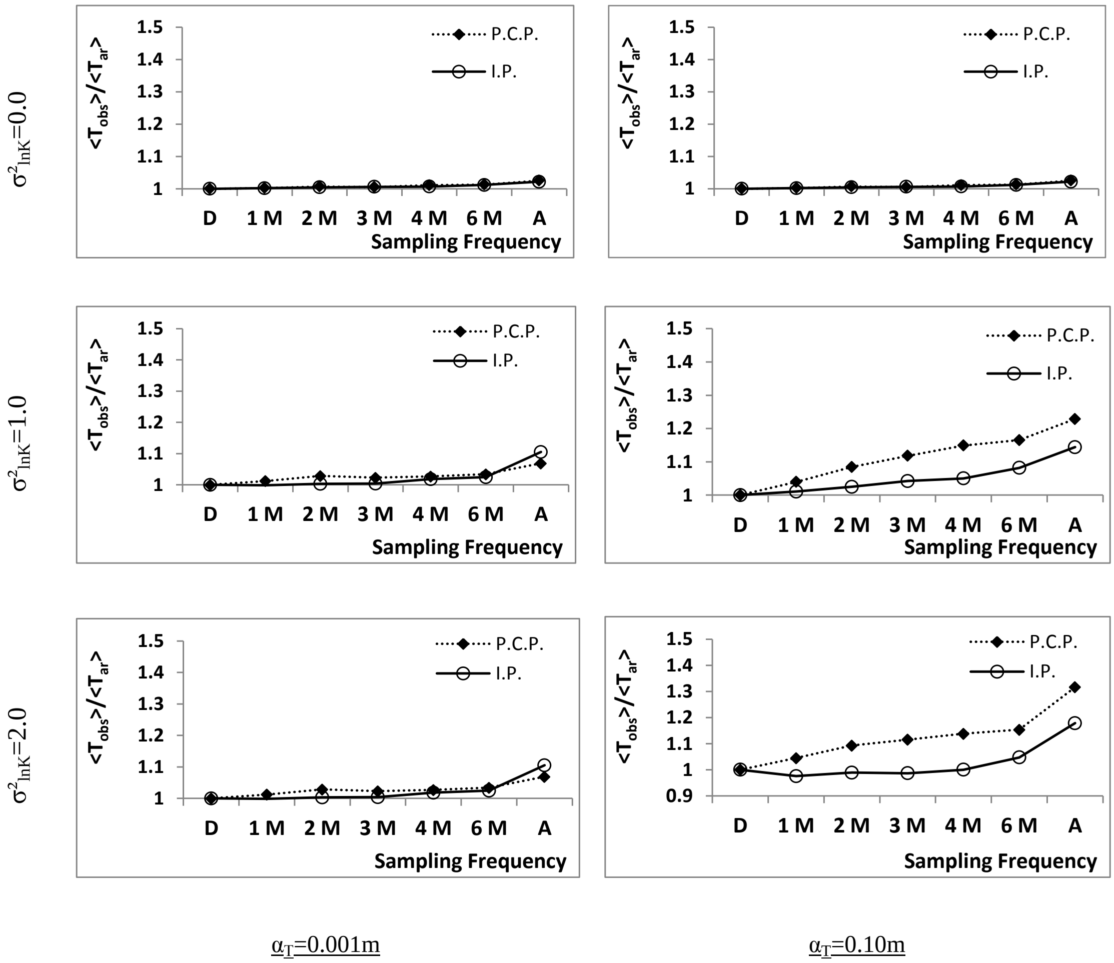


Figure 6.8: Change of ratio between average time of pollution arrival on monitoring installation ($<T_{ar}>$) and time of actual pollution observation ($<T_{obs}>$) in relation to sampling frequency for a 3-well monitoring arrangement.

An immediate result of late detection is the fact that the polluted area is growing larger. Pollution dispersion is again the main mechanism that multiples the polluted area as this is increased. Figure 6.9 depicts the ratio of average polluted area $\langle A_{pol} \rangle$ when groundwater pollution is actually detected by an 8-well monitoring network, to the control area L in relation to the logarithm of transverse dispersion coefficient. The striking feature of the diagram (Figure 6.9) is that for dispersion values above $a_T = 0.10m$ the relative polluted area is almost 3 times bigger than when dispersion coefficient is $a_T = 0.10m$. This means that there is an upper limit beyond which the contaminated area increases very fast, making a possible remediation decision really expensive. It is noteworthy that this behavior is practically independent of the field's heterogeneity.

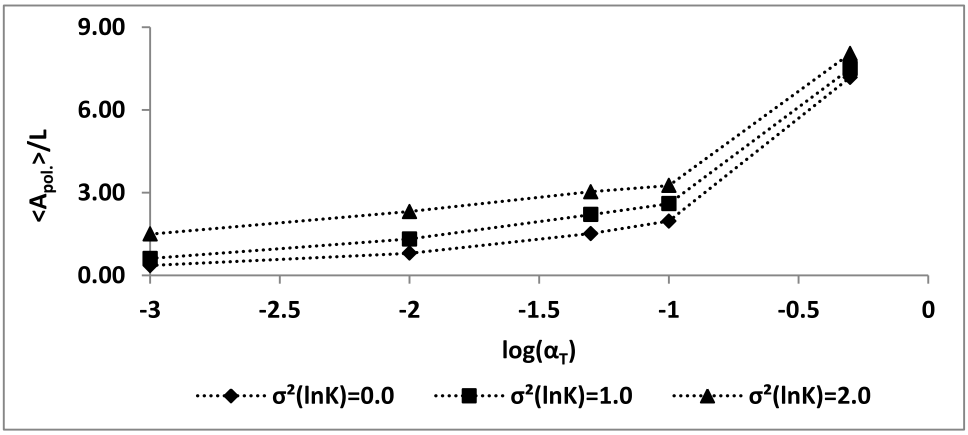


Figure 6.9: Change of ratio of the average polluted area $<A_{pol.}>$ to the area L of the contaminant potential source area in relation to the logarithm of transverse dispersion coefficient a_T for three different cases of field heterogeneity.

Comparing average detection in relation to sampling frequency, we verified for the cases simulated that if sampling is performed at least twice a year in a low dispersion environment then average detection time is not practically affected. If again we assume that $\langle A_{ar} \rangle$ is the average polluted area as soon as the plume actually arrives at and is detected by the monitoring wells arrangement, it is noticed that at a low dispersion field the average polluted area ratio changes less than 20% if groundwater is sampled at least 3 times a year, despite heterogeneity. In a homogeneous field the average change in area ratio is 7% if the aquifer is sampled at least twice a year, while in heterogeneous cases the difference in ratio is 19% if $\sigma^2_{\ln K} = 1.0$ and 29% if $\sigma^2_{\ln K} = 2.0$ respectively. In case sampling policy dictates annual sampling, then in highly heterogeneous aquifers the average polluted area is increased by 75%. Consequently, it is noticed that even if there is a 10% increase at detection time at low dispersion fields, when sampled annually the polluted area is dramatically increased, creating this way an expensive remediation background.

Examining greater dispersion value where $a_T = 0.50m$, it can be seen that the effect of sampling frequency is more pronounced on $< A_{obs} >/< A_{ar} >$ ratio. There is an almost linear increase of the polluted area as sampling is performed more scarcely, until the biannual frequency is reached, where the contaminated area is two times larger than the one at the time of the plume's actual arrival at the monitoring installation. At the point where sampling is performed once a year, the contaminated area becomes 2.7 times larger than the $\langle A_{ar} \rangle$, considering the heterogeneous cases, and 3.5 at the homogeneous case. In heterogeneous cases the effect of groundwater sampling frequency is less than in the homogeneous one, something which is due to the fact that aquifer heterogeneity causes plume deformations leading to creation of multiple pollution branches that may be transported in different directions from the main bulk of contamination and, in conjunction with high dispersion of multiple ejected pollutant, may provide larger detectable areas, easier to find even if sampling is performed annually.

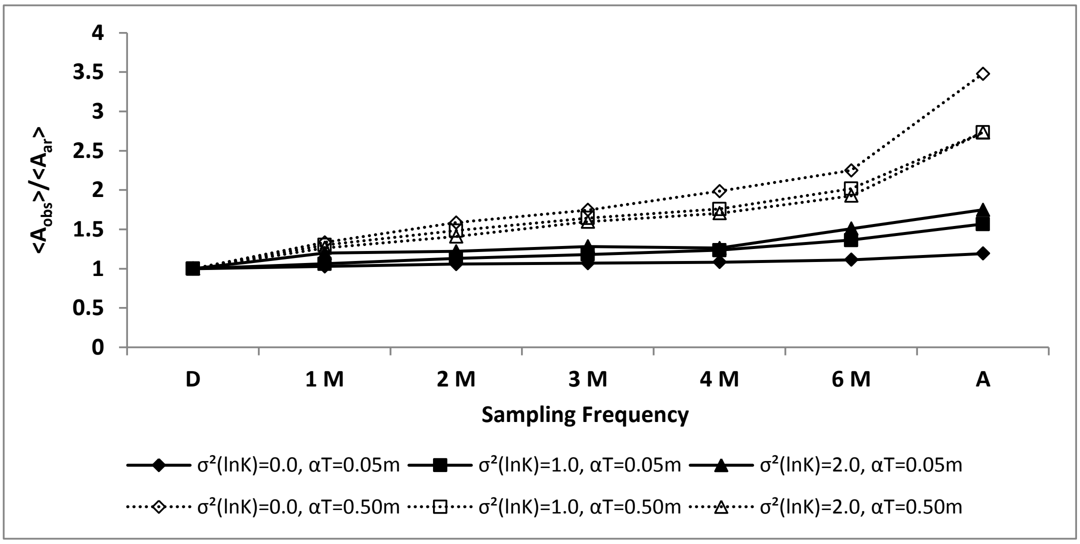


Figure 6.10: Change of ratio between the average polluted area $<A_{obs.}>$ at the plume's actual detection by an 8-well monitoring arrangement and the average polluted area $<A_{obs}>$ when the plume is actually observed upon its arrival at the monitoring installation in relation to sampling frequency.

6.3.6 Remediation delay

Papapetridis and Paleologos (2011a) defined a corrected risk R^{cor} that accounts for the remedial action delay time (RADTi) as follows:

$$R^{cor} = P_d^{cor} C_d + P_f^{cor} C_f \tag{6.1}$$

where

$$P_d^{cor} = P_d \left(\frac{A_t}{A_{t+dt}} \right) \tag{6.2}$$

and

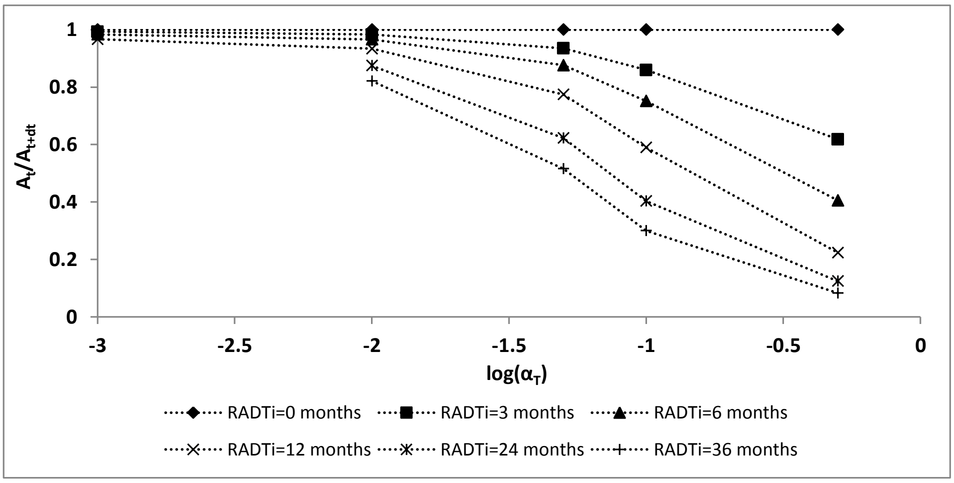
$$P_f^{cor} = 1 - P_d^{cor} \tag{6.3}$$

The corrected detection probability P_d^{cor} has been proposed as a measure of the economic impact of a remedial action delay, when the contaminated area has extended to A_{t+dt}, dictating a divergence from the maximum economic outcome that would take place at detection time, when the contaminated area is A_t. This procedure results in increasing the failure probability and weighed cost of failure in the calculation of the risk factor as the time interval dt increases. Sensitivity analysis can then illustrate to decision-makers the influence of delays on the cost of remediation, as risk analysis can be sub-optimal when it has high costs, low probability of success, or inconclusive results (Lund, 2008). An extensive study in case of instantaneous aquifer pollution can be found in the work of *Papapetridis and Paleologos* (2012).

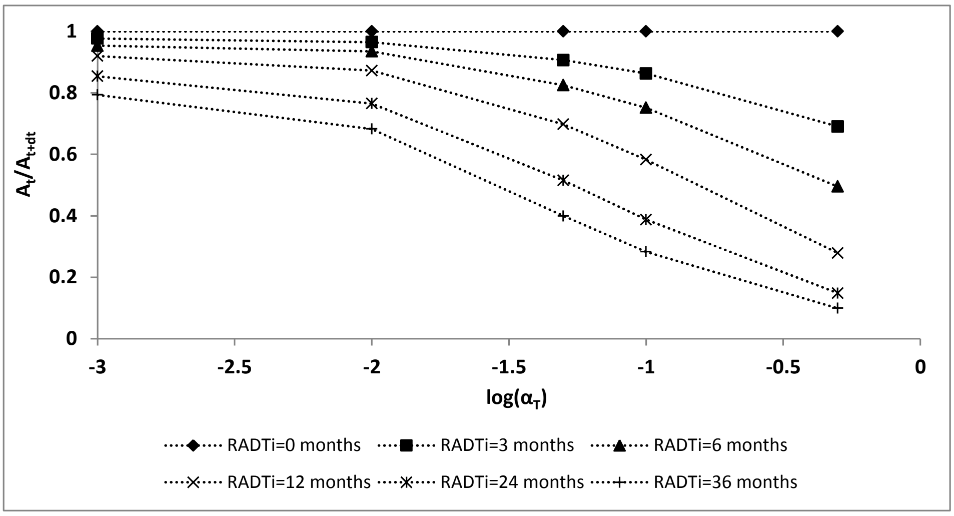
In order to study the effect of RADTi when PCP event takes place, the change of A_t / A_{t+dt} ratio, achieved by 6 monitoring wells, in relation to aquifer dispersion is demonstrated in Figure 6.11 (a)-(c), for each of the three heterogeneous cases that have been computationally studied. A common feature in all three diagrams is the fact that the more remediation actions are delayed, the more the contaminated area increases, causing the degradation of the initial probability's P_d value, according to Equation (6.2). In Figure 6.11(a) data referring to 24 and 36 months RADTi was not able to be calculated because the time of detection was already long enough. Therefore, adding more time to monitor the evolution of the plume overran the total 30-year simulation time.

In the only case heterogeneity does not practically affect P_d is when the aquifer is homogeneous and the dispersion of the pollution is as low as $a_T = 0.001m$. As heterogeneity increases, even at this low level of dispersion, the A_t / A_{t+dt} ratio decreases. In the case of a 6-well configuration at $\sigma^2_{\ln K} = 2.0$ and RADTi equal to 12 months, the polluted area ratio is 0.86, altering the initial detection probability P_d from 49% to 42.5% and for RADTi equal to 36 months to 32%. When dispersion is increased beyond $a_T = 0.01m$, the effect of RADTi is more pronounced, degrading probability P_d to 10% of its initial value, irrespectively of the aquifer's heterogeneity.

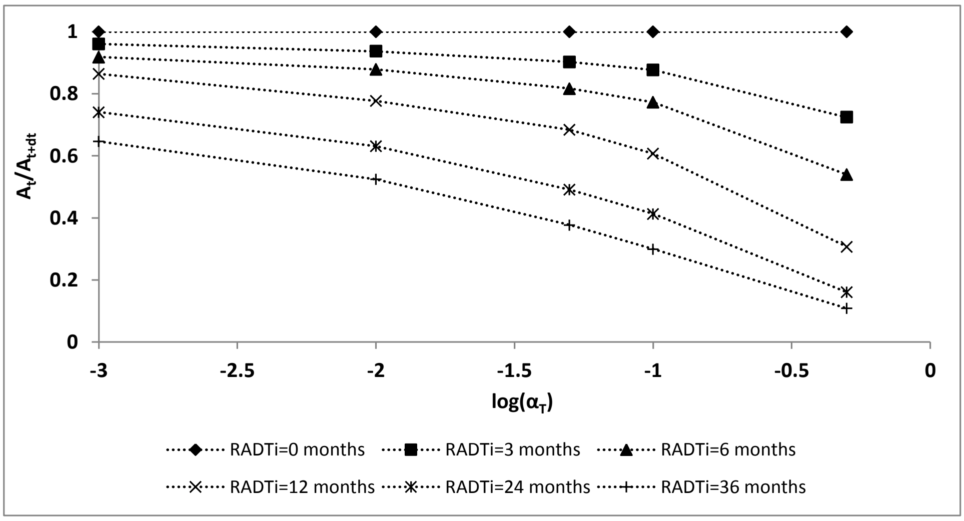
In the case of landfill originating groundwater pollution 99/31/ EU Directive states that the sampling frequency must be based on possibility for remedial actions between two samplings if a trigger level is reached. This may be interpreted in RADTi occurring in less than the sampling frequency, which should be at least once a year for a landfill installation, according to the same Directive. But, if this is the case, then assuming an aquifer where transverse dispersion coefficient is at least $a_T = 0.10m$ and is sampled annually, the corrective detection probability will be 70% of its initial value of 96%, providing a P_d^{cor} equal to 67%. This is the detection probability that 3 monitoring wells may achieve if sampled annually, which is increased only by 10% when 2 wells are sampled daily.



(a)



(b)



(c)

Figure 6.11: A_t/A_{t+dt} versus $\log(\alpha_T)$ for 6 monitoring wells and different Remedial Action Delay Times (RADTi): (a) homogeneous, (b) heterogeneous soils with $\sigma_Y^2 = 1.0$ and (c) heterogeneous soils with $\sigma_Y^2 = 2.0$

Instantaneous pollution cases that have been simulated in the authors’ previous works (Papapetridis & Paleologos, 2011a, 2011b, 2012), presented a similar to precipitation triggered pollution behavior. In former studies, though, it was considered that an area specified inside a grid cell was contaminated even if there was the smallest amount of pollution inside it, and not necessarily a detectable pollutant concentration above the threshold limit. This was assumed to demonstrate the immediate effect of RADTi, otherwise due to pollution dilution into the aquifer there would be a false increase of detection probability, originating by the fact that the contaminated area above the threshold limit would actually be diminished. However, the above hypothesis can stand true if the chemical footprint of the pollutant is of such nature that the overall quality degradation of groundwater renders it unusable for desired uses, such as potable water, even in small concentrations. So, even if there is a similarity in RADTi between instantaneous and precipitation related pollution cases, it is a fact that the absolute polluted area in the latter case is larger, rendering it more expensive in terms of remediation.

6.4 Conclusions

In this study groundwater pollution triggered by local precipitation events was investigated in relation to its detection probability by various linear arrangements of monitoring wells, and how this probability is affected by the number of wells, hydro-geological parameters, sampling frequency and remediation action delay time. Moreover, comparisons where made with instantaneous cases of groundwater pollution, assuming the same hydro-geological conditions.

It was shown in this set of simulations that detection probability of a monitoring arrangement increases faster in precipitation event related pollution than in instantaneous cases, as the number of wells increases. In fact, a small number of monitoring wells, even less than 6, may achieve a 100% detection, in case of a homogeneous and of a medium dispersion aquifer. Moreover, a 3-well installation can detect groundwater pollution more than 50% of the time, depending on the field’s hydro-geological properties.

Dispersion and heterogeneity are the hydro-geological parameters that directly affect the efficiency of the monitoring network. Preferential flow due to heterogeneity deformation and scattering of the plume is rather the main mechanism responsible for P_d decrease as the field gets more heterogeneous, and dilution of plume is hindered by pollutant mass pulsing injection. In any heterogeneity case dispersion amplifies the effectiveness of the monitoring wells. In fact, detection probability augmentation is so strong that even 3 wells computationally succeed 100% detection in a very high dispersion aquifer, where

$a_T = 0.50m$. On the contrary, at instantaneous pollution cases dispersion initially increases P_d, but after a maximum has been reached detection probability diminishes due to fast dilution of pollution.

In the case of precipitation event triggered heterogeneous aquifer pollution, sampling frequency practically does not seem to affect detection probability of the monitoring network. Even if sampling is performed annually the improvement of P_d in relation to monthly sampling is 8%, while the effort made is 12 times bigger. On the other side, if instantaneous pollution is assumed it appears that under all conditions at least biannual sampling should occur and, moreover, if one wants higher detection probability then monthly sampling is the optimum choice for most well arrangements. In order for sufficient levels of monitoring groundwater pollution to be achieved, one must focus on the problems arising from an instantaneous ejection rather than a precipitation related one.

The average detection time of groundwater pollution in the case of precipitation triggered events does not practically change as sampling frequency increases up to biannual sampling and the simulated aquifer presents as low a transverse dispersion as $a_T = 0.001m$. However, as dispersion increases to $a_T = 0.10m$ and, at the same, a heterogeneous aquifer of hydraulic conductivity variation $\sigma^2_{\ln K} = 1.0$ is assumed, simulations showed that the ratio $< T_{obs} > / < T_{ar} >$ increases up to 22% between monthly and annual sampling. Either way, heterogeneity increase in a high dispersion geological environment causes delayed pollution detection by the same monitoring wells network. Results showed that as heterogeneity increases, differences in average detection time between different sampling frequencies tend to decrease when sampling is performed at least twice a year or more. Time ratio $< T_{obs} > / < T_{ar} >$ concerning detection of instantaneous pollution cases changes in relation to sampling frequency, similarly to precipitation triggered cases. However, when dispersion and heterogeneity are increased their effects are less acute when it comes to detection time.

Average polluted area ratio $< A_{obs} > / < A_{ar} >$ in a low dispersion environment changes less than 20% if groundwater is sampled at least 3 times a year, despite heterogeneity. However, if annual sampling is adapted, then in highly heterogeneous aquifers the average polluted area is increased by 75%. This means that even if there is a 10% increase at detection time at low dispersion fields, the polluted area is dramatically increased when sampled annually. When dispersion is $a_T = 0.50m$, it is seen that the effect of sampling frequency is more pronounced on $< A_{obs} > / < A_{ar} >$ ratio. The polluted area is almost linearly increased as sampling is performed more scarcely until the biannual frequency is reached, when the contaminated area is twice as large as the one at the time of the plume's actual arrival at the monitoring installation. When annual sampling is assumed, the contaminated area becomes 2.7 times larger than the $\langle A_{ar} \rangle$ in the heterogeneous cases and 3.5 in the homogeneous case.

In all simulations the main hydro-geological parameter was the field's dispersion, affecting detection probability, average detection time and the contaminated area, all in relation to sampling frequency. In conjunction with the fact that pollutant mass is constantly added when precipitation occurs, even in different quantities and in random time, depending on rain events, dispersion causes greater detectable areal coverage. Consequently, when it increases it creates a favorable background in terms of pollution detection and renders the effectiveness of monitoring wells arrangements tolerable in scarce sampling frequency, when it is performed at least twice a year.

On the other hand, when RADTi is increased, dispersion results on the detection probability corrective factor in Equation (2) are more pronounced. In a high dispersion aquifer P_d^{cor} rapidly deteriorates even if RADTi is 6 months or less. Heterogeneity seems to affect RADTi when dispersion is equal or less than $a_T = 0.01m$, causing less than 7% decrease at the initial detection probability in case of a 12-month delay and assuming a homogeneous aquifer. Similarly, when the hydraulic conductivity variance is $\sigma^2_{\ln K} = 1.0$, the respective decrease is 13% and when $\sigma^2_{\ln K} = 2.0$ the decrease is 23%.

In any case RADTi is essential in estimating the risk concerning the ability of a groundwater monitoring installation to detect pollution, as it is a hidden parameter that may give a very big offset in risk calculations. Even if, according to current legislation, remedial actions should take place as soon as a trigger event occurs, this is not always the case, as locating and controlling a groundwater source is usually a set of many actions, performed by different collaborating groups of people (installation operator, local contractors). This kind of collaborations, among people of different interests and disciplines, in conjunction with funding problems, may lead in longer RADTi and, consequently, in bigger and more complicated environmental issues.

CHAPTER 7

Conclusions

The objective of this research was to numerically investigate groundwater contamination detection probability achieved by a linear monitoring arrangement of wells and to provide a novel framework that modifies traditional risk analysis by supplying a corrected detection probability that accounts for delays in remedial actions. A stochastic two-dimensional model was developed that performed high resolution Monte Carlo simulations, coupling a finite difference flow model and a Random Walk Particle Tracking algorithm that simulated contamination plume advection and dispersion. Uncertainty stemming from the subsoil field itself was simulated with the Spectral Turning Bands method.

Pollution source was assumed to be a randomly selected point inside the controlled area boundaries where the pollution is considered to have started. Two major cases concerning duration of the pollution were examined. The instantaneous case, whose duration of pollution is less than the modeling time step Δt which was set equal to one day, and the precipitation triggered pollution, where it was assumed that each time rain occurred a quantity of pollution, proportional to the daily average precipitation height, injected into the aquifer. Conclusions are summarized at the next paragraphs.

7.1 Instantaneous groundwater pollution detection probability in heterogeneous aquifers

Pollution originated instantaneously from a random point source within a landfill facility. Different arrangements and distances of monitoring wells from a landfill were considered, and the corresponding detection probabilities P_d and contaminated groundwater areas, at different time periods, were calculated.

It was observed that convergence of the probability of detection P_d to a constant value was attained, for all monitoring configurations, at about 3,000 Monte Carlo simulations. The number of tracking particles used to simulate contaminant transport had a strong influence on the values of P_d calculated through numerical experiments. For all monitoring arrangements convergence of the P_d to a stable value was attained at 8,000 tracking particles.

In all cases of hydro-geological heterogeneity and dispersion, the more wells utilized for detection purposes the greater the P_d. For a fixed heterogeneity level, for each specific arrangement of wells, the maximum detection probability increases, along with dispersion coefficient up to a certain value of α_T, and then decreases. For transverse dispersion greater than $0.2m$, maximum detection is attained very close to the trailing edge of the landfill. As a general rule, the efficiency of contaminant detection from a specific well arrangement decreases as the variance of $\ln K$ increases.

The frequency of sampling is critical in heterogeneous aquifers of high dispersion. In generally, it appears that under all conditions at least biannual sampling should occur at a monitoring system. If one wants a higher detection probability, then sampling at a monthly frequency appears to be the optimum choice for most well arrangements, considering both the effort involved, if one were to proceed with a much more intense sampling, and the improvements on detection attained at this level. It is interesting to note that in heterogeneous aquifers if a large number of monitoring wells is sampled infrequently, they do not perform much better in terms of detection than arrangements having a lower number of wells but which are sampled more regularly.

Decision-making analysis that evaluates the economic worth of different arrangements of wells calculates remediation costs based on contaminated groundwater volumes that are estimated at the time of detection. In practice there is always a remedial action response delay and hence remedial costs surpass those calculated at detection time. To correct this situation an expression is proposed for a corrected risk factor R^{cor} that accounts for remedial action response delay,

$$R^{cor} = P_d^{cor} C_d + P_f^{cor} C_f \tag{6.4}$$

$$P_d^{cor} = P_d \left(\frac{A_t}{A_{t+dt}} \right), \ and \ P_f^{cor} = 1 - P_d^{cor} \tag{6.5}$$

A_t corresponds to the contaminated area (volume) at detection time t, and A_{t+dt} is the contaminated area (volume) at a later time, due to delays in remediation procedures. Our approach can be viewed as a way to downgrade the importance of early detection, if not followed by quick remedial response, in risk analysis calculations. This expression estimates, for example, in a heterogeneous field where twelve monitoring wells operate and are sampled every day, that a remediation delay of 36 months almost doubles the failure cost which enters risk calculations.

7.2 Sampling frequency of groundwater monitoring system and remediation delay at contaminated sites

Using high-resolution numerical Monte Carlo two-dimensional simulations, the impact of sampling frequency on the probability of detecting groundwater contamination in various subsurface environments was investigated, as well as the effects that sampling schedules and remediation delays have on the growth of contaminated subsurface areas and remediation costs. In homogeneous media of low dispersion, a large number of wells provide such density of coverage of the area downstream a landfill that a plume cannot remain undetected, even with few observations. On the other hand, in homogeneous soils of high dispersion, irrespective of the density of the monitoring network, because contaminants disperse strongly and concentrations at the monitoring points drop below the threshold limits quickly, a rigorous sampling schedule must be followed in order to retain a network's performance.

A similar situation holds for heterogeneous soils of high dispersion, with the existence of low permeability zones appearing to ameliorate the dispersion effects, but not sufficiently enough in order to alter the conclusion about the criticality of the sampling schedule. The frequency of sampling is also of interest in order to minimize the time lag between the time that concentrations above a threshold limit first appear at monitoring locations and the time that these concentrations are observed through sampling. The objective, of course, is to delineate the extent of the contaminated area and to initiate remediation efforts as soon as possible. Analysis of the lag between the time that contaminants appeared at monitoring sites and the time they were observed led to the conclusion that, in terms of time delay, bimonthly sampling constitutes a safe strategy for a wide range of hydro-geological environments. In the case of aquifers that exhibit fast pathways of contaminant transport, through the existence of high permeability zones, further investigation is required. However, in terms of the growth of the contaminated are, with the exception of monthly sampling, all other less frequent schedules resulted in significant enlargement of plume areas, thus leading to more costly remediation. Moreover, it was demonstrated that remedial response delays in highly dispersive environments must be of the order of a few months if one does not wish the contaminated areas and remediation costs to grow significantly.

7.3 Parameters on stochastic simulation of contaminant detection probability

It was studied how the number of point sources, the size of the controlled area (e.g. a landfill facility) and the quantity of an instantaneous injected pollution affect plume detection of a monitoring well setting. In each examined parameter it was considered that the rest of the factors affecting estimation remain constant. Simulations were performed in the context of uncertainty factors deriving from the environment itself, reflected on the parameter of hydraulic conductivity and the lack of information about the initial conditions of a leak.

It was numerically verified, in the cases examined, that as the size of the control area becomes larger and the number of wells remains constant, then detection probability decreases. If the width of a control area is to be increased, so must the number of monitoring wells, maintaining at least the same density as in the initial size.

In all simulated cases, the general observation is that when two equivalent groundwater pollution sources are present their detection is easier. More often aquifer sampling does not alter monitoring efficiency in terms of the presence of more pollution sources.

Simulation results indicated that when the initial concentration of pollution is very low (below 1,000 mgr/lt) then its detection is very hard, regardless of the aquifer's hydro-geological parameters. The monitoring wells efficiency of low to medium dispersion aquifers reaches a maximum, which is independent of the initial mass of pollution intruding the aquifer. The turning point of initial pollution concentration is $C = 8,000 mgr/lt$, which is the value where P_d reaches a plateau. In every case, lower concentrations were harder to detect, dictating that in order for a monitoring setting to be sensitive, at least at simulation level, even for small amounts of pollution at least 12 wells must be used.

7.4 Modeling of aquifer pollution detection probability triggered by precipitation

Groundwater pollution triggered by local precipitation events was investigated in relation to its detection probability by various linear arrangements of monitoring wells. Also, the way this probability is affected by the number of wells, hydro-geological parameters, sampling frequency and remediation action delay time was examined. Moreover, comparisons where made with instantaneous cases of groundwater pollution, assuming the same hydro-geological conditions.

It was shown that detection probability of a monitoring arrangement increases faster in precipitation event related pollution than in instantaneous cases, as the number of wells increases. In fact, a small number of monitoring wells, even less than 6, may achieve a 100% detection, in the case of a homogeneous medium dispersion aquifer. Moreover, a 3-well installation can detect groundwater pollution more than 50% of the time, depending on the field's hydro-geological properties.

Dispersion and heterogeneity are the hydro-geological parameters that directly affect the efficiency of the monitoring network. Preferential flow due to heterogeneity deformation and scattering of the plume is possibly the main mechanism responsible for P_d decrease, as the field gets more heterogeneous and dilution of plume is hindered by pollutant mass pulsing injection. In any heterogeneity case, dispersion amplifies the effectiveness of the monitoring wells. On the contrary, at instantaneous pollution cases, dispersion initially increases P_d but, after a maximum has been reached, detection probability diminishes due to fast dilution of pollution.

In the case of precipitation event triggered heterogeneous aquifer pollution, sampling frequency practically does not seem to affect detection probability of the monitoring network. On the other hand, if instantaneous pollution is assumed, it appears that under all conditions at least biannual sampling should occur and, moreover, if one wants higher detection probability, monthly sampling is the optimum choice for most well arrangements. In order for sufficient levels of monitoring groundwater pollution to be achieved, one must focus on the problems arising from an instantaneous ejection rather than a precipitation related one.

The average detection time of groundwater pollution in the case of precipitation triggered events does not practically change as sampling frequency increases up to biannual sampling and the simulated aquifer presents very low transverse dispersion ($a_T = 0.001m$). Heterogeneity increase in a high dispersion geological environment causes delayed pollution detection from the same monitoring wells network. Time ratio $<T_{obs}>/<T_{ar}>$ concerning detection of instantaneous pollution cases changes in relation to sampling frequency similar to those of precipitation triggered cases. However, when dispersion and heterogeneity are increased, their effects are less acute when it comes to detection time.

The average polluted area ratio $< A_{obs} > / < A_{ar} >$ increases as field dispersion increases. When dispersion is very high ($a_T = 0.50m$) the polluted area is almost linearly increased, as sampling is performed more scarcely until the biannual frequency is reached.

In all simulations the main hydro-geological parameter was the field's dispersion, affecting detection probability, average detection time and the contaminated area, all in relation to sampling frequency. In conjunction with the fact that pollutant mass is constantly added when precipitation occurs, even in different quantities and in random time, depending on rain events, dispersion causes greater detectable areal coverage. Consequently, when it increases it creates a favorable background in terms of pollution detection and renders the effectiveness of monitoring wells arrangements tolerable in scarce sampling frequency, when it is performed at least twice a year.

When RADTi is increased, dispersion results are more pronounced for the detection probability corrective factor. In a high dispersion aquifer P_d^{cor} rapidly deteriorates even if RADTi is 6 months or less.As heterogeneity increases, it seems that RADTi affects less P_d assuming the same pollution dispersion. In any case, RADTi is essential to estimate the risk concerning the ability of a groundwater monitoring installation to detect pollution, as it is a hidden parameter that may give a very big offset in risk calculations.

APPENDIX A

2-D Source Code

Source code for all cases that have been numerically simulated is provided. In Section 1 source code for the instantaneous case of pollution is provided. In Section 2 code modeling pollution related to precipitation events is provided. Because of the fact that subroutines that solve steady flow equations numerically and Spectral Turning Bands that produce random fields are common between them, they are referred at Section 3 and 4 respectively. It must be noted that Turning Bands algorithm in 2-D is different from that in 3-D. In order TUBA subroutine to run it needs a complementary file named "tuba211d.inc", which must be located in the folder where compilation is to take place. The listing for this file is:

```
C      INCLUDE FILE FOR TUBA VERSION 2.11d
C-----------------------------------------------------------------------------
--
      COMMON /TBAPAR/ ICOVF,IPAA,LINES,FMAX,NHAR,NMAX,UN,FX,FY,
     1 XO,YO,TBMX,KS,IP,NX,NY,XMAX,YMAX,DX,DY,NXY, AM,AN,AV,CLX,CLY,
     1 IDFP,IURN, DS,UD,KD,NR,CK,FM,FA, A1,A3,A5,KT,DT,SG,B0,B1,B2,
     1 NF,IPF,ISAJ,IULP,MSK,IMSEX
```

In order a a 2-D model simulation top take place, source coede of Section 1 or 2 along with code of Section 3 and 4 must be combined and compiled together. All source code is programmed in FORTRAN 77 and has been compiled using the freeware editor and compiler FORCE 2.0. All runs performed in a workstation equipped with two quad core Xeon microprocessors and 12 GB of RAM memory.

A-1 Instantaneous Pollution

```
      PROGRAM TBRW
C
C     TBRW CODE HAS BEEN DEVELOPED BY PAPAPETRIDIS KONSTANTINOS
C     TUBA HAS BEEN DEVELOPED BY DR A.MANTOGLOU
C     FLOW HAS BEEN DEVELOPED BY DR A.J.DESBARATS
C
C-----------------------------------------------------------------------
C     MONTE CARLO STOCHASTIC SCHEME SIMULATING 2-D POLLUTION FLOW
C          INTO A HETEROGENEOUS AQUIFERS. HETEROGENEOUS AQUIFERS IN THE
C          MODEL WERE SIMULATED USING THE 2-D SPECTRAL TURNING BANDS
C          METHOD(STUBA) (ABABOU ET AL., 1989; MANTOGLOU AND WILSON, 1982;
C          MCLAUGHLIN ET AL., 1993; PALEOLOGOS AND SARRIS, 2011; TOMPSON
C          AND GELHAR, 1990B).  THE AQUIFER IS ASSUMED TO BE CONFINED,
C          WITH GIVEN HYDRAULIC HEAD AT LEFT AND RIGHT BOUNDARIES,
C          RESULTING IN A MACROSCOPICALLY CONSTANT HYDRAULIC GRADIENT OF
C          0.001. SOURCE LOCATION UNCERTAINTY WAS ENVISAGED CONSIDERING
C          EQUALLY PROBABLE DIFFERENT POINT OF POLLUTION ORIGIN DURING
C          EACH DIFFERENT SIMULATION, WHICH BELONGS INSIDE THE CONTROL AREA
C
C     LOGNORMAL MEDIA
C     CORRELATED CONDUCTIVITY FIELD
C     2-D TURNING BANDS METHOD (TUBA)
C     DOUBLE PRECISION USED
C     HYBRID INTERPOLATION VELOCITY SCHEME
C
C     PARAMETER IDENTIFICATION:
C       IMEM= 1024000 MAX PARTICLES
C       KW=8 MONITORING WELLS ARRANGEMENT (1,2,3,4,6,8,12,20)
C       KSA=7 SAMPLING FREQUENCIES (1,30,60,90,120,180,360 DAYS)
C       MDS=7 DISPERSION CASES (0.001,0.01,0.02,0.05,0.10,0.20,0.50 M)
C
C     ONE INPUT FILE IS REQUIRED: TUBA211.INC
C     THIS FILE IS PROVIDED BY TUBA DEVELOPER
C
C-----------------------------------------------------------------------
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
C     KW:No OF WELLS, KSA:SAMPLING INTERVALS, MDS:TRANSVERSE DISPERSION
      PARAMETER (IMEM=1024000)
      PARAMETER (KW=8,KSA=7,MDS=7)
      DOUBLE PRECISION P(IMEM),VELX(IMEM),VELY(IMEM),VELZ(IMEM),RK(IMEM)
      DOUBLE PRECISION  TATOD(MDS,0:KSA-1,KW),ATOD(0:KSA-1,KW),
     & TDCM(MDS)
      DOUBLE PRECISION NCAR(0:KSA-1,KW),CAR1(0:KSA-1,KW),
     & CAR3(0:KSA-1,KW),CAR6(0:KSA-1,KW),CAR12(0:KSA-1,KW),
     & CAR24(0:KSA-1,KW),CAR36(0:KSA-1,KW),TNCAR(MDS,0:KSA-1,KW),
     & TCAR1(MDS,0:KSA-1,KW),TCAR3(MDS,0:KSA-1,KW),TCAR6(MDS,0:KSA-1,
     & KW),TCAR12(MDS,0:KSA-1,KW),TCAR24(MDS,0:KSA-1,KW),
     & TCAR36(MDS,0:KSA-1,KW)
      INTEGER TS,TEND,TPRD,SNSIM,TVC,TDET(MDS,0:KSA-1,KW),FDET(MDS,
     & 0:KSA-1,KW),NOW(KW),ISA(0:KSA-1),ORPOSO,PX,PY,PZ,LFC(100000)
      LOGICAL DET(0:KSA-1,KW),MONITOR
      CHARACTER SDATE_R*8,DATE_R*8,T_R*10,ST_R*10
C
      COMMON /PARAM/ P0,P1,EP,DX,DY,DZ,NX,NY,NZ,NSEED
      COMMON /SOLVE/ OMEGA,TOL,TOL1,MITER,SNSIM
      COMMON /VELOCITY/ VELX,VELY,VELZ
      COMMON /PARTICLE/ PM,TVC,NPAR
```

```
      COMMON /LANDFILL/ LFXI,LFXE,LFYI,LFYE,LFAR,LFC
      COMMON /MONITORING/ SIGMA,MONITOR,NOW,ISA
      COMMON /TIME/ TS,TEND,TPRD,NSIM
      COMMON /WAREA/ NCAR,CAR1,CAR3,CAR6,CAR12,CAR24,CAR36
C
C-----------------------------------------------------------------------
C-    GRID SPACING FOR TURNING BAND SIMULATIONS IN X
C-     DIFFERENT FROM ABOVE SO AS TO CREATE ANISOTROPY. NOTE
C-     THAT TURNING BAND ROUTINE CAN ONLY SIMULATE ISOTROPIC
C-     FIELDS AND THAT, TO GENERATE ANISOTROPIC FIELDS, YOU HAVE
C-     TO TRANSFORM THE GRID SPACING....
C-----------------------------------------------------------------------
C
C------HETEREOGENITY OF THE FIELD ---------------------------------------
C
      SIGMA=1.00D0
C
C------PARAMETER INITIALIZATION-----------------------------------------
C
      NSIM=3000                 !NUMBER OF SIMULATIONS
C
      TEND=10950                !TIME MONITOR ENDS (30 YEARS)
      TPRD=1                    !PERIOD OF TIME THAT LEAK OCCURS
      TS=1                      !TIME STEP (DAYS)
C
      LNDFX=1000                !LENGHT OF SIMULATION AREA (METERS)
      LNDFY=400                 !WIDTH OF SIMULATION AREA (METERS)
      LNDFZ=1                   !DEPTH OF SIMULATION AREA (METERS)
      DX=2                      !DX STEP ON X AXIS (METERS)
      DY=2                      !DY STEP ON Y AXIS (METERS)
      DZ=1                      !DZ STEP ON X AXIS (METERS)
      NX=INT(LNDFX/DX)          !NODES IN X-DIRECTION (DIMENSIONLESS)
      NY=INT(LNDFY/DY)          !NODES IN Y-DIRECTION (DIMENSIONLESS)
      NZ=INT(LNDFZ/DZ)          !NODES IN Z-DIRECTION (DIMENSIONLESS)
C
      DL=0.D0                   !TB BLOCK DIMENSION
      DC=0.D0                   !TB BLOCK DIMENSION
      DN=0.D0                   !TB BLOCK DIMENSION
C
      A=20.D0                   !CORELLATION COEFFICIENT (METERS)
      A=(-1.D0)*ABS(A)
      HEADG=0.001D0
      P0=0.D0                   !STARTING HYDRAULIC HEAD
      P1=NX*DX*HEADG            !ENDING HYDRAULIC HEAD
      EP=0.25D0                 !EFFECTIVE POROSITY
      ALPHA=2.3D0               !MEAN lnK
C
      NPAR=8000                 !TOTAL PARTICLES TO BE EJECTED
      PM=1                      !PARTICLE'S MASS
      TVC=112                   !THRESHOLD VOLUMETRIC CONCENTRATION
C
      MONITOR=.TRUE.            !PARAMETER THAT CONTROLS IF WE MONITOR OR NOT
C
C     RANDOM NUMBER SEEDS
      DSEED=2147811051.D0       !seed number for RNG`
      NSEED=1236547896          !15.8
C
C
C     BETA FOR NOW ON IS THE STANDARD DEVIATION NOT THE VARIANCE
      BETA=SQRT(SIGMA)
C
      TOL=0.00001D0
      TOL1=0.00005D0
      MITER=2000
      SNSIM=0                    ! NUMBER OF SIMULATIONS WITH FLOW FIELD
SOLUTION
      NNNN=NX*NY*NZ
      NXNY=NX*NY
```

```
      DSEED=DSEED*NXNY*NY*BETA*DX/(NSIM*NSIM)
      SSXEN=0.D0
      RKPOIN21=0.D0
      RKPOIN22=0.D0
      RKPOINT1=0.D0
      RKPOINT2=0.D0
      SSX2EN=0.D0
C
      DO 22 K=1,MDS
        DO 22 J=0,KSA-1
          DO 22 I=1,KW
            TDET(K,J,I)=0
            FDET(K,J,I)=0
            TATOD(K,J,I)=0.D0
   22 CONTINUE
C
C     FLOW EQUATIONS RELAXATION FACTOR
C     — DEPEDENCE HAS BEEN OBSERVED. BEST RESULTS ARE ACCOMPLISHED
C     WHEN RELAXATION FACTOR IS THE HIGHER POSSIBLE (INITIAL WAS 1.85)
      OMEGA0=1.85D0
C
      IF(nnnn.GE.180000)OMEGA0=1.88D0
      IF(nnnn.GE.240000)OMEGA0=1.91D0
      IF(nnnn.GE.390000)OMEGA0=1.92D0
      IF(nnnn.GE.490000)OMEGA0=1.95D0
      IF(nnnn.GE.700000)OMEGA0=1.97D0
      IF(nnnn.GE.850000)OMEGA0=1.98D0
      IF(nnnn.GE.850000)TOL=0.0001D0
      IF(nnnn.GE.850000)TOL1=0.0005D0
C
C
C     PRINTING ON SCREEN THE STARTING TIME
      CALL DATE_AND_TIME (SDATE_R,ST_R)
C
C     3-D TB INPUT DATA (BLOCK DIMENSIONS)
      IF(DL.EQ.0.0)DL=DX
      IF(DC.EQ.0.0)DC=DY
      IF(DN.EQ.0.0)DN=DZ
C
C
C -----PRINTING INITIAL INFORMATION-----------------------------------
C
      PRINT*,'THIS IS THE TOTAL PLUME TRANSPORT SIMULATION!'
      PRINT*,'NUMBER OF REALIZATIONS :',NSIM
      PRINT 715,NX,NY,NZ
      PRINT 716,DX,DY,DZ
      PRINT 717,DL,DC,DN
C
  715 FORMAT(' GRID SIZE :  ',I3,'X',I3,'X',I3)
  716 FORMAT(' BLOCK DIMENSIONS    : ',F5.2,' X',F5.2,' X',F5.2)
  717 FORMAT(' TB BLOCK DIMENSIONS : ',F5.2,' X',F5.2,' X',F5.2)
C
      PRINT*,'CORRELATION RANGE (LENGTH UNITS) : ',A
      PRINT*,'                       & VARIANCE : ',BETA*BETA
      PRINT*
      PRINT*,'       ******* STARTING SIMULATIONS *******'
      PRINT*
C
C
C------ESTABLISHING MONITOR SYSTEM AND SAMPLING POLICY---------------
C     LANDFILL'S GEOMETRY
      CALL LANDF
C
C     NUMBER OF WELLS
      DO IW=1,KW
        IF(IW.LE.4)NOW(IW)=IW
        IF(IW.EQ.5)NOW(IW)=6
        IF(IW.EQ.6)NOW(IW)=8
```

```
          IF(IW.EQ.7)NOW(IW)=12
          IF(IW.EQ.8)NOW(IW)=20
        ENDDO
C
C       SAMPLING INTERVALS
        DO JS=0,KSA-1
          IF(JS.GE.1.AND.JS.LE.4) ISA(JS)=JS*30
          IF(JS.EQ.0) ISA(JS)=1
          IF(JS.EQ.5) ISA(JS)=180
          IF(JS.EQ.6) ISA(JS)=365
        ENDDO
C
C       DISPERSIVITY FACTOR
        DO MTDC=1,MDS
          IF(MTDC.EQ.1) TDCM(MTDC)=0.001D0
          IF(MTDC.EQ.2) TDCM(MTDC)=0.01D0
          IF(MTDC.EQ.3) TDCM(MTDC)=0.02D0
          IF(MTDC.EQ.4) TDCM(MTDC)=0.05D0
          IF(MTDC.EQ.5) TDCM(MTDC)=0.10D0
          IF(MTDC.EQ.6) TDCM(MTDC)=0.20D0
          IF(MTDC.EQ.7) TDCM(MTDC)=0.50D0
        ENDDO
C
C       INITIALISING AVERAGE CONTAMINATED CELL AREA
        DO 28 MTDC=1,MDS
         DO 28 JS=0,KSA-1
          DO 28 IW=1,KW
            TNCAR(MTDC,JS,IW)=0.D0
            TCAR1(MTDC,JS,IW)=0.D0
            TCAR3(MTDC,JS,IW)=0.D0
            TCAR6(MTDC,JS,IW)=0.D0
            TCAR12(MTDC,JS,IW)=0.D0
            TCAR24(MTDC,JS,IW)=0.D0
            TCAR36(MTDC,JS,IW)=0.D0
     28 CONTINUE
C
C
C -----CREATING REPORT FILES -------------------------------------------
        OPEN(9,FILE='ERROR.TXT',STATUS='REPLACE')
C        OPEN(11,FILE='RESULTS.TXT',STATUS='REPLACE')
C        OPEN(14,FILE='K_EXAMPLE.TXT',STATUS='UNKNOWN')
C        OPEN(22,FILE='VELOCITIES_EXAMPLE.TXT',STATUS='UNKNOWN')
C        OPEN(23,FILE='HEADS_EXAMPLE.TXT',STATUS='UNKNOWN')
        OPEN(48,FILE='PROBALITIES.TXT',STATUS='UNKNOWN')
        OPEN(39,FILE='SOURCE.TXT',STATUS='UNKNOWN')
        OPEN(50,FILE='RWREPORT.TXT',STATUS='UNKNOWN')
C
        SNSIMOLD=0      ! PARAMETER THAT CONTROLS PROBABILITIES FILE OUTPUT
C
C
C***********************************************************************
C------LOOP ON THE NUMBER OF SIMULATIONS--------------------------------
C
        IS=0
        DOWHILE(SNSIM.LT.NSIM)              ! BASIC SIMULATION LOOP BEGINS
C
        IS=IS+1                             !SIMULATION COUNTER
C
        CALL DATE_AND_TIME (DATE_R,T_R)
C
        WRITE(9,719)IS,NSIM,t_r(1:2),t_r(3:4),t_r(5:6)
        PRINT 718,IS,INT(SNSIM)+1,NSIM,SNSIM*100./NSIM,T_R(1:2),
       & T_R(3:4),T_R(5:6)
C
  718   FORMAT('TOT.SIM.No:',I4,2X,' SIM.No:',I4,' OF ',I4,3X,
       +  F4.1,1X,'% COMPLETED ',' START TIME:  ',A2,':',A2,':',A2)
  719   FORMAT('SIM #',I4,'/',I4,3X,'START TIME:  ',A2,':',A2,':',A2)
C
```

```
C
C------SIMULATE STANDARD NORMAL DEVIATES BY TURNING BANDS---------------
C
C
      PRINT*
      PRINT*,'   STARTING TURNING BANDS ALGORITHM ...   '
      CALL TUBA(NX,NY,DX,DY,ALPHA,BETA,-A,RK)
C
C
C------CALCULATING MEAN ENSAMBLE MEAN AND VARIANCE----------------------
C
      SUM=0.D0
      SSX=0.D0
      SSX2=0.D0
      RKPOINT1=RKPOINT1+BETA*RK(432)
      RKPOINT2=RKPOINT2+BETA*RK(845)
      RKPOIN21=RKPOIN21+BETA*BETA*RK(432)*RK(432)
      RKPOIN22=RKPOIN22+BETA*BETA*RK(845)*RK(845)
      DO 12 K=1,NZ
        DO 12 J=1,NY
          DO 12 I=1,NX
            IP=(K-1)*NXNY+(J-1)*NX+I
C            TEMP=ALPHA+BETA*RK(IP)
            TEMP=RK(IP)
            SSX=SSX+TEMP
            SSX2=SSX2+TEMP*TEMP
            TEMP=EXP(TEMP)
            RK(IP)=TEMP
            SUM=SUM+TEMP
            P(IP)=P0+(P1-P0)*(I-0.5D0)/NX
  12  CONTINUE
C
      SSX=SSX/NNNN
      SSXEN=SSXEN+SSX
      SSX2EN=SSX2EN+(SSX2/NNNN)
      SSX2=SSX2/NNNN-SSX*SSX
C
C
C------SOLVE FLOW EQUATION----------------------------------------------
C
      PRINT*,'   STARTING TO SOLVE THE FLOW PROBLEM ...   '
C
      OMEGA=OMEGA0
      CHECKSNSIM=SNSIM               ! KEEPING OLD VALUE OF SOLVED CASES
C
      CALL FLOW3D(RK,P,ICON,DMAX)
C
C
C     !!! PROCEED ONLY IF THERE IS A SOLUTION OF THE FLOW PROBLEM !!!
      IF(SNSIM.GT.CHECKSNSIM)THEN       ! CHECKING
C
C------CALCULATING THE VELOCITY FIELD FOR EACH REALISATION--------------
C
      PRINT*,'   STARTING TO CALCULATE THE VELOCITY FIELD ...   '
C
      CALL VEL(RK,P,VELX,VELY,VELZ)
      PRINT*,'     Velocity Field Calculated!'
      PRINT*
C
C
C------OUTPUT VALUES FOR VELOCITIES,K AND H FOR VISUALIZATION PURPOSES--
C       IF(SNSIM.EQ.NSIM)THEN
C
C       DO 221 K=1,NZ
C         DO 221 J=1,NY
C           DO 221 I=1,NX
C             IP=(K-1)*NXNY+(J-1)*NX+I
C             WRITE(14,667)I,J,K,RK(IP)
```

```
C              WRITE(22,668)I,J,K,VELX(IP),VELY(IP),VELZ(IP)
C              WRITE(23,667)I,J,K,P(IP)
C  221 CONTINUE
C        ENDIF
C
C 667  FORMAT(3(I4,1X),F10.4)
C 668  FORMAT(3(I4,1X),3(F9.6,1X))
C
C
C------CREATING AND MONITOR POLLUTION--------------------------------
       IF(MONITOR.EQV..TRUE.)THEN
         PRINT*,'   CREATING AND MONITOR POLLUTION ...      '
       ELSE
         PRINT*,'   CREATING POLLUTION ...      '
       ENDIF
C
       CALL RANDORIGIN(XO,YO,ORPOSO) ! DERMINING POLLUTION ORIGIN
         PX=INT(XO)
         PY=INT(YO)
         PZ=1
         IF(YO-PY.GE.0.5)PY=PY+1        !COUNTS ON CENTRAL Y
         IF(XO-PX.GE.0.5)PX=PX+1        !COUNTS ON CENTRAL X
       PRINT*
       PRINT 900,PX,PY,PZ
C
      DO 115 MTDC=1,MDS              ! LOOP OVER DIRPERSION FACTOR
       TDC=TDCM(MTDC)
       WRITE(50,*)'TDC=',TDC
       CALL RANDOMWALK(IS,TDC,XO,YO,ORPOSO,DET,ATOD)
C
       DO 125 JS=0,KSA-1
         DO 130 IW=1,KW                        ! MULTI-WELL LOOP
          IF(DET(JS,IW).EQV..TRUE.)THEN
            TDET(MTDC,JS,IW)=TDET(MTDC,JS,IW)+1
          ELSEIF(DET(JS,IW).EQV..FALSE.)THEN
            FDET(MTDC,JS,IW)=FDET(MTDC,JS,IW)+1
          ENDIF
C
C      CALCULATING CONTAMINATED AREA
       TNCAR(MTDC,JS,IW)=TNCAR(MTDC,JS,IW)+NCAR(JS,IW)
       TCAR1(MTDC,JS,IW)=TCAR1(MTDC,JS,IW)+CAR1(JS,IW)
       TCAR3(MTDC,JS,IW)=TCAR3(MTDC,JS,IW)+CAR3(JS,IW)
       TCAR6(MTDC,JS,IW)=TCAR6(MTDC,JS,IW)+CAR6(JS,IW)
       TCAR12(MTDC,JS,IW)=TCAR12(MTDC,JS,IW)+CAR12(JS,IW)
       TCAR24(MTDC,JS,IW)=TCAR24(MTDC,JS,IW)+CAR24(JS,IW)
       TCAR36(MTDC,JS,IW)=TCAR36(MTDC,JS,IW)+CAR36(JS,IW)
C
C      CALCULATING AVERAGE TIME OF DETECTION
       TATOD(MTDC,JS,IW)=TATOD(MTDC,JS,IW)+ATOD(JS,IW)
C
C
      IF(IW.EQ.7.AND.MTDC.EQ.5.AND.JS.EQ.0.AND.(SNSIM.EQ.1.OR.SNSIM
     & .NE.SNSIMOLD))THEN
      WRITE(48,*) SNSIM,NOW(IW),1.*TDET(MTDC,JS,IW)/SNSIM
      SNSIMOLD=SNSIM
      PRINT*, 'HI',NOW(IW)
      ENDIF
C
  130    CONTINUE                          ! CLOSING MULTI-WELL LOOP
C
  125  CONTINUE                            ! CLOSING SAMPLING LOOP
       WRITE(50,*)'*****************************************************'
       WRITE(50,*)'*****************************************************'
       WRITE(50,*)'*****************************************************'
       WRITE(50,*)
C
       IF(JS.EQ.KSA.AND.IW.EQ.KW)GOTO 115
       PRINT*,'-----------------------------------------------------'
```

```
C
  115 CONTINUE                                 ! DISPERSION LOOP
C
      ENDIF                                    ! CHECKING IF
C
      PRINT*,'*****************************************************
     &*********'
      PRINT*,'*****************************************************
     &*********'
      PRINT*
      PRINT*
      ENDDO                                    ! CLOSING SIMULATION LOOP
C
C*******************************************************************
C
C
C------CALCULATE THE ENSEMBLE STATISTICS AND WRITE THE RESULTS----------
C
         ALLREP=1.D0*IS
         RKPOINT1=RKPOINT1/ALLREP
         RKPOIN21=RKPOIN21/ALLREP-RKPOINT1*RKPOINT1
         RKPOINT2=RKPOINT2/ALLREP
         RKPOIN22=RKPOIN22/ALLREP-RKPOINT2*RKPOINT2
         SSXEN=SSXEN/ALLREP
         SSX2EN=SSX2EN/ALLREP-SSXEN*SSXEN
C
C       CONTAMINATED AREA RELATIVE TO LANDFILL'S AREA FOR EACH PERIOD
      DO 510 MTDC=1,MDS
        DO 510 JS=0,KSA-1
         DO 510 IW=1,KW
          IF(FDET(MTDC,JS,IW).NE.0)TNCAR(MTDC,JS,IW)=(TNCAR(MTDC,JS,IW)/
     &      FDET(MTDC,JS,IW))/LFAR
          IF(TDET(MTDC,JS,IW).NE.0)THEN
           TCAR1(MTDC,JS,IW)=(TCAR1(MTDC,JS,IW)/TDET(MTDC,JS,IW))/LFAR
           TCAR3(MTDC,JS,IW)=(TCAR3(MTDC,JS,IW)/TDET(MTDC,JS,IW))/LFAR
           TCAR6(MTDC,JS,IW)=(TCAR6(MTDC,JS,IW)/TDET(MTDC,JS,IW))/LFAR
           TCAR12(MTDC,JS,IW)=(TCAR12(MTDC,JS,IW)/TDET(MTDC,JS,IW))/LFAR
           TCAR24(MTDC,JS,IW)=(TCAR24(MTDC,JS,IW)/TDET(MTDC,JS,IW))/LFAR
           TCAR36(MTDC,JS,IW)=(TCAR36(MTDC,JS,IW)/TDET(MTDC,JS,IW))/LFAR
C
C         AVERAGE TIME OF DETECTION
          TATOD(MTDC,JS,IW)=TATOD(MTDC,JS,IW)/TDET(MTDC,JS,IW)
C
        ENDIF
  510 CONTINUE
C
C------WRITTING OUTPUT-------------------------------------------------
      OPEN(16,FILE='FINAL_REPORT.TXT',STATUS='UNKNOWN')
      OPEN(17,FILE='Pd_EXCEL.TXT',STATUS='UNKNOWN')
      OPEN(18,FILE='TOTAL_EXCEL.TXT',STATUS='UNKNOWN')
C
      PRINT*
      WRITE(*,*)'TOTAL FIELD SIMULATIONS: ',NSIM
      WRITE(*,*) 'NUMBER THAT FLOW FIELD WAS SIMULATED: ',SNSIM
C
      CALL DATE_AND_TIME (DATE_R,T_R)
C
      WRITE(16,*)'THIS IS THE FINAL REPORT:'
      WRITE(16,*)
      WRITE(16,*)'TOTAL FIELD SIMULATIONS: ',NSIM
      WRITE(16,*) 'NUMBER THAT FLOW FIELD WAS SIMULATED: ',SNSIM
      WRITE(16,*)
      WRITE(16,*)'START TIME : ',ST_R(1:2),':',ST_R(3:4),':',ST_R(5:6),
     +  '  AT ',SDATE_R(5:6),'/',SDATE_R(7:8),'/',SDATE_R(3:4)
      WRITE(16,*)'END TIME : ',T_R(1:2),':',T_R(3:4),':',T_R(5:6),
     +  '  AT ',DATE_R(5:6),'/',DATE_R(7:8),'/',DATE_R(3:4)
      WRITE(16,811)NX,NY,NZ
      WRITE(16,812)DX,DY,DZ
```

```
      WRITE(16,813)DL,DC,DN
      WRITE(16,*)
C
      PRINT*
      PRINT*
      WRITE(16,*)'START TIME : ',ST_R(1:2),':',ST_R(3:4),':',ST_R(5:6),
     +  '  AT ',SDATE_R(5:6),'/',SDATE_R(7:8),'/',SDATE_R(3:4)
      PRINT*,'END TIME : ',T_R(1:2),':',T_R(3:4),':',T_R(5:6),
     +  '  AT ',DATE_R(5:6),'/',DATE_R(7:8),'/',DATE_R(3:4)
      PRINT 811,NX,NY,NZ
      PRINT 812,DX,DY,DZ
      PRINT 813,DL,DC,DN
C
 811  FORMAT(' GRID SIZE :  ',I3,'X',I3,'X',I3)
 812  FORMAT(' BLOCK DIMENSIONS    : ',F5.2,'X',F5.2,'X',F5.2)
 813  FORMAT(' TB BLOCK DIMENSIONS : ',F5.2,'X',F5.2,'X',F5.2)
 900  FORMAT('STARTING POINT OF POLLUTION: ','PX=',I3,2X,'PY=',I3,
     & 2X,'PZ=',I3)
C
      WRITE(16,*)
      WRITE(16,*)'THE ENS.MEAN IS:',SSXEN,' AND THE ENS.VAR IS:',SSX2EN
      WRITE(16,*)'THE ENS.MEAN IN TWO POINTS IS : ',RKPOINT1,RKPOINT2
      WRITE(16,*)'  AND THE ENS. VARIANCE IS : ',RKPOIN21,RKPOIN22
      WRITE(16,*)
      WRITE(16,*)'CORRELATION SCALE = ',A,' WITH ',SNSIM,'  SIMULATIONS'
      WRITE(16,*)'INITIAL HEAD: ',HEADG
      WRITE(16,*)'No OF PARTICLES:',NPAR
      WRITE(16,*)'TVC:',TVC,' PARTICLES'
      WRITE(16,*)'VARIANCE : ',BETA*BETA
      WRITE(16,*)
C
C     DETECTION REPORT FILE
      WRITE(16,*)
      WRITE(16,*)'No OF SIMULATION=',SNSIM
      WRITE(16,*)'TOTAL MONITOR TIME=',TEND
      WRITE(16,*)
      DO MTDC=1,MDS
       WRITE(16,*)'DISPERSION FACTOR:',TDCM(MTDC)
       DO 512 JS=0,KSA-1
        WRITE(16,*)'**************************************************'
        WRITE(16,*)'SAMPLING TIME INTERVALS (DAYS): ',ISA(JS)
        WRITE(16,*)'          -----------            '
        DO 512 IW=1,KW
          WRITE(16,*)'NUMBER OF MONITOR WELLS : ',NOW(IW)
          WRITE(16,*)'NORMALIZED DISTANCE AMONG WELLS: ',1./NOW(IW)
          WRITE(16,*)'DETECTED POLLUTION=',TDET(MTDC,JS,IW)
          WRITE(16,*)'NOT DETECTED POLLUTION=',FDET(MTDC,JS,IW)
          WRITE(16,*)'PROBABILITY OF DETECTION=',100.*TDET(MTDC,JS,IW)/
     &     SNSIM,'%'
          WRITE(16,*)'PROBABILITY OF FAILURE=',100.*FDET(MTDC,JS,IW)/
     &     SNSIM,'%'
          WRITE(16,*)
          WRITE(16,*)'AVERAGE TIME OF CONTAMINATION DETECTION=',
     &     TATOD(MTDC,JS,IW)
          WRITE(16,*)
          WRITE(16,*)'AVERAGE POLLUTED VOLUME ON FAILURE=',
     &     TNCAR(MTDC,JS,IW)
          WRITE(16,*)'AVERAGE POLLUTED VOLUME ON DETECTION=',
     &     TCAR1(MTDC,JS,IW)
          WRITE(16,*)'AVERAGE POLLUTED VOLUME 3 MONTHS LATER=',
     &     TCAR3(MTDC,JS,IW)
          WRITE(16,*)'AVERAGE POLLUTED VOLUME 6 MONTHS LATER=',
     &     TCAR6(MTDC,JS,IW)
          WRITE(16,*)'AVERAGE POLLUTED VOLUME 12 MONTHS LATER=',
     &     TCAR12(MTDC,JS,IW)
          WRITE(16,*)'AVERAGE POLLUTED VOLUME 24 MONTHS LATER=',
     &     TCAR24(MTDC,JS,IW)
          WRITE(16,*)'AVERAGE POLLUTED VOLUME 36 MONTHS LATER=',
```

```
     &    TCAR36(MTDC,JS,IW)
          WRITE(16,*)
  512  CONTINUE
       WRITE(16,*)'************************************************'
       WRITE(16,*)'************************************************'
      ENDDO
C
C     REPORTING  DATA FOR EXCEL USE
      DO K=1,MDS
        DO I=1,KW
         WRITE(17,540)(100.0*TDET(K,J,I)/SNSIM,J=0,KSA-1)
         WRITE(18,560)( 100.0*TDET(K,J,I)/SNSIM,INT(TATOD(K,J,I)),
     &    TNCAR(K,J,I),TCAR1(K,J,I),TCAR3(K,J,I),TCAR6(K,J,I),
     &    TCAR12(K,J,I),TCAR24(K,J,I),TCAR36(K,J,I),J=0,KSA-1)
        ENDDO
      ENDDO
C
  540  FORMAT(7(F5.1,1X))
  560  FORMAT(7(F5.1,1X,I4,1X,7(F6.4,1X)))
C
C
      PRINT*,'THE ENS.MEAN IS:',SSXEN,' AND THE ENS.VAR IS:',SSX2EN
      PRINT*,'THE ENS.MEAN IN TWO POINTS IS : ',RKPOINT1,RKPOINT2
      PRINT*,'  AND THE ENS. VARIANCE IS : ',RKPOIN21,RKPOIN22
      PRINT*
      PRINT*,'CORRELATION SCALE = ',A,' WITH ',SNSIM,'  SIMULATIONS'
      PRINT*,'INITIAL HEAD: ',HEADG
      PRINT*,'No OF PARTICLES:',NPAR
      PRINT*,'VARIANCE : ',SIGMA
      PRINT*
      PRINT*
      PRINT*,'DONE ..... '
C
      STOP
      END          !END OF MAIN PROGRAM
C
C
C
C-*****SUBROUTINES*****SUBROUTINES*********SUBROUTINES*****************
C
C
C*********************************************************************
C****** SUBROUTINE RANDOMWALK(DET,TDETECTED,POLVOL)*********************
C*********************************************************************
C
C     The random walk particle tracking (RWPT) method treats the transport
C     of a solute mass via a large number of particles. It moves each
C     particle through the porous medium using the velocity field obtained
C     from the solution of the flow equation to simulate advection and
C     adds a random displacement to simulate dispersion
C
C
      SUBROUTINE RANDOMWALK(IS,TDC,RPX,RPY,ORPOS,DET,TOD)
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      PARAMETER (IMEM=1024000)
      PARAMETER (KW=8,KSA=7)
C
      DOUBLE PRECISION X(IMEM),Y(IMEM),Z(IMEM),XPR(IMEM),YPR(IMEM),
     & ZPR(IMEM),LDC,NDFS,TOD(0:KSA-1,KW)
      DOUBLE PRECISION NCAR(0:KSA-1,KW),CAR1(0:KSA-1,KW),
     & CAR3(0:KSA-1,KW),CAR6(0:KSA-1,KW),CAR12(0:KSA-1,KW),
     & CAR24(0:KSA-1,KW),CAR36(0:KSA-1,KW)
      DIMENSION C(IMEM),PRPOS(IMEM),LFC(100000)
      DIMENSION RLOCLAND(IMEM),CC(20),NW(20),MWX(20),MWY(20)
      INTEGER C,POS,PX,PY,PZ,PAR,PRPOS,ORPOS,PART,CC,TVC
      INTEGER TEND,TPRD,TS,TTL,PRSMTTL(0:KSA-1,KW),NOW(KW),ISA(0:KSA-1)
      LOGICAL MW(0:KSA-1,KW,20),MONITOR,DET(0:KSA-1,KW)
```

```
C
      COMMON /PARAM/ P0,P1,EP,DX,DY,DZ,NX,NY,NZ,NSEED
      COMMON /PARTICLE/ PM,TVC,NPAR
      COMMON /POLLUTION/ C,OOB
      COMMON /LANDFILL/ LFXI,LFXE,LFYI,LFYE,LFAR,LFC
      COMMON /MONITORING/ SIGMA,MONITOR,NOW,ISA
      COMMON /TIME/ TS,TEND,TPRD,NSIM
      COMMON /WAREA/ NCAR,CAR1,CAR3,CAR6,CAR12,CAR24,CAR36
C
C      OPEN(30,FILE='C_ANALYTICALLY.TXT',STATUS='UNKNOWN')
C
C------INITIALIZATION OF MATRICES AND PARAMETERS------------------------
      NXNY=NX*NY                ! LEVEL NODES
      OOB=0                     ! PARTICLES OUT OF BOUNDARIES
      TOTALPART=0               ! TOTAL PARTICLE COUNTER
      LDC=10*TDC                !LONGITUDAL DISPERSSION
C
C     COORDINATES OF POLLUTION ORIGIN
      PX=INT(RPX)
      PY=INT(RPY)
      PZ=1
      IF(RPY-PY.GE.0.5)PY=PY+1        !COUNTS ON CENTRAL Y
      IF(RPX-PX.GE.0.5)PX=PX+1        !COUNTS ON CENTRAL X
C
      DO JS=0,KSA-1
        DO IW=1,KW
          DO K=1,NOW(IW)
            MW(JS,IW,K)=.FALSE.     ! MONITOR WELL INITIAL DETECTION VALUE
          ENDDO
        ENDDO
      ENDDO
C
      DO JS=0,KSA-1
        DO IW=1,KW
          DET(JS,IW)=.FALSE.        ! DETECTION PARAMETER (IF PLUME IS
DETECTED THEN TRUE)
          TOD(JS,IW)=0.D0           ! AVERAGE TIME OF DETECTION
          PRSMTTL(JS,IW)=0          ! INITIAL TIME OF SAMPLING
C
C     INITIALISING CONTAMINATED CELL AREA
          NCAR(JS,IW)=0.D0
          CAR1(JS,IW)=0.D0
          CAR3(JS,IW)=0.D0
          CAR6(JS,IW)=0.D0
          CAR12(JS,IW)=0.D0
          CAR24(JS,IW)=0.D0
          CAR36(JS,IW)=0.D0
        ENDDO
      ENDDO
C
      DO I=1,IMEM
        X(I)=0.D0
        Y(I)=0.D0
        Z(I)=0.D0
        XPR(I)=0.D0
        YPR(I)=0.D0
        ZPR(I)=0.D0
        C(I)=0
      ENDDO
C
      CALL WNDFS(SIGMA,TDC,NDFS)
C
C     DIMENSION RESTORATION FACTORS
       DISTLENGT=DX
       DISTTIME=TS
C       DISTVEL=DX/TS
C
C     REMOVING DIMENSIONS
```

```
          LDC=LDC/DX
          TDC=TDC/DY
          DX=DX/DX
          DY=DY/DY
          DZ=DZ/DZ
          TEND=TEND/TS
          TPRD=TPRD/TS
          TS=TS/TS
C
C
C ****************RANDOM WALK PARTICLE TRACKING ALGORITHM***************
C
C -----TIME PROGRESSION-----------------------------------------------
C
           DO 20 TTL=1,TEND,TS
C
C         NUMBER OF PARTICLES TO BE RELEASED EACH TIME
C          INSTANT LEAK (TPRD=1) - CONTINUOUS LEAK (TPRD>1)
           IF(TTL.LE.TPRD)THEN
             PART=NPAR+NPAR*(TTL-1)
             TOTALPART=PART
             C(ORPOS)=C(ORPOS)+NPAR
             DO PAR=PART-NPAR+1,PART
                PRPOS(PAR)=ORPOS
                X(PAR)=RPX
                Y(PAR)=RPY
                Z(PAR)=PZ
                XPR(PAR)=X(PAR)
                YPR(PAR)=Y(PAR)
                ZPR(PAR)=Z(PAR)
             ENDDO
           ENDIF
C
C -----PARTICLE'S PROGRESSION ALGORITHM-------------------------------
C
             DO 10 PAR=1,PART
C
C         CHECKING IF PARTICLE WAS INSIDE BOUNDARIES, THEN
C         EXECUTE THE NEXT POSITION ALGORITHM
         IF(XPR(PAR).GE.1.AND.XPR(PAR).LE.NX-1.AND.YPR(PAR).LE.NY-1.AND.
     &    YPR(PAR).GE.1.AND.ZPR(PAR).GT.0.AND.ZPR(PAR).LE.NZ)THEN
C
C            DETERMINING 3 RANDOM NUMBERS
             R1=RVNORMAL(NSEED)
             R2=RVNORMAL(NSEED)
C             R3=RVNORMAL(NSEED)
C
C        CALCULATING PARTICLE'S VELOCITY
             CALL VCL(X(PAR),Y(PAR),Z(PAR),VLX,VLY,VLZ)
             CALL VCB(X(PAR),Y(PAR),Z(PAR),VBX,VBY,VBZ)
C
             VB=SQRT(VBX**2+VBY**2+VBZ**2)
C
C        CALCULATING VELOCITY DERIVATIVES (BETWEEN CELL BOUNDARIES)
             XIP=INT(X(PAR))
             YIP=INT(Y(PAR))
             CALL VCL(X(PAR),YIP,Z(PAR),VLXD,VLYD,VLZ)
             CALL VCL(X(PAR),YIP+1,Z(PAR),VLXU,VLYU,VLZ)
             CALL VCL(XIP,Y(PAR),Z(PAR),VLXL,VLYL,VLZ)
             CALL VCL(XIP+1,Y(PAR),Z(PAR),VLXR,VLYR,VLZ)
C
             UXUVX=(VLXL-VLXR)/DX
             UYUVY=(VLYU-VLYD)/DY
             UYUVX=(VLXU-VLXD)/DY
             UXUVY=(VLYL-VLYR)/DX
C
C        CALCULATING FOKKER-PLANCK EQUATION ADDITIONAL TERM
             DLT=LDC-TDC
```

```
C
            UXUDYX=(DLT/VB**3)*((VBY**3)*UXUVX+(VBX**3)*UXUVY)
C
            UYUDYY=(2.D0*TDC*VBX*VB**2-TDC*VBX**3-LDC*VBX*VBY**2)*
     &              UYUVX/VB**3+(2.D0*LDC*VBY*VB**2-TDC*VBY*VBX**2-
     &              LDC*VBY**3)*UYUVY/VB**3
C
C           Y COMPONENT FOKKER-PLANK STAGNATION TERM
            FPTY=UXUDYX+UYUDYY
C
C
            UXUDXX=(2.D0*LDC*VBX*VB**2-LDC*VBX**3-TDC*VBX*VBY**2)*
     &              UXUVX/VB**3+(2.D0*TDC*VBY*VB**2-LDC*VBY*VBX**2-
     &              TDC*VBY**3)*UXUVY/VB**3
C
            UYUDXY=(DLT/VB**3)*((VBY**3)*UYUVX+(VBX**3)*UYUVY)
C
C           X COMPONENT FOKKER-PLANK STAGNATION TERM
            FPTX=UXUDXX+UYUDXY
C
C           DETERMINING THE NEW POSITION
            FLDC=R1*SQRT(2.D0*LDC*VB*TS)
            FTDC=R2*SQRT(2.D0*TDC*VB*TS)
C
           X(PAR)=XPR(PAR)+VLX*TS+(VBX/VB)*FLDC-(VBY/VB)*FTDC+FPTX*TS
           Y(PAR)=YPR(PAR)+VLY*TS+(VBY/VB)*FLDC+(VBX/VB)*FTDC+FPTY*TS
C
C             CHECKING IF BOYNDARIES HAVE BEEN REACHED
C             CHECKING X END BOUNDARY
              IF(X(PAR).LT.1.OR.X(PAR).GT.NX-1)THEN
                 C(PRPOS(PAR))=C(PRPOS(PAR))-1
                 XPR(PAR)=X(PAR)
                 OOB=OOB+1
                 GOTO 10
              ENDIF
C             CHECKING Y END BOUNDARY
              IF(Y(PAR).GT.NY-1.OR.Y(PAR).LT.1)THEN
                 C(PRPOS(PAR))=C(PRPOS(PAR))-1
                 YPR(PAR)=Y(PAR)
                 OOB=OOB+1
                 GOTO 10
              ENDIF
C             CHECKING Z DOWN END BOUNDARY
              IF(Z(PAR).LT.0)THEN
                 C(PRPOS(PAR))=C(PRPOS(PAR))-1
                 ZPR(PAR)=Z(PAR)
                 OOB=OOB+1
                 GOTO 10
              ENDIF
C        CHECKING Z TOP END BOUNDARY.IF EQUAL NZ ASSIGN PREVIOUS VALUE
C        PLUME IS FORCED INSIDE THE VOLUME. THIS POLICY MAY BE ALTERED
              IF(Z(PAR).GT.NZ) Z(PAR)=NZ
C
C           KEEPING POSITIONS
            XPR(PAR)=X(PAR)
            YPR(PAR)=Y(PAR)
            ZPR(PAR)=Z(PAR)
C
C -----CALCULATING CONCENTRATIONS---------------------------------------
C
C        WELLS ARE LOCATED ON GRID'S NODES
         MCLX=INT(X(PAR))
         MCLY=INT(Y(PAR))
C
         DIFX=X(PAR)-MCLX
         DIFY=Y(PAR)-MCLY
C
         IF(DIFX.GE.0.5) MCLX=MCLX+1
```

```
          IF(DIFY.GE.0.5) MCLY=MCLY+1
C
          POS=(MCLY-1)*NX+MCLX
C
          C(POS)=C(POS)+1
          C(PRPOS(PAR))=C(PRPOS(PAR))-1
          PRPOS(PAR)=POS
C
C
        ENDIF     ! INSIDE BOUNDARIES IF
C
C
   10       CONTINUE
C
C -----MONITOR-------------------------------------------------------
        IF(MONITOR.EQV..TRUE.)THEN
C       ESTABLISHING A SAMPLING POLICY (INVSM=INTERVAL OF SAMPLING)
        DO 90 JS=0,KSA-1
C
C           MONITOR WELLS
          DO 95 IW=1,KW
            IF(INT(TTL-PRSMTTL(JS,IW)).EQ.ISA(JS))THEN
               PRSMTTL(JS,IW)=TTL              ! KEEPING TIME OF PREVIOUS STEP
               DO KK=1,NOW(IW)
                  BW=(LFYE-LFYI)/NOW(IW)
                  IBW=INT(BW/2)
                  MWX(KK)=INT(LFXE+(LFYE-LFYI)*NDFS)  !X DIMENSION OF MONITOR
WELL
                  MWY(KK)=INT(LFYI+(IBW+(KK-1)*BW))   !Y DIMENSION OF MONITOR
WELL
               ENDDO
C
C           MONITORING WELLS 1 - NOW(IW) (NUMBER OF WELLS)
               DO 70 K=1,NOW(IW)
                  CC(K)=0
C               DEPTH OF WELLS (NZ=1 EQV 2-D)
                  DO 80 IZ=1,NZ
                     NW(K)=(IZ-1)*NXNY+(MWY(K)-1)*NX+MWX(K)
                     CC(K)=CC(K)+C(NW(K))
                     IF(CC(K)*PM.GE.TVC)THEN
                       IF(DET(JS,IW).EQV..FALSE.)THEN
                          MW(JS,IW,K)=.TRUE.
                          DET(JS,IW)=.TRUE.
                          TOD(JS,IW)=TTL
                       ENDIF
                     ENDIF
   80             CONTINUE
C
   70          CONTINUE      ! CLOSING MONITOR LOOP
            ENDIF            ! SAMPLING POLICY IF
C
            IF(DET(JS,IW).EQV..TRUE.)THEN
              IF(TTL.EQ.TOD(JS,IW)) CALL POLVOL(CAR1(JS,IW))
              IF(TTL.EQ.TOD(JS,IW)+90) CALL POLVOL(CAR3(JS,IW))
              IF(TTL.EQ.TOD(JS,IW)+180) CALL POLVOL(CAR6(JS,IW))
              IF(TTL.EQ.TOD(JS,IW)+365) CALL POLVOL(CAR12(JS,IW))
              IF(TTL.EQ.TOD(JS,IW)+730) CALL POLVOL(CAR24(JS,IW))
              IF(TTL.EQ.TOD(JS,IW)+1095) CALL POLVOL(CAR36(JS,IW))
            ENDIF
C
C
   95   CONTINUE        ! CLOSING WELL LOOP
   90 CONTINUE          ! CLOSING SAMPLING LOOP
C
      ENDIF             ! MONITOR IF
C
   20   CONTINUE
C
```

```
C
      DO JS=0,KSA-1
        DO IW=1,KW
         IF(DET(JS,IW).EQV..FALSE.) CALL POLVOL(NCAR(JS,IW))
        ENDDO
      ENDDO
C
C -----EXPORTING CONCENTRATIONS ON A SELECTED REALISATION --------------
C       IF(IS.EQ.NSIM)THEN
      OPEN(32,FILE='CONCENTRATION.TXT',STATUS='UNKNOWN')
      QWVAL=20
      LVAL=10
      DO 40 K=1,NZ
       DO 40 J=1,NY
          DO 40 I=1,NX
            IP=(K-1)*NXNY+(J-1)*NX+I
            RLOCLAND(IP)=C(IP)
C     VISUALIZATION OF LANDFILL'S LOCATION ON THE FIELD LATTICE AND
C     ITS MONITOR WELLS
               DO KK=1,NOW(IW)
                  IF(I.EQ.MWX(KK).AND.J.EQ.MWY(KK)) RLOCLAND(IP)=QWVAL
               ENDDO
C
                IF(K.EQ.NZ.AND.J.GE.LFYI.AND.J.LE.LFYE.AND.
     $          I.GE.LFXI.AND.I.LT.LFXE) RLOCLAND(IP)=LVAL
C
       WRITE(32,*)I,J,K,RLOCLAND(IP)
C
   40 CONTINUE
C
      CLOSE(32)
C
C -----CHECKING HOW MANY PARTICLES WERE COUNTED AND IF WE HAD C<0 ------
      NP=0
      E0=0
      DO 45 K=1,NZ
       DO 45 J=1,NY
         DO 45 I=1,NX
           IP=(K-1)*NXNY+(J-1)*NX+I
           IF(C(IP).LT.0)THEN
             E0=E0+1
             PRINT 145,C(IP),I,J
             WRITE(50,145)C(IP),I,J
           ENDIF
           NP=NP+C(IP)
   45 CONTINUE
  145 FORMAT('ATTENTION:NEGATIVE VALUE OF CONCENTRATION C',I5,
     &', AT POSITION X=',I4,' AND Y=',I4)
C
C     RESTORING DIMENSIONS
       LDC=LDC*DISTLENGT
       TDC=TDC*DISTLENGT
       DX=DX*DISTLENGT
       DY=DY*DISTLENGT
       DZ=DZ
       TEND=TEND*DISTTIME
       TPRD=TPRD*DISTTIME
       TS=TS*DISTTIME
C
C
C      REPORTING VALUES
      WRITE(50,*) IS,'/',NSIM
      WRITE(50,800)NX,NY,NZ
      WRITE(50,900)PX,PY,PZ
      WRITE(50,*)
      WRITE(50,*)'TIME STEP: ',TS
      WRITE(50,*)'TOTAL PARTICLES INJECTED: ',TOTALPART
      WRITE(50,*)'PARTICLES TRACKED:  ',NP
```

```
      WRITE(50,*)'PARTICLES MISSED:  ',OOB
      WRITE(50,*)'TOTAL TRACKED & MISSED= ',NP+OOB
      WRITE(50,*)
C
      DO JS=0,KSA-1
       WRITE(50,*)'*****************************************************'
       DO IW=1,KW
C      WRITE(50,*)'LOCATION OF WELLS : ',
C     & ('WELL:',K,' (',MWX(K),',',MWY(K),')',' - ',K=1,NOW(IW))
         WRITE(50,*)'SAMPLING INTERVAL (DAYS):',ISA(JS)
         IF(DET(JS,IW).EQV..TRUE.)THEN
          DO K=1,NOW(IW)
           IF(MW(JS,IW,K).EQV..TRUE.)THEN
             WRITE(50,*)NOW(IW),'-WELLS, MONITORING WELL:',K,
     &         ' HAS DETECTED POLLUTION'
             WRITE(50,*)'DETECTION TIME= ',TOD(JS,IW),' OF ',TEND
           ENDIF
          ENDDO
         ELSEIF(DET(JS,IW).EQV..FALSE.)THEN
          WRITE(50,*)'NO DETECTION SUCCEEDED BY ',NOW(IW),
     &       ' MONITORING WELLS '
         ENDIF
C
        WRITE(50,*)
        WRITE(50,*)'POLLUTED VOLUME ON FAILURE=',NCAR(JS,IW)/LFAR
        WRITE(50,*)'POLLUTED VOLUME ON DETECTION=',CAR1(JS,IW)/LFAR
        WRITE(50,*)'POLLUTED VOLUME 3 MONTHS LATER=',CAR3(JS,IW)/LFAR
        WRITE(50,*)'POLLUTED VOLUME 6 MONTHS LATER=',CAR6(JS,IW)/LFAR
        WRITE(50,*)'POLLUTED VOLUME 12 MONTHS LATER=',CAR12(JS,IW)/LFAR
        WRITE(50,*)'POLLUTED VOLUME 24 MONTHS LATER=',CAR24(JS,IW)/LFAR
        WRITE(50,*)'POLLUTED VOLUME 36 MONTHS LATER=',CAR36(JS,IW)/LFAR
        WRITE(50,*)'----------------------------------------------------'
        WRITE(50,*)
       ENDDO
      ENDDO
C
C      PRINTING ON SCREEN
      PRINT*
      PRINT*,'TDC: ',TDC
      PRINT*,'TOT INJ:',TOTALPART,' / TRACKED:',NP,' / MISSED:',OOB,
     & ' / TOT TRACKED & MISSED=',NP+OOB
      PRINT*
C
C
  800 FORMAT('X=',I4,2X,'Y=',I4,2X,'Z=',I4)
  900  FORMAT('STARTING POINT OF POLLUTION: ','PX=',I3,2X,'PY=',I3,
     & 2X,'PZ=',I3)
C
      RETURN
      END
C
C
C---------------------------------------------------------------
C     NORMAL RANDOM NUMBER FUNCTION GENERATOR
C---------------------------------------------------------------
C
        FUNCTION RVNORMAL(SEED)
        IMPLICIT DOUBLE PRECISION (A-H,O-Z)
        DATA S,T / 0.449871,-0.386595 /
        DATA A,B / 0.19600,0.25472 /
        INTEGER SEED
C
  100   U=RANDM(SEED)
        V=RANDM(SEED)
        V=1.7156D0*(V-0.5D0)
        X=U-S
        Y=ABS(V)-T
        Q=X*X+Y*(A*Y-B*X)
```

```
C
            IF(V**2.GT.-4*LOG(U)*U**2) GOTO 100
            IF(Q.GT.0.27846) GOTO 100
            IF(Q.LT.0.27597) RVNORMAL=V/U
            RETURN
            END
C
C
C------------------------------------------------------------------
C      RANDOM NUMBER FUNCTION  (0-1 EQUAL PROBABLE)
C------------------------------------------------------------------
C
         FUNCTION RANDM(IDUM)
         INTEGER IDUM,IM1,IM2,IMM1,IA1,IQ1,IQ2,IR1,NTAB,NDIV
         DOUBLE PRECISION RANDM,AM,EPS,RNMX
         PARAMETER (IM1=2147483563,IM2=2147483399,AM=1.D0/IM1,IMM1=IM1-1,
        *      IA1=40014,IA2=40692,IQ1=53668,IQ2=52774,IR1=12211,
        *      NTAB=32,NDIV=1+IMM1/NTAB,EPS=1.2E-7,RNMX=1.D0-EPS)
         INTEGER IDUM2,J,K,IV(NTAB),IY
         SAVE IV,IY,IDUM2
         DATA IDUM2/123456789/,IV/NTAB*0/,IY/0/
         IF (IDUM.LE.0)THEN
            IDUM=MAX(-IDUM,1)
            IDUM2=IDUM
         DO 11 J=NTAB+8,1,-1
               K=IDUM/IQ1
               IDUM=IA1*(IDUM-K*IQ1)-K*IR1
               IF (IDUM.LT.0) IDUM=IDUM+IM1
               IF (J.LE.NTAB) IV(J)=IDUM
  11     CONTINUE
         IY=IV(1)
         ENDIF
         K=IDUM/IQ1
         IDUM=IA1*(IDUM-K*IQ1)-K*IR1
         IF (IDUM.LT.0) IDUM=IDUM+IM1
         K=IDUM2/IQ2
         IDUM2=IA2*(IDUM2-K*IQ2)
         IF (IDUM2.LT.0) IDUM2=IDUM+IM2
         J=1+IY/NDIV
         IY=IV(J)-IDUM2
         IV(J)=IDUM
         IF (IY.LT.1) IY=IY+IMM1
         RANDM=MIN(AM*IY,RNMX)
         RETURN
         END
C
C
C
C******************************************************************
C      SUBROUTINE LANDFL: LANDFILL'S SHAPE AND BOUNDARIES
C******************************************************************
C
         SUBROUTINE LANDF
         IMPLICIT DOUBLE PRECISION (A-H,O-Z)
         COMMON /PARAM/ P0,P1,EP,DX,DY,DZ,NX,NY,NZ,NSEED
         COMMON /LANDFILL/ LFXI,LFXE,LFYI,LFYE,LFAR,LFC
         INTEGER LFC(100000)
C
         NN=NX*NY
C
         DO I=1,NN
           LFC(I)=0
         ENDDO
C
C      --> RECTAGULAR LANDFILL <--
C      LANDFILL (COORDINATIONS IN METERS/D TO GET DIMENSIONLESS NUMBERS)
         LFXI=INT(10/DX)              !LANDFILL'S X INITIAL BOUNDARY LIMIT
         LFXE=INT(60/DX)             !LANDFILL'S X ENDING BOUNDARY LIMIT
```

```
      LFYI=INT(140/DY)          !LANDFILL'S Y INITIAL BOUNDARY LIMIT
      LFYE=INT(260/DY)          !LANDFILL'S Y ENDING BOUNDARY LIMIT
      LFAR=(LFXE-LFXI-1)*(LFYE-LFYI-1) !LF'S DIMENSIONLESS AREA (No OF
CELLS)
C
      DO J=1,NY
         DO I=1,NX
           IP=(J-1)*NX+I
           IF(J.GE.LFYI.AND.J.LE.LFYE.AND.I.GE.LFXI.AND.I.LT.LFXE)THEN
              LFC(IP)=1
           ENDIF
         ENDDO
      ENDDO
C
      RETURN
      END
C
C
C
C***************************************************************
C     SUBROUTINE RANDORIGIN: CREATING RANDOM ORIGIN POINT OF POLLUTION
C***************************************************************
C
      SUBROUTINE RANDORIGIN(RPX,RPY,ORPOS)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON /PARAM/ P0,P1,EP,DX,DY,DZ,NX,NY,NZ,NSEED
      COMMON /LANDFILL/ LFXI,LFXE,LFYI,LFYE,LFAR,LFC
      INTEGER ORPOS,LFC(100000)
C
      XL=ABS(LFXE-LFXI)
      YL=ABS(LFYE-LFYI)
      RPX=XL*RANDM(NSEED)+LFXI
      RPY=YL*RANDM(NSEED)+LFYI
      PX=INT(RPX)
      PY=INT(RPY)
      PZ=1
      IF(RPY-PY.GE.0.5)PY=PY+1       !COUNTS ON CENTRAL Y
      IF(RPX-PX.GE.0.5)PX=PX+1       !COUNTS ON CENTRAL X
C
      ORPOS=(PY-1)*NX+PX   ! INITIAL CUBIC ELEMENT POSITION OF PARTICLES
C
      WRITE(39,*)PX,PY
C
      RETURN
      END
C
C
C
C***************************************************************
C     SUBROUTINE WNDFS: WELLS' DISTANCE FROM SOURCE (NORMALIZED)
C***************************************************************
C
      SUBROUTINE WNDFS(SIGMA,AT,DFS)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
      IF(SIGMA.EQ.0.D0)THEN
        IF(AT.EQ.0.001D0)DFS=3.0D0
        IF(AT.EQ.0.01D0)DFS=2.25D0
        IF(AT.EQ.0.02D0)DFS=1.50D0
        IF(AT.EQ.0.05D0)DFS=0.50D0
        IF(AT.EQ.0.1D0)DFS=0.125D0
        IF(AT.EQ.0.2D0)DFS=0.030D0
        IF(AT.EQ.0.5D0)DFS=0.015D0
      ENDIF
C
      IF(SIGMA.EQ.0.25D0)THEN
        IF(AT.EQ.0.001D0)DFS=1.75D0
        IF(AT.EQ.0.01D0)DFS=1.50D0
```

```
        IF(AT.EQ.0.02D0)DFS=1.00D0
        IF(AT.EQ.0.05D0)DFS=0.50D0
        IF(AT.EQ.0.1D0)DFS=0.125D0
        IF(AT.EQ.0.2D0)DFS=0.30D0
        IF(AT.EQ.0.5D0)DFS=0.015D0
      ENDIF
C
      IF(SIGMA.EQ.0.50D0)THEN
        IF(AT.EQ.0.001D0)DFS=1.75D0
        IF(AT.EQ.0.01D0)DFS=1.50D0
        IF(AT.EQ.0.02D0)DFS=0.50D0
        IF(AT.EQ.0.05D0)DFS=0.50D0
        IF(AT.EQ.0.1D0)DFS=0.125D0
        IF(AT.EQ.0.2D0)DFS=0.030D0
        IF(AT.EQ.0.5D0)DFS=0.015D0
      ENDIF
C
      IF(SIGMA.EQ.0.75D0)THEN
        IF(AT.EQ.0.001D0)DFS=1.75D0
        IF(AT.EQ.0.01D0)DFS=1.25D0
        IF(AT.EQ.0.02D0)DFS=0.50D0
        IF(AT.EQ.0.05D0)DFS=0.25D0
        IF(AT.EQ.0.1D0)DFS=0.125D0
        IF(AT.EQ.0.2D0)DFS=0.030D0
        IF(AT.EQ.0.5D0)DFS=0.015D0
      ENDIF
C
      IF(SIGMA.EQ.1.D0)THEN
        IF(AT.EQ.0.001D0)DFS=1.75D0
        IF(AT.EQ.0.01D0)DFS=1.25D0
        IF(AT.EQ.0.02D0)DFS=0.50D0
        IF(AT.EQ.0.05D0)DFS=0.125D0
        IF(AT.EQ.0.1D0)DFS=0.0625D0
        IF(AT.EQ.0.2D0)DFS=0.030D0
        IF(AT.EQ.0.5D0)DFS=0.015D0
      ENDIF
C
      IF(SIGMA.EQ.1.5D0)THEN
        IF(AT.EQ.0.001D0)DFS=1.25D0
        IF(AT.EQ.0.01D0)DFS=1.00D0
        IF(AT.EQ.0.02D0)DFS=0.50D0
        IF(AT.EQ.0.05D0)DFS=0.125D0
        IF(AT.EQ.0.1D0)DFS=0.0625D0
        IF(AT.EQ.0.2D0)DFS=0.015D0
        IF(AT.EQ.0.5D0)DFS=0.015D0
      ENDIF
C
      IF(SIGMA.EQ.2.0D0)THEN
        IF(AT.EQ.0.001D0)DFS=0.75D0
        IF(AT.EQ.0.01D0)DFS=0.50D0
        IF(AT.EQ.0.02D0)DFS=0.25D0
        IF(AT.EQ.0.05D0)DFS=0.125D0
        IF(AT.EQ.0.1D0)DFS=0.0625D0
        IF(AT.EQ.0.2D0)DFS=0.015D0
        IF(AT.EQ.0.5D0)DFS=0.015D0
      ENDIF
C
      RETURN
      END
C
C
C
C***************************************************************
C     SUBROUTINE POLVOL: ESTIMATING THE POLLUTED VOLUME
C***************************************************************
      SUBROUTINE POLVOL(VOL)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
```

```
      PARAMETER (IMEM=1024000)
      COMMON /PARAM/ P0,P1,EP,DX,DY,DZ,NX,NY,NZ,NSEED
      COMMON /POLLUTION/ C,OOB
      INTEGER C(IMEM)
C
      NXNY=NX*NY
      VOL=0
      DO 50 K=1,NZ
        DO 50 J=1,NY
          DO 50 I=1,NX
            IP=(K-1)*NXNY+(J-1)*NX+I
            IF(C(IP).GT.0)VOL=VOL+1
   50 CONTINUE
C
      VOL=VOL+OOB     !PARTICLES OUT OF BOUNDARIES INCLUDED (1 CELL/PAR)
C
      RETURN
      END
C
C
C*****************************************************************
C     CALCULATING THE VELOCITY FIELD
C*****************************************************************
C
      SUBROUTINE VEL(RK,P,VELX,VELY,VELZ)
C
C     VELOCITIES ARE CALCULATED IN A SHIFTED GRID, EQUAL TO 1/2 IN RELATION
C     TO THE INITIAL GRID WHERE K AND H ARE CALCULATED. THIS MEANS THAT
C     VX(I+1/2,J,K), VY(I,J+1/2,K), VZ(I,J,K+1/2). CALCULATIONS OF VELOCITY
C     ONTO OTHER POINTS OF SIMULATION AREA MUST ACCOUNT FOR THIS SHIFT.
C     VELOCITIES ON INITIAL GRID NODES ARE LINEARLY INTERPOLATED,
C     BETWEEN I+1,I AND J+1,J.
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      PARAMETER (IMEM=1024000)
      DOUBLE PRECISION P(IMEM),RK(IMEM),VELX(IMEM),VELY(IMEM),VELZ(IMEM)
      DOUBLE PRECISION VELXI(IMEM),VELYI(IMEM),VELZI(IMEM)
      INTEGER TS,TEND,TPRD
      COMMON /PARAM/ P0,P1,EP,DX,DY,DZ,NX,NY,NZ,NSEED
      COMMON /TIME/ TS,TEND,TPRD,NSIM
C
C     INITIALIZATION OF MATRICES AND PARAMETERS
      DO I=1,IMEM
      VELXI(I)=0.D0
      VELYI(I)=0.D0
      VELZI(I)=0.D0
      VELX(I)=0.D0
      VELY(I)=0.D0
      VELZ(I)=0.D0
      ENDDO
C
      NXNY=NX*NY
C
C     CALCULATING
      DO 810 K=1,NZ
      DO 810 J=1,NY
      DO 810 I=1,NX
      IP=(K-1)*NXNY+(J-1)*NX+I
C
C     VELOCITY ON X AXIS (I+1/2)
      IF(I.GE.1.AND.I.LE.NX-1)THEN                 ! CALCULATING grad(H)
        GRADHX=(P(IP+1)-P(IP))/DX
        RKPX=2.D0*RK(IP+1)*RK(IP)/(RK(IP+1)+RK(IP))
        VELXI(IP)=RKPX*GRADHX/EP                   ! CALCULATING VELOCITY
      ENDIF
C
      IF(I.EQ.NX) VELXI(IP)=VELXI((K-1)*NXNY+(J-1)*NX+NX-1)
C
C     VELOCITY ON Y AXIS (J+1/2)
```

```
      IF(J.GE.1.AND.J.LE.NY-1)THEN                ! CALCULATING grad(H)
        GRADHY=(P(IP+NX)-P(IP))/DY
        RKPY=2.D0*RK(IP+NX)*RK(IP)/(RK(IP+NX)+RK(IP))
        VELYI(IP)=RKPY*GRADHY/EP                  ! CALCULATING VELOCITY
      ENDIF
C
      IF(J.EQ.NY) VELYI(IP)=VELYI((K-1)*NXNY+(J-1-1)*NX+I)
C
C     VELOCITY ON Z AXIS  (K+1/2)
      IF(K.GT.1.AND.K.LT.NZ)THEN                  ! CALCULATING grad(H)
        GRADHZ=(P(IP+NXNY)-P(IP))/DZ
        RKPZ=2.D0*RK(IP+NXNY)*RK(IP)/(RK(IP+NXNY)+RK(IP))
        VELZI(IP)=RKPZ*GRADHZ/EP                   ! CALCULATING VELOCITY
      ENDIF
C
      IF(K.EQ.NZ) VELZI(IP)=VELZ((K-1-1)*NXNY+(J-1)*NX+I)
C
  810 CONTINUE
C
C     LINEARLY INTERPOLATING VELOCITIES ON (I,J)
C     VELOCITY ON X AXIS [(I+1/2)+(I-1/2)]/2
      DO 820 K=1,NZ
       DO 820 J=1,NY
         DO 820 I=2,NX-1
           IP=(K-1)*NXNY+(J-1)*NX+I
           IB=(K-1)*NXNY+(J-1)*NX+I-1
           VELX(IP)=(VELXI(IP)+VELXI(IB))/2.D0
  820 CONTINUE
C
C     VELOCITY ON Y AXIS [(J+1/2)+(J-1/2)]/2
      DO 830 K=1,NZ
       DO 830 J=2,NY-1
         DO 830 I=1,NX
           IP=(K-1)*NXNY+(J-1)*NX+I
           IB=(K-1)*NXNY+(J-1-1)*NX+I
           VELY(IP)=(VELYI(IP)+VELYI(IB))/2.D0
  830 CONTINUE
C
C     VELOCITY ON (NX,J) SIDE
      DO J=1,NY
         IP=(J-1)*NX+1
         IE=(J-1)*NX+NX
         VELX(IP)=VELXI(IP)
         VELX(IE)=VELXI(IE)
      ENDDO
C
C     VELOCITY ON (I,NY) SIDE
      DO I=1,NX
         IE=(NY-1)*NX+I
         VELY(I)=VELYI(I)
         VELX(IE)=VELXI(IE)
      ENDDO
C
C
C     REMOVING DIMENSIONS (VELOCITY IN DX/TS M/DAY UNITS)
      DO 850 K=1,NZ
       DO 850 J=1,NY
         DO 850 I=1,NX
            IP=(K-1)*NXNY+(J-1)*NX+I
            VELX(IP)=VELX(IP)/(DX/TS)
            VELY(IP)=VELY(IP)/(DY/TS)
            VELZ(IP)=VELZ(IP)/(DZ/TS)
  850 CONTINUE
C
C
      RETURN
      END
C
```

```
C
C***************************************************************
C       3D HYBRID VELOCITY INTERPOLATION SCEME SUBROUTINES
C***************************************************************
C
C
      SUBROUTINE VCL(XPR,YPR,ZPR,VLX,VLY,VLZ)
C
C***************************************************************
C     LINEAR VELOCITY INTERPOLATION
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      PARAMETER (IMEM=1024000)
C
      DOUBLE PRECISION VELX(IMEM),VELY(IMEM),VELZ(IMEM)
C
      COMMON /VELOCITY/ VELX,VELY,VELZ
      COMMON /PARAM/ P0,P1,EP,DX,DY,DZ,NX,NY,NZ,NSEED
C
C
      NXNY=NX*NY
      VLX=0.D0
      VLY=0.D0
      VLZ=0.D0
      I=INT(XPR)
      J=INT(YPR)
      K=INT(ZPR)
C
      FX=XPR-INT(XPR)
      FY=YPR-INT(YPR)
C
C     ---------------- X-AXIS -----------------------------------
      IF(INT(XPR).GE.1.AND.INT(XPR).LE.NX-1)THEN
         VLX=(DX-FX)*VELX((K-1)*NXNY+(J-1)*NX+I)+
     &         FX*VELX((K-1)*NXNY+(J-1)*NX+I+1)
      ENDIF
C
      IF(INT(XPR).EQ.NX)VLX=VELX((K-1)*NXNY+(J-1)*NX+NX)
C
C
C     ---------------- Y-AXIS -----------------------------------
      IF(INT(YPR).GE.1.AND.INT(YPR).LE.NY-1)THEN
         VLY=(DY-FY)*VELY((K-1)*NXNY+(J-1)*NX+I)+
     &         FY*VELY((K-1)*NXNY+(J-1+1)*NX+I)
       ENDIF
C
      IF(INT(YPR).EQ.NY)VLY=VELY((K-1)*NXNY+(NY-1)*NX+I)
      RETURN
      END
C
C
C
C***************************************************************
C
      SUBROUTINE VCB(XPR,YPR,ZPR,VBX,VBY,VBZ)
C
C***************************************************************
C     BILINEAR VELOCITY INTERPOLATION
C
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      PARAMETER (IMEM=1024000)
C
      DOUBLE PRECISION VELX(IMEM),VELY(IMEM),VELZ(IMEM)
C
      COMMON /VELOCITY/ VELX,VELY,VELZ
      COMMON /PARAM/ P0,P1,EP,DX,DY,DZ,NX,NY,NZ,NSEED
C
```

```
C
      NXNY=NX*NY
      VBX=0.D0
      VBY=0.D0
      VBZ=0.D0
      I=INT(XPR)
      J=INT(YPR)
      K=INT(ZPR)
C
      FX=XPR-INT(XPR)
      FY=YPR-INT(YPR)
C
C     ---------------- X-AXIS -----------------------------------
      IF(INT(XPR).GE.1.AND.INT(XPR).LE.NX-1.AND.INT(YPR).LE.NY-1)THEN
         BVX1=(DX-FX)*(DY-FY)*VELX((K-1)*NXNY+(J-1)*NX+I)
         BVX2=FX*(DY-FY)*VELX((K-1)*NXNY+(J-1)*NX+I+1)
         BVX3=(DX-FX)*FY*VELX((K-1)*NXNY+(J-1+1)*NX+I)
         BVX4=FX*FY*VELX((K-1)*NXNY+(J-1+1)*NX+I+1)
         VBX=BVX1+BVX2+BVX3+BVX4
      ENDIF
C
      IF(INT(XPR).EQ.NX)VBX=VELX((K-1)*NXNY+(J-1)*NX+NX)
C
C     ---------------- Y-AXIS -----------------------------------
      IF(INT(YPR).GE.1.AND.INT(YPR).LE.NY-1.AND.INT(XPR).LE.NX-1)THEN
         BVY1=(DX-FX)*(DY-FY)*VELY((K-1)*NXNY+(J-1)*NX+I)
         BVY2=FX*(DY-FY)*VELY((K-1)*NXNY+(J-1)*NX+I+1)
         BVY3=(DX-FX)*FY*VELY((K-1)*NXNY+(J-1+1)*NX+I)
         BVY4=FX*FY*VELY((K-1)*NXNY+(J-1+1)*NX+I+1)
         VBY=BVY1+BVY2+BVY3+BVY4
      ENDIF
C
      IF(INT(YPR).EQ.NY)VBY=VELX((K-1)*NXNY+(NY-1)*NX+I)
      RETURN
      END
```

A-2 Precipitation Event Pollution Source Code

```
      PROGRAM TBRW
C
C     Last change:  28 FEB 2012
C     CASES RAIN DATA INPUT
C     LANDFILL RECTAGULAR
C     ONE INPUT FILE IS REQUIRED: TUBA211.INC
C
C-----------------------------------------------------------------------
C     FLOW MODELLING
C     LOGNORMAL MEDIA
C     CORRELATED CONDUCTIVITY FIELD
C     2-D TURNING BANDS METHOD (TUBA)
C     DOUBLE PRECISION USED
C     HYBRID INTERPOLATION VELOCITY SCHEME
C
C     PARAMETER IDENTIFICATION:
C       IMEM= 1024000 MAX PARTICLES
C       KW=8 MONITORING WELLS ARRANGEMENT (1,2,3,4,6,8,12,20)
C       KSA=7 SAMPLING FREQUENCIES (1,30,60,90,120,180,360 DAYS)
C       MDS=7 DISPERSION CASES (0.001,0.01,0.02,0.05,0.10,0.20,0.50 M)
C
C-----------------------------------------------------------------------
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
C     MUST CHANGE IN FLOW3D,VELOCITY,RANDOMWALK,INTERVEL SUBROUTINES TOO
      PARAMETER (IMEM=1024000)
      PARAMETER (KW=8,KSA=7,MDS=5)
C     KW:No OF WELLS, KSA:SAMPLING INTERVALS, MDS:TRANSVERSE DISPERSION
C
C     DIMENSION RVARIO(300),GAM(300)
      DOUBLE PRECISION P(IMEM),VELX(IMEM),VELY(IMEM),VELZ(IMEM),RK(IMEM)
      DOUBLE PRECISION  TATOD(MDS,0:KSA-1,KW),ATOD(0:KSA-1,KW),
     & TDCM(MDS)
      DOUBLE PRECISION NCAR(0:KSA-1,KW),CAR1(0:KSA-1,KW),
     & CAR3(0:KSA-1,KW),CAR6(0:KSA-1,KW),CAR12(0:KSA-1,KW),
     & CAR24(0:KSA-1,KW),CAR36(0:KSA-1,KW),TNCAR(MDS,0:KSA-1,KW),
     & TCAR1(MDS,0:KSA-1,KW),TCAR3(MDS,0:KSA-1,KW),TCAR6(MDS,0:KSA-1,
     & KW),TCAR12(MDS,0:KSA-1,KW),TCAR24(MDS,0:KSA-1,KW),
     & TCAR36(MDS,0:KSA-1,KW),RAIN(10950)
      INTEGER TS,TEND,TPRD,SNSIM,TVC,TDET(MDS,0:KSA-1,KW),FDET(MDS,
     & 0:KSA-1,KW),NOW(KW),ISA(0:KSA-1),ORPOSO,PX,PY,PZ,LFC(100000),
     & NPAR(10950)
      LOGICAL DET(0:KSA-1,KW),MONITOR
      CHARACTER SDATE_R*8,DATE_R*8,T_R*10,ST_R*10
C
      COMMON /PARAM/ P0,P1,EP,DX,DY,DZ,NX,NY,NZ,NSEED
      COMMON /SOLVE/ OMEGA,TOL,TOL1,MITER,SNSIM
      COMMON /VELOCITY/ VELX,VELY,VELZ
      COMMON /PARTICLE/ PM,TVC,NPAR
      COMMON /LANDFILL/ LFXI,LFXE,LFYI,LFYE,LFAR,LFC
      COMMON /MONITORING/ SIGMA,MONITOR,NOW,ISA
      COMMON /TIME/ TS,TEND,TPRD,NSIM
      COMMON /WAREA/ NCAR,CAR1,CAR3,CAR6,CAR12,CAR24,CAR36
C
C-----------------------------------------------------------------------
C-    GRID SPACING FOR TURNING BAND SIMULATIONS IN X
C-     DIFFERENT FROM ABOVE SO AS TO CREATE ANISOTROPY. NOTE
C-     THAT TURNING BAND ROUTINE CAN ONLY SIMULATE ISOTROPIC
C-     FIELDS AND THAT, TO GENERATE ANISOTROPIC FIELDS, YOU HAVE
C-     TO TRANSFORM THE GRID SPACING....
C-----------------------------------------------------------------------
C
C------HETEREOGENITY OF THE FIELD ---------------------------------------
C
```

```
      SIGMA=1.00D0
C
C------PARAMETER INITIALIZATION------------------------------------------
C
      NSIM=50                !NUMBER OF SIMULATIONS
C
      TEND=10950                !TIME MONITOR ENDS (30 YEARS)
      TPRD=10950                 !PERIOD OF TIME THAT LEAK OCCURS
      TS=1                      !TIME STEP (DAYS)
C
      LNDFX=1000                !LENGHT OF SIMULATION AREA (METERS)
      LNDFY=400                 !WIDTH OF SIMULATION AREA (METERS)
      LNDFZ=1                   !DEPTH OF SIMULATION AREA (METERS)
      DX=2                      !DX STEP ON X AXIS (METERS)
      DY=2                      !DY STEP ON Y AXIS (METERS)
      DZ=1                      !DZ STEP ON X AXIS (METERS)
      NX=INT(LNDFX/DX)          !NODES IN X-DIRECTION (DIMENSIONLESS)
      NY=INT(LNDFY/DY)          !NODES IN Y-DIRECTION (DIMENSIONLESS)
      NZ=INT(LNDFZ/DZ)          !NODES IN Z-DIRECTION (DIMENSIONLESS)
C
      DL=0.D0                   !TB BLOCK DIMENSION
      DC=0.D0                   !TB BLOCK DIMENSION
      DN=0.D0                   !TB BLOCK DIMENSION
C
      A=20.D0                   !CORELLATION COEFFICIENT (METERS)
      A=(-1.D0)*ABS(A)
      HEADG=0.001D0
      P0=0.D0                   !STARTING HYDRAULIC HEAD
      P1=NX*DX*HEADG            !ENDING HYDRAULIC HEAD
      EP=0.25D0                 !EFFECTIVE POROSITY
      ALPHA=2.3D0               !MEAN lnK
C
C     CONTAMINATION PARTICLES CALCULATION
      PM=28                      !PARTICLE'S MASS
      TVC=28                  !THRESHOLD VOLUMETRIC CONCENTRATION
      NTPART=0
C
C     READING RAIN HEIGHT (mm) DATA
      OPEN(20,FILE='RAIN30.TXT',STATUS='OLD')
      DO I=1,TPRD
        READ(20,*) RAIN(I)
        NPAR(I)=INT(RAIN(I)*PM)
        NTPART=NTPART+NPAR(I)
C         PRINT*,I,NPAR(I),NTPART
      ENDDO
      CLOSE(20)
C
C
      MONITOR=.TRUE.            !PARAMETER THAT CONTROLS IF WE MONITOR OR NOT
C
C     RANDOM NUMBER SEEDS
      DSEED=2147811051.D0       !seed number for RNG`
      NSEED=1236541350          !15.8
C
C
C-    BETA FOR NOW ON IS THE STANDARD DEVIATION NOT THE VARIANCE
      BETA=SQRT(SIGMA)
C
      TOL=0.00001D0
      TOL1=0.00005D0
      MITER=2000
      SNSIM=0                    ! NUMBER OF SIMULATIONS WITH FLOW FIELD
SOLUTION
      NNNN=NX*NY*NZ
      NXNY=NX*NY
      DSEED=DSEED*NXNY*NY*BETA*DX/(NSIM*NSIM)
      SSXEN=0.D0
      RKPOIN21=0.D0
```

```
      RKPOIN22=0.D0
      RKPOINT1=0.D0
      RKPOINT2=0.D0
      SSX2EN=0.D0
C
      DO 22 K=1,MDS
        DO 22 J=0,KSA-1
          DO 22 I=1,KW
            TDET(K,J,I)=0
            FDET(K,J,I)=0
            TATOD(K,J,I)=0.D0
   22 CONTINUE
C
C     FLOW EQUATIONS RELAXATION FACTOR
C     — DEPEDENCE HAS BEEN OBSERVED. BEST RESULTS (?) ARE ACCOMPLISHED
C     WHEN RELAXATION FACTOR IS THE HIGHER POSSIBLE (INITIAL WAS 1.85)
      OMEGA0=1.85D0
C
      IF(nnnn.GE.180000)OMEGA0=1.88D0
      IF(nnnn.GE.240000)OMEGA0=1.91D0
      IF(nnnn.GE.390000)OMEGA0=1.92D0
      IF(nnnn.GE.490000)OMEGA0=1.95D0
      IF(nnnn.GE.700000)OMEGA0=1.97D0
      IF(nnnn.GE.850000)OMEGA0=1.98D0
      IF(nnnn.GE.850000)TOL=0.0001D0
      IF(nnnn.GE.850000)TOL1=0.0005D0
C
C
C     PRINTING ON SCREEN THE STARTING TIME
      CALL DATE_AND_TIME (SDATE_R,ST_R)
C
C     3-D TB INPUT DATA (BLOCK DIMENSIONS)
      IF(DL.EQ.0.0)DL=DX
      IF(DC.EQ.0.0)DC=DY
      IF(DN.EQ.0.0)DN=DZ
C
C
C -----PRINTING INITIAL INFORMATION-------------------------------------
C
      PRINT*,'THIS IS THE TOTAL PLUME TRANSPORT SIMULATION!'
      PRINT*,'NUMBER OF REALIZATIONS :',NSIM
      PRINT 715,NX,NY,NZ
      PRINT 716,DX,DY,DZ
      PRINT 717,DL,DC,DN
C
  715 FORMAT(' GRID SIZE :  ',I3,'X',I3,'X',I3)
  716 FORMAT(' BLOCK DIMENSIONS    : ',F5.2,' X',F5.2,' X',F5.2)
  717 FORMAT(' TB BLOCK DIMENSIONS : ',F5.2,' X',F5.2,' X',F5.2)
C
      PRINT*,'CORRELATION RANGE (LENGTH UNITS) : ',A
      PRINT*,'                       & VARIANCE : ',BETA*BETA
      PRINT*
      PRINT*,'       ******* STARTING SIMULATIONS *******'
      PRINT*
C
C
C------ESTABLISHING MONITOR SYSTEM AND SAMPLING POLICY---------------
C     LANDFILL'S GEOMETRY
      CALL LANDF
C
C     NUMBER OF WELLS
      DO IW=1,KW
        IF(IW.LE.4)NOW(IW)=IW
        IF(IW.EQ.5)NOW(IW)=6
        IF(IW.EQ.6)NOW(IW)=8
        IF(IW.EQ.7)NOW(IW)=12
        IF(IW.EQ.8)NOW(IW)=20
      ENDDO
```

```
C
C     SAMPLING INTERVALS
      DO JS=0,KSA-1
        IF(JS.GE.1.AND.JS.LE.4) ISA(JS)=JS*30
        IF(JS.EQ.0) ISA(JS)=1
        IF(JS.EQ.5) ISA(JS)=180
        IF(JS.EQ.6) ISA(JS)=365
      ENDDO
C
C     DISPERSIVITY FACTOR
      DO MTDC=1,MDS
        IF(MTDC.EQ.1) TDCM(MTDC)=0.001D0
        IF(MTDC.EQ.2) TDCM(MTDC)=0.01D0
C        IF(MTDC.EQ.3) TDCM(MTDC)=0.02D0
        IF(MTDC.EQ.3) TDCM(MTDC)=0.05D0
        IF(MTDC.EQ.4) TDCM(MTDC)=0.10D0
C        IF(MTDC.EQ.6) TDCM(MTDC)=0.20D0
        IF(MTDC.EQ.5) TDCM(MTDC)=0.50D0
      ENDDO
C
C     INITIALISING AVERAGE CONTAMINATED CELL AREA
      DO 28 MTDC=1,MDS
       DO 28 JS=0,KSA-1
        DO 28 IW=1,KW
          TNCAR(MTDC,JS,IW)=0.D0
          TCAR1(MTDC,JS,IW)=0.D0
          TCAR3(MTDC,JS,IW)=0.D0
          TCAR6(MTDC,JS,IW)=0.D0
          TCAR12(MTDC,JS,IW)=0.D0
          TCAR24(MTDC,JS,IW)=0.D0
          TCAR36(MTDC,JS,IW)=0.D0
   28 CONTINUE
C
C
C -----CREATING REPORT FILES ---------------------------------------------
      OPEN(9,FILE='ERROR.TXT',STATUS='REPLACE')
C      OPEN(11,FILE='RESULTS.TXT',STATUS='REPLACE')
C      OPEN(14,FILE='K_EXAMPLE.TXT',STATUS='UNKNOWN')
C      OPEN(22,FILE='VELOCITIES_EXAMPLE.TXT',STATUS='UNKNOWN')
C      OPEN(23,FILE='HEADS_EXAMPLE.TXT',STATUS='UNKNOWN')
      OPEN(48,FILE='PROBALITIES.TXT',STATUS='UNKNOWN')
      OPEN(39,FILE='SOURCE.TXT',STATUS='UNKNOWN')
      OPEN(50,FILE='RWREPORT.TXT',STATUS='UNKNOWN')
C
      SNSIMOLD=0     ! PARAMETER THAT CONTROLS PROBABILITIES FILE OUTPUT
C
C
C*************************************************************************
C------LOOP ON THE NUMBER OF SIMULATIONS--------------------------------
C
      IS=0
      DOWHILE(SNSIM.LT.NSIM)             ! BASIC SIMULATION LOOP BEGINS
C
      IS=IS+1                            !SIMULATION COUNTER
C
      CALL DATE_AND_TIME (DATE_R,T_R)
C
      WRITE(9,719)IS,NSIM,t_r(1:2),t_r(3:4),t_r(5:6)
      PRINT 718,IS,INT(SNSIM)+1,NSIM,SNSIM*100./NSIM,T_R(1:2),
     & T_R(3:4),T_R(5:6)
C
 718  FORMAT('TOT.SIM.No:',I4,2X,' SIM.No:',I4,' OF ',I4,3X,
     +  F4.1,1X,'% COMPLETED ',' START TIME:  ',A2,':',A2,':',A2)
 719  FORMAT('SIM #',I4,'/',I4,3X,'START TIME:  ',A2,':',A2,':',A2)
C
C
C------SIMULATE STANDARD NORMAL DEVIATES BY TURNING BANDS---------------
C-
```

```
C
      PRINT*
      PRINT*,'   STARTING TURNING BANDS ALGORITHM ...   '
      CALL TUBA(NX,NY,DX,DY,ALPHA,BETA,-A,RK)
C
C
C------CALCULATING MEAN ENSAMBLE MEAN AND VARIANCE----------------------
C
      SUM=0.D0
      SSX=0.D0
      SSX2=0.D0
      RKPOINT1=RKPOINT1+BETA*RK(432)
      RKPOINT2=RKPOINT2+BETA*RK(845)
      RKPOIN21=RKPOIN21+BETA*BETA*RK(432)*RK(432)
      RKPOIN22=RKPOIN22+BETA*BETA*RK(845)*RK(845)
      DO 12 K=1,NZ
        DO 12 J=1,NY
          DO 12 I=1,NX
            IP=(K-1)*NXNY+(J-1)*NX+I
C            TEMP=ALPHA+BETA*RK(IP)
            TEMP=RK(IP)
            SSX=SSX+TEMP
            SSX2=SSX2+TEMP*TEMP
            TEMP=EXP(TEMP)
            RK(IP)=TEMP
            SUM=SUM+TEMP
            P(IP)=P0+(P1-P0)*(I-0.5D0)/NX
  12  CONTINUE
C
      SSX=SSX/NNNN
      SSXEN=SSXEN+SSX
      SSX2EN=SSX2EN+(SSX2/NNNN)
      SSX2=SSX2/NNNN-SSX*SSX
C
C
C------SOLVE FLOW EQUATION----------------------------------------------
C
      PRINT*,'   STARTING TO SOLVE THE FLOW PROBLEM ...   '
C
      OMEGA=OMEGA0
      CHECKSNSIM=SNSIM               ! KEEPING OLD VALUE OF SOLVED CASES
C
      CALL FLOW3D(RK,P,ICON,DMAX)
C
C
C     !!! PROCEED ONLY IF THERE IS A SOLUTION OF THE FLOW PROBLEM !!!
      IF(SNSIM.GT.CHECKSNSIM)THEN       ! CHECKING
C
C------CALCULATING THE VELOCITY FIELD FOR EACH REALISATION--------------
C
      PRINT*,'   STARTING TO CALCULATE THE VELOCITY FIELD ...   '
C
      CALL VEL(RK,P,VELX,VELY,VELZ)
      PRINT*,'     Velocity Field Calculated!'
      PRINT*
C
C
C------OUTPUT VALUES FOR VELOCITIES,K AND H FOR VISUALIZATION PURPOSES--
C      IF(SNSIM.EQ.NSIM)THEN
C
C      DO 221 K=1,NZ
C        DO 221 J=1,NY
C          DO 221 I=1,NX
C            IP=(K-1)*NXNY+(J-1)*NX+I
C            WRITE(14,667)I,J,K,RK(IP)
C            WRITE(22,668)I,J,K,VELX(IP),VELY(IP),VELZ(IP)
C            WRITE(23,667)I,J,K,P(IP)
C  221 CONTINUE
```

```
C       ENDIF
C
C 667   FORMAT(3(I4,1X),F10.4)
C 668   FORMAT(3(I4,1X),3(F9.6,1X))
C
C
C------CREATING AND MONITOR POLLUTION--------------------------------
        IF(MONITOR.EQV..TRUE.)THEN
          PRINT*,'   CREATING AND MONITOR POLLUTION ...     '
        ELSE
          PRINT*,'   CREATING POLLUTION ...     '
        ENDIF
C
        CALL RANDORIGIN(XO,YO,ORPOSO) ! DERMINING POLLUTION ORIGIN
          PX=INT(XO)
          PY=INT(YO)
          PZ=1
          IF(YO-PY.GE.0.5)PY=PY+1       !COUNTS ON CENTRAL Y
          IF(XO-PX.GE.0.5)PX=PX+1       !COUNTS ON CENTRAL X
        PRINT*
        PRINT 900,PX,PY,PZ
C
       DO 115 MTDC=1,MDS            ! LOOP OVER DIRPERSION FACTOR
        TDC=TDCM(MTDC)
        WRITE(50,*)'TDC=',TDC
        CALL RANDOMWALK(IS,TDC,XO,YO,ORPOSO,DET,ATOD)
C
        DO 125 JS=0,KSA-1
          DO 130 IW=1,KW                       ! MULTI-WELL LOOP
           IF(DET(JS,IW).EQV..TRUE.)THEN
             TDET(MTDC,JS,IW)=TDET(MTDC,JS,IW)+1
           ELSEIF(DET(JS,IW).EQV..FALSE.)THEN
             FDET(MTDC,JS,IW)=FDET(MTDC,JS,IW)+1
           ENDIF
C
C       CALCULATING CONTAMINATED AREA
        TNCAR(MTDC,JS,IW)=TNCAR(MTDC,JS,IW)+NCAR(JS,IW)
        TCAR1(MTDC,JS,IW)=TCAR1(MTDC,JS,IW)+CAR1(JS,IW)
        TCAR3(MTDC,JS,IW)=TCAR3(MTDC,JS,IW)+CAR3(JS,IW)
        TCAR6(MTDC,JS,IW)=TCAR6(MTDC,JS,IW)+CAR6(JS,IW)
        TCAR12(MTDC,JS,IW)=TCAR12(MTDC,JS,IW)+CAR12(JS,IW)
        TCAR24(MTDC,JS,IW)=TCAR24(MTDC,JS,IW)+CAR24(JS,IW)
        TCAR36(MTDC,JS,IW)=TCAR36(MTDC,JS,IW)+CAR36(JS,IW)
C
C       CALCULATING AVERAGE TIME OF DETECTION
        TATOD(MTDC,JS,IW)=TATOD(MTDC,JS,IW)+ATOD(JS,IW)
C
C
       IF(IW.EQ.7.AND.MTDC.EQ.5.AND.JS.EQ.0.AND.(SNSIM.EQ.1.OR.SNSIM
     & .NE.SNSIMOLD))THEN
       WRITE(48,*) SNSIM,NOW(IW),1.*TDET(MTDC,JS,IW)/SNSIM
       SNSIMOLD=SNSIM
       PRINT*, 'HI',NOW(IW)
       ENDIF
C
  130   CONTINUE                               ! CLOSING MULTI-WELL LOOP
C
  125  CONTINUE                                ! CLOSING SAMPLING LOOP
        WRITE(50,*)'**************************************************'
        WRITE(50,*)'**************************************************'
        WRITE(50,*)'**************************************************'
        WRITE(50,*)
C
        IF(JS.EQ.KSA.AND.IW.EQ.KW)GOTO 115
        PRINT*,'--------------------------------------------------'
C
  115 CONTINUE                                ! DISPERSION LOOP
C
```

```
      ENDIF                                 ! CHECKING IF
C
      PRINT*,'**********************************************************
     &*********'
      PRINT*,'**********************************************************
     &*********'
      PRINT*
      PRINT*
      ENDDO                                 ! CLOSING SIMULATION LOOP
C
C***********************************************************************
C
C
C------CALCULATE THE ENSEMBLE STATISTICS AND WRITE THE RESULTS----------
C-
         ALLREP=1.D0*IS
         RKPOINT1=RKPOINT1/ALLREP
         RKPOIN21=RKPOIN21/ALLREP-RKPOINT1*RKPOINT1
         RKPOINT2=RKPOINT2/ALLREP
         RKPOIN22=RKPOIN22/ALLREP-RKPOINT2*RKPOINT2
         SSXEN=SSXEN/ALLREP
         SSX2EN=SSX2EN/ALLREP-SSXEN*SSXEN
C
C       CONTAMINATED AREA RELATIVE TO LANDFILL'S AREA FOR EACH PERIOD
      DO 510 MTDC=1,MDS
        DO 510 JS=0,KSA-1
         DO 510 IW=1,KW
          IF(FDET(MTDC,JS,IW).NE.0)TNCAR(MTDC,JS,IW)=(TNCAR(MTDC,JS,IW)/
     &      FDET(MTDC,JS,IW))/LFAR
          IF(TDET(MTDC,JS,IW).NE.0)THEN
           TCAR1(MTDC,JS,IW)=(TCAR1(MTDC,JS,IW)/TDET(MTDC,JS,IW))/LFAR
           TCAR3(MTDC,JS,IW)=(TCAR3(MTDC,JS,IW)/TDET(MTDC,JS,IW))/LFAR
           TCAR6(MTDC,JS,IW)=(TCAR6(MTDC,JS,IW)/TDET(MTDC,JS,IW))/LFAR
           TCAR12(MTDC,JS,IW)=(TCAR12(MTDC,JS,IW)/TDET(MTDC,JS,IW))/LFAR
           TCAR24(MTDC,JS,IW)=(TCAR24(MTDC,JS,IW)/TDET(MTDC,JS,IW))/LFAR
           TCAR36(MTDC,JS,IW)=(TCAR36(MTDC,JS,IW)/TDET(MTDC,JS,IW))/LFAR
C
C         AVERAGE TIME OF DETECTION
          TATOD(MTDC,JS,IW)=TATOD(MTDC,JS,IW)/TDET(MTDC,JS,IW)
C
        ENDIF
  510 CONTINUE
C
C------WRITTING OUTPUT--------------------------------------------------
      OPEN(16,FILE='FINAL_REPORT.TXT',STATUS='UNKNOWN')
      OPEN(17,FILE='Pd_EXCEL.TXT',STATUS='UNKNOWN')
      OPEN(18,FILE='TOTAL_EXCEL.TXT',STATUS='UNKNOWN')
C
      PRINT*
      WRITE(*,*)'TOTAL FIELD SIMULATIONS: ',NSIM
      WRITE(*,*) 'NUMBER THAT FLOW FIELD WAS SIMULATED: ',SNSIM
C
      CALL DATE_AND_TIME (DATE_R,T_R)
C
      WRITE(16,*)'THIS IS THE FINAL REPORT:'
      WRITE(16,*)
      WRITE(16,*)'TOTAL FIELD SIMULATIONS: ',NSIM
      WRITE(16,*) 'NUMBER THAT FLOW FIELD WAS SIMULATED: ',SNSIM
      WRITE(16,*)
      WRITE(16,*)'START TIME : ',ST_R(1:2),':',ST_R(3:4),':',ST_R(5:6),
     +  '  AT ',SDATE_R(5:6),'/',SDATE_R(7:8),'/',SDATE_R(3:4)
      WRITE(16,*)'END TIME : ',T_R(1:2),':',T_R(3:4),':',T_R(5:6),
     +  '  AT ',DATE_R(5:6),'/',DATE_R(7:8),'/',DATE_R(3:4)
      WRITE(16,811)NX,NY,NZ
      WRITE(16,812)DX,DY,DZ
      WRITE(16,813)DL,DC,DN
      WRITE(16,*)
C
```

```
      PRINT*
      PRINT*
      WRITE(16,*)'START TIME : ',ST_R(1:2),':',ST_R(3:4),':',ST_R(5:6),
     +  '  AT ',SDATE_R(5:6),'/',SDATE_R(7:8),'/',SDATE_R(3:4)
      PRINT*,'END TIME : ',T_R(1:2),':',T_R(3:4),':',T_R(5:6),
     +  '  AT ',DATE_R(5:6),'/',DATE_R(7:8),'/',DATE_R(3:4)
      PRINT 811,NX,NY,NZ
      PRINT 812,DX,DY,DZ
      PRINT 813,DL,DC,DN
C
 811  FORMAT(' GRID SIZE :  ',I3,'X',I3,'X',I3)
 812  FORMAT(' BLOCK DIMENSIONS    : ',F5.2,'X',F5.2,'X',F5.2)
 813  FORMAT(' TB BLOCK DIMENSIONS : ',F5.2,'X',F5.2,'X',F5.2)
 900  FORMAT('STARTING POINT OF POLLUTION: ','PX=',I3,2X,'PY=',I3,
     & 2X,'PZ=',I3)
C
      WRITE(16,*)
      WRITE(16,*)'THE ENS.MEAN IS:',SSXEN,' AND THE ENS.VAR IS:',SSX2EN
      WRITE(16,*)'THE ENS.MEAN IN TWO POINTS IS : ',RKPOINT1,RKPOINT2
      WRITE(16,*)'  AND THE ENS. VARIANCE IS : ',RKPOIN21,RKPOIN22
      WRITE(16,*)
      WRITE(16,*)'CORRELATION SCALE = ',A,' WITH ',SNSIM,'  SIMULATIONS'
      WRITE(16,*)'INITIAL HEAD: ',HEADG
      WRITE(16,*)'No OF PARTICLES:',TOTALPART
      WRITE(16,*)'TVC:',TVC,' PARTICLES'
      WRITE(16,*)'VARIANCE : ',BETA*BETA
      WRITE(16,*)
C
C     DETECTION REPORT FILE
      WRITE(16,*)
      WRITE(16,*)'No OF SIMULATION=',SNSIM
      WRITE(16,*)'TOTAL MONITOR TIME=',TEND
      WRITE(16,*)
      DO MTDC=1,MDS
       WRITE(16,*)'DISPERSION FACTOR:',TDCM(MTDC)
       DO 512 JS=0,KSA-1
        WRITE(16,*)'*************************************************'
        WRITE(16,*)'SAMPLING TIME INTERVALS (DAYS): ',ISA(JS)
        WRITE(16,*)'          -----------           '
        DO 512 IW=1,KW
          WRITE(16,*)'NUMBER OF MONITOR WELLS : ',NOW(IW)
          WRITE(16,*)'NORMALIZED DISTANCE AMONG WELLS: ',1./NOW(IW)
          WRITE(16,*)'DETECTED POLLUTION=',TDET(MTDC,JS,IW)
          WRITE(16,*)'NOT DETECTED POLLUTION=',FDET(MTDC,JS,IW)
          WRITE(16,*)'PROBABILITY OF DETECTION=',100.*TDET(MTDC,JS,IW)/
     &     SNSIM,'%'
          WRITE(16,*)'PROBABILITY OF FAILURE=',100.*FDET(MTDC,JS,IW)/
     &     SNSIM,'%'
          WRITE(16,*)
          WRITE(16,*)'AVERAGE TIME OF CONTAMINATION DETECTION=',
     &     TATOD(MTDC,JS,IW)
          WRITE(16,*)
          WRITE(16,*)'AVERAGE POLLUTED VOLUME ON FAILURE=',
     &     TNCAR(MTDC,JS,IW)
          WRITE(16,*)'AVERAGE POLLUTED VOLUME ON DETECTION=',
     &     TCAR1(MTDC,JS,IW)
          WRITE(16,*)'AVERAGE POLLUTED VOLUME 3 MONTHS LATER=',
     &     TCAR3(MTDC,JS,IW)
          WRITE(16,*)'AVERAGE POLLUTED VOLUME 6 MONTHS LATER=',
     &     TCAR6(MTDC,JS,IW)
          WRITE(16,*)'AVERAGE POLLUTED VOLUME 12 MONTHS LATER=',
     &     TCAR12(MTDC,JS,IW)
          WRITE(16,*)'AVERAGE POLLUTED VOLUME 24 MONTHS LATER=',
     &     TCAR24(MTDC,JS,IW)
          WRITE(16,*)'AVERAGE POLLUTED VOLUME 36 MONTHS LATER=',
     &    TCAR36(MTDC,JS,IW)
          WRITE(16,*)
  512  CONTINUE
```

```
           WRITE(16,*)'**************************************************'
           WRITE(16,*)'**************************************************'
          ENDDO
C
C         REPORTING  DATA FOR EXCEL USE
          DO K=1,MDS
            DO I=1,KW
             WRITE(17,540)(100.0*TDET(K,J,I)/SNSIM,J=0,KSA-1)
             WRITE(18,560)( 100.0*TDET(K,J,I)/SNSIM,INT(TATOD(K,J,I)),
         &    TNCAR(K,J,I),TCAR1(K,J,I),TCAR3(K,J,I),TCAR6(K,J,I),
         &    TCAR12(K,J,I),TCAR24(K,J,I),TCAR36(K,J,I),J=0,KSA-1)
            ENDDO
          ENDDO
C
  540  FORMAT(7(F5.1,1X))
  560  FORMAT(7(F5.1,1X,I4,1X,7(F6.4,1X)))
C
C
          PRINT*,'THE ENS.MEAN IS:',SSXEN,' AND THE ENS.VAR IS:',SSX2EN
          PRINT*,'THE ENS.MEAN IN TWO POINTS IS : ',RKPOINT1,RKPOINT2
          PRINT*,'  AND THE ENS. VARIANCE IS : ',RKPOIN21,RKPOIN22
          PRINT*
          PRINT*,'CORRELATION SCALE = ',A,' WITH ',SNSIM,'  SIMULATIONS'
          PRINT*,'INITIAL HEAD: ',HEADG
          PRINT*,'No OF PARTICLES:',NTPART
          PRINT*,'VARIANCE : ',SIGMA
          PRINT*
          PRINT*
          PRINT*,'DONE ..... '
C
C          PAUSE
          STOP
          END          !END OF MAIN PROGRAM
C
C
C
C
C-*****SUBROUTINES*****SUBROUTINES*********SUBROUTINES******************
C
C
C***********************************************************************
C****** SUBROUTINE RANDOMWALK(DET,TDETECTED,POLVOL) ********************
C***********************************************************************
C
          SUBROUTINE RANDOMWALK(IS,TDC,RPX,RPY,ORPOS,DET,TOD)
C
          IMPLICIT DOUBLE PRECISION (A-H,O-Z)
          PARAMETER (IMEM=1024000)
          PARAMETER (KW=8,KSA=7)
C
          DOUBLE PRECISION X(IMEM),Y(IMEM),Z(IMEM),XPR(IMEM),YPR(IMEM),
         & ZPR(IMEM),LDC,NDFS,TOD(0:KSA-1,KW)
          DOUBLE PRECISION NCAR(0:KSA-1,KW),CAR1(0:KSA-1,KW),
         & CAR3(0:KSA-1,KW),CAR6(0:KSA-1,KW),CAR12(0:KSA-1,KW),
         & CAR24(0:KSA-1,KW),CAR36(0:KSA-1,KW)
          DIMENSION C(IMEM),PRPOS(IMEM),LFC(100000)
          DIMENSION RLOCLAND(IMEM),CC(20),NW(20),MWX(20),MWY(20)
          INTEGER C,POS,PX,PY,PZ,PAR,PRPOS,ORPOS,PART,CC,TVC,NPAR(10950)
          INTEGER TEND,TPRD,TS,TTL,PRSMTTL(0:KSA-1,KW),NOW(KW),ISA(0:KSA-1)
          LOGICAL MW(0:KSA-1,KW,20),MONITOR,DET(0:KSA-1,KW)
C
          COMMON /PARAM/ P0,P1,EP,DX,DY,DZ,NX,NY,NZ,NSEED
          COMMON /PARTICLE/ PM,TVC,NPAR
          COMMON /POLLUTION/ C,OOB
          COMMON /LANDFILL/ LFXI,LFXE,LFYI,LFYE,LFAR,LFC
          COMMON /MONITORING/ SIGMA,MONITOR,NOW,ISA
          COMMON /TIME/ TS,TEND,TPRD,NSIM
          COMMON /WAREA/ NCAR,CAR1,CAR3,CAR6,CAR12,CAR24,CAR36
```

```
C
C       OPEN(30,FILE='C_ANALYTICALLY.TXT',STATUS='UNKNOWN')
C
C------INITIALIZATION OF MATRICES AND PARAMETERS-------------------------
      NXNY=NX*NY                ! LEVEL NODES
      OOB=0                     ! PARTICLES OUT OF BOUNDARIES
      TOTALPART=0               ! TOTAL PARTICLE COUNTER
      LDC=10*TDC                !LONGITUDAL DISPERSSION
      PART=0                    !INITIAL PARTICLE COUNTER
C
C     COORDINATES OF POLLUTION ORIGIN
      PX=INT(RPX)
      PY=INT(RPY)
      PZ=1
      IF(RPY-PY.GE.0.5)PY=PY+1        !COUNTS ON CENTRAL Y
      IF(RPX-PX.GE.0.5)PX=PX+1        !COUNTS ON CENTRAL X
C
      DO JS=0,KSA-1
        DO IW=1,KW
          DO K=1,NOW(IW)
            MW(JS,IW,K)=.FALSE.    ! MONITOR WELL INITIAL DETECTION VALUE
          ENDDO
        ENDDO
      ENDDO
C
      DO JS=0,KSA-1
        DO IW=1,KW
          DET(JS,IW)=.FALSE.       ! DETECTION PARAMETER (IF PLUME IS
DETECTED THEN TRUE)
          TOD(JS,IW)=0.D0          ! AVERAGE TIME OF DETECTION
          PRSMTTL(JS,IW)=0         ! INITIAL TIME OF SAMPLING
C
C     INITIALISING CONTAMINATED CELL AREA
          NCAR(JS,IW)=0.D0
          CAR1(JS,IW)=0.D0
          CAR3(JS,IW)=0.D0
          CAR6(JS,IW)=0.D0
          CAR12(JS,IW)=0.D0
          CAR24(JS,IW)=0.D0
          CAR36(JS,IW)=0.D0
        ENDDO
      ENDDO
C
      DO I=1,IMEM
        X(I)=0.D0
        Y(I)=0.D0
        Z(I)=0.D0
        XPR(I)=0.D0
        YPR(I)=0.D0
        ZPR(I)=0.D0
        C(I)=0
      ENDDO
C
      CALL WNDFS(SIGMA,TDC,NDFS)
C
C     DIMENSION RESTORATION FACTORS
       DISTLENGT=DX
       DISTTIME=TS
C       DISTVEL=DX/TS
C
C     REMOVING DIMENSIONS
       LDC=LDC/DX
       TDC=TDC/DY
       DX=DX/DX
       DY=DY/DY
       DZ=DZ/DZ
       TEND=TEND/TS
       TPRD=TPRD/TS
```

```
      TS=TS/TS
C
C
C ****************RANDOM WALK PARTICLE TRACKING ALGORITHM***************
C
C -----TIME PROGRESSION--------------------------------------------------
C
       DO 20 TTL=1,TEND,TS
C
C     NUMBER OF PARTICLES TO BE RELEASED EACH TIME
C      INSTANT LEAK (TPRD=1) - CONTINUOUS LEAK (TPRD>1)
       IF(TTL.LE.TPRD)THEN
         PART=PART+NPAR(TTL)
C         PRINT*,TTL,NPAR(TTL),PART
         TOTALPART=PART
         C(ORPOS)=C(ORPOS)+NPAR(TTL)
         DO PAR=PART-NPAR(TTL)+1,PART
            PRPOS(PAR)=ORPOS
            X(PAR)=RPX
            Y(PAR)=RPY
            Z(PAR)=PZ
            XPR(PAR)=X(PAR)
            YPR(PAR)=Y(PAR)
            ZPR(PAR)=Z(PAR)
         ENDDO
       ENDIF
C
C -----PARTICLE'S PROGRESSION ALGORITHM---------------------------------
C
         DO 10 PAR=1,PART
C
C     CHECKING IF PARTICLE WAS INSIDE BOUNDARIES, THEN
C     EXECUTE THE NEXT POSITION ALGORITHM
      IF(XPR(PAR).GE.1.AND.XPR(PAR).LE.NX-1.AND.YPR(PAR).LE.NY-1.AND.
     &   YPR(PAR).GE.1.AND.ZPR(PAR).GT.0.AND.ZPR(PAR).LE.NZ)THEN
C
C        DETERMINING 3 RANDOM NUMBERS
         R1=RVNORMAL(NSEED)
         R2=RVNORMAL(NSEED)
C         R3=RVNORMAL(NSEED)
C
C    CALCULATING PARTICLE'S VELOCITY
         CALL VCL(X(PAR),Y(PAR),Z(PAR),VLX,VLY,VLZ)
         CALL VCB(X(PAR),Y(PAR),Z(PAR),VBX,VBY,VBZ)
C
         VB=SQRT(VBX**2+VBY**2+VBZ**2)
C
C    CALCULATING VELOCITY DERIVATIVES (BETWEEN CELL BOUNDARIES)
         XIP=INT(X(PAR))
         YIP=INT(Y(PAR))
         CALL VCL(X(PAR),YIP,Z(PAR),VLXD,VLYD,VLZ)
         CALL VCL(X(PAR),YIP+1,Z(PAR),VLXU,VLYU,VLZ)
         CALL VCL(XIP,Y(PAR),Z(PAR),VLXL,VLYL,VLZ)
         CALL VCL(XIP+1,Y(PAR),Z(PAR),VLXR,VLYR,VLZ)
C
         UXUVX=(VLXL-VLXR)/DX
         UYUVY=(VLYU-VLYD)/DY
         UYUVX=(VLXU-VLXD)/DY
         UXUVY=(VLYL-VLYR)/DX
C
C    CALCULATING FOKKER-PLANCK EQUATION ADDITIONAL TERM
         DLT=LDC-TDC
C
         UXUDYX=(DLT/VB**3)*((VBY**3)*UXUVX+(VBX**3)*UXUVY)
C
         UYUDYY=(2.D0*TDC*VBX*VB**2-TDC*VBX**3-LDC*VBX*VBY**2)*
     &             UYUVX/VB**3+(2.D0*LDC*VBY*VB**2-TDC*VBY*VBX**2-
     &             LDC*VBY**3)*UYUVY/VB**3
```

```
C
C         Y COMPONENT FOKKER-PLANK STAGNATION TERM
          FPTY=UXUDYX+UYUDYY
C
C
          UXUDXX=(2.D0*LDC*VBX*VB**2-LDC*VBX**3-TDC*VBX*VBY**2)*
     &             UXUVX/VB**3+(2.D0*TDC*VBY*VB**2-LDC*VBY*VBX**2-
     &             TDC*VBY**3)*UXUVY/VB**3
C
          UYUDXY=(DLT/VB**3)*((VBY**3)*UYUVX+(VBX**3)*UYUVY)
C
C         X COMPONENT FOKKER-PLANK STAGNATION TERM
          FPTX=UXUDXX+UYUDXY
C
C         DETERMINING THE NEW POSITION
          FLDC=R1*SQRT(2.D0*LDC*VB*TS)
          FTDC=R2*SQRT(2.D0*TDC*VB*TS)
C
         X(PAR)=XPR(PAR)+VLX*TS+(VBX/VB)*FLDC-(VBY/VB)*FTDC+FPTX*TS
         Y(PAR)=YPR(PAR)+VLY*TS+(VBY/VB)*FLDC+(VBX/VB)*FTDC+FPTY*TS
C
C           CHECKING IF BOYNDARIES HAVE BEEN REACHED
C           CHECKING X END BOUNDARY
            IF(X(PAR).LT.1.OR.X(PAR).GT.NX-1)THEN
               C(PRPOS(PAR))=C(PRPOS(PAR))-1
               XPR(PAR)=X(PAR)
               OOB=OOB+1
               GOTO 10
            ENDIF
C           CHECKING Y END BOUNDARY
            IF(Y(PAR).GT.NY-1.OR.Y(PAR).LT.1)THEN
               C(PRPOS(PAR))=C(PRPOS(PAR))-1
               YPR(PAR)=Y(PAR)
               OOB=OOB+1
               GOTO 10
            ENDIF
C           CHECKING Z DOWN END BOUNDARY
            IF(Z(PAR).LT.0)THEN
               C(PRPOS(PAR))=C(PRPOS(PAR))-1
               ZPR(PAR)=Z(PAR)
               OOB=OOB+1
               GOTO 10
            ENDIF
C      CHECKING Z TOP END BOUNDARY.IF EQUAL NZ ASSIGN PREVIOUS VALUE
C      PLUME IS FORCED INSIDE THE VOLUME. THIS POLICY MAY BE ALTERED
            IF(Z(PAR).GT.NZ) Z(PAR)=NZ
C
C         KEEPING POSITIONS
          XPR(PAR)=X(PAR)
          YPR(PAR)=Y(PAR)
          ZPR(PAR)=Z(PAR)
C
C -----CALCULATING CONCENTRATIONS---------------------------------------
C
C      WELLS ARE LOCATED ON GRID'S NODES
       MCLX=INT(X(PAR))
       MCLY=INT(Y(PAR))
C
       DIFX=X(PAR)-MCLX
       DIFY=Y(PAR)-MCLY
C
       IF(DIFX.GE.0.5) MCLX=MCLX+1
       IF(DIFY.GE.0.5) MCLY=MCLY+1
C
       POS=(MCLY-1)*NX+MCLX
C
       C(POS)=C(POS)+1
       C(PRPOS(PAR))=C(PRPOS(PAR))-1
```

```
          PRPOS(PAR)=POS
C
C
        ENDIF      ! INSIDE BOUNDARIES IF
C
C
   10       CONTINUE
C
C -----MONITOR-------------------------------------------------------
        IF(MONITOR.EQV..TRUE.)THEN
C       ESTABLISHING A SAMPLING POLICY (INVSM=INTERVAL OF SAMPLING)
        DO 90 JS=0,KSA-1
C
C           MONITOR WELLS
          DO 95 IW=1,KW
            IF(INT(TTL-PRSMTTL(JS,IW)).EQ.ISA(JS))THEN
               PRSMTTL(JS,IW)=TTL              ! KEEPING TIME OF PREVIOUS STEP
               DO KK=1,NOW(IW)
                  BW=(LFYE-LFYI)/NOW(IW)
                  IBW=INT(BW/2)
                  MWX(KK)=INT(LFXE+(LFYE-LFYI)*NDFS)  !X DIMENSION OF MONITOR
WELL
                  MWY(KK)=INT(LFYI+(IBW+(KK-1)*BW))   !Y DIMENSION OF MONITOR
WELL
               ENDDO
C
C           MONITORING WELLS 1 - NOW(IW) (NUMBER OF WELLS)
               DO 70 K=1,NOW(IW)
                  CC(K)=0
C               DEPTH OF WELLS (NZ=1 EQV 2-D)
                  DO 80 IZ=1,NZ
                     NW(K)=(IZ-1)*NXNY+(MWY(K)-1)*NX+MWX(K)
                     CC(K)=CC(K)+C(NW(K))
                     IF(CC(K)*PM.GE.TVC)THEN
                       IF(DET(JS,IW).EQV..FALSE.)THEN
                          MW(JS,IW,K)=.TRUE.
                          DET(JS,IW)=.TRUE.
                          TOD(JS,IW)=TTL
                       ENDIF
                     ENDIF
   80             CONTINUE
C
   70          CONTINUE      ! CLOSING MONITOR LOOP
            ENDIF            ! SAMPLING POLICY IF
C
            IF(DET(JS,IW).EQV..TRUE.)THEN
              IF(TTL.EQ.TOD(JS,IW)) CALL POLVOL(CAR1(JS,IW))
              IF(TTL.EQ.TOD(JS,IW)+90) CALL POLVOL(CAR3(JS,IW))
              IF(TTL.EQ.TOD(JS,IW)+180) CALL POLVOL(CAR6(JS,IW))
              IF(TTL.EQ.TOD(JS,IW)+365) CALL POLVOL(CAR12(JS,IW))
              IF(TTL.EQ.TOD(JS,IW)+730) CALL POLVOL(CAR24(JS,IW))
              IF(TTL.EQ.TOD(JS,IW)+1095) CALL POLVOL(CAR36(JS,IW))
            ENDIF
C
C
   95   CONTINUE          ! CLOSING WELL LOOP
   90 CONTINUE            ! CLOSING SAMPLING LOOP
C
        ENDIF             ! MONITOR IF
C
   20   CONTINUE
C
C
        DO JS=0,KSA-1
          DO IW=1,KW
           IF(DET(JS,IW).EQV..FALSE.) CALL POLVOL(NCAR(JS,IW))
          ENDDO
        ENDDO
```

```
C
C -----EXPORTING CONCENTRATIONS ON A SELECTED REALISATION --------------
C       IF(IS.EQ.NSIM)THEN
      OPEN(32,FILE='CONCENTRATION.TXT',STATUS='UNKNOWN')
      QWVAL=20
      LVAL=10
      DO 40 K=1,NZ
       DO 40 J=1,NY
          DO 40 I=1,NX
            IP=(K-1)*NXNY+(J-1)*NX+I
            RLOCLAND(IP)=C(IP)
C     VISUALIZATION OF LANDFILL'S LOCATION ON THE FIELD LATTICE AND
C     ITS MONITOR WELLS
             DO KK=1,NOW(IW)
                IF(I.EQ.MWX(KK).AND.J.EQ.MWY(KK)) RLOCLAND(IP)=QWVAL
             ENDDO
C
              IF(K.EQ.NZ.AND.J.GE.LFYI.AND.J.LE.LFYE.AND.
     $        I.GE.LFXI.AND.I.LT.LFXE) RLOCLAND(IP)=LVAL
C
       WRITE(32,*)I,J,K,RLOCLAND(IP)
C
   40 CONTINUE
C
      CLOSE(32)
C
C -----CHECKING HOW MANY PARTICLES WERE COUNTED AND IF WE HAD C<0 ------
      NP=0
      E0=0
      DO 45 K=1,NZ
       DO 45 J=1,NY
         DO 45 I=1,NX
           IP=(K-1)*NXNY+(J-1)*NX+I
           IF(C(IP).LT.0)THEN
             E0=E0+1
             PRINT 145,C(IP),I,J
             WRITE(50,145)C(IP),I,J
           ENDIF
           NP=NP+C(IP)
   45 CONTINUE
  145 FORMAT('ATTENTION:NEGATIVE VALUE OF CONCENTRATION C',I5,
     &', AT POSITION X=',I4,' AND Y=',I4)
C
C     RESTORING DIMENSIONS
       LDC=LDC*DISTLENGT
       TDC=TDC*DISTLENGT
       DX=DX*DISTLENGT
       DY=DY*DISTLENGT
       DZ=DZ
       TEND=TEND*DISTTIME
       TPRD=TPRD*DISTTIME
       TS=TS*DISTTIME
C
C
C      REPORTING VALUES
      WRITE(50,*) IS,'/',NSIM
      WRITE(50,800)NX,NY,NZ
      WRITE(50,900)PX,PY,PZ
      WRITE(50,*)
      WRITE(50,*)'TIME STEP: ',TS
      WRITE(50,*)'TOTAL PARTICLES INJECTED: ',TOTALPART
      WRITE(50,*)'PARTICLES TRACKED:  ',NP
      WRITE(50,*)'PARTICLES MISSED:  ',OOB
      WRITE(50,*)'TOTAL TRACKED & MISSED= ',NP+OOB
      WRITE(50,*)
C
      DO JS=0,KSA-1
       WRITE(50,*)'**************************************************'
```

```
       DO IW=1,KW
C      WRITE(50,*)'LOCATION OF WELLS : ',
C     & ('WELL:',K,' (',MWX(K),',',MWY(K),')',' - ',K=1,NOW(IW))
         WRITE(50,*)'SAMPLING INTERVAL (DAYS):',ISA(JS)
         IF(DET(JS,IW).EQV..TRUE.)THEN
          DO K=1,NOW(IW)
           IF(MW(JS,IW,K).EQV..TRUE.)THEN
             WRITE(50,*)NOW(IW),'-WELLS, MONITORING WELL:',K,
     &         ' HAS DETECTED POLLUTION'
             WRITE(50,*)'DETECTION TIME= ',TOD(JS,IW),' OF ',TEND
           ENDIF
          ENDDO
         ELSEIF(DET(JS,IW).EQV..FALSE.)THEN
          WRITE(50,*)'NO DETECTION SUCCEEDED BY ',NOW(IW),
     &       ' MONITORING WELLS '
         ENDIF
C
        WRITE(50,*)
        WRITE(50,*)'POLLUTED VOLUME ON FAILURE=',NCAR(JS,IW)/LFAR
        WRITE(50,*)'POLLUTED VOLUME ON DETECTION=',CAR1(JS,IW)/LFAR
        WRITE(50,*)'POLLUTED VOLUME 3 MONTHS LATER=',CAR3(JS,IW)/LFAR
        WRITE(50,*)'POLLUTED VOLUME 6 MONTHS LATER=',CAR6(JS,IW)/LFAR
        WRITE(50,*)'POLLUTED VOLUME 12 MONTHS LATER=',CAR12(JS,IW)/LFAR
        WRITE(50,*)'POLLUTED VOLUME 24 MONTHS LATER=',CAR24(JS,IW)/LFAR
        WRITE(50,*)'POLLUTED VOLUME 36 MONTHS LATER=',CAR36(JS,IW)/LFAR
        WRITE(50,*)'----------------------------------------------------'
        WRITE(50,*)
       ENDDO
      ENDDO
C
C      PRINTING ON SCREEN
      PRINT*
      PRINT*,'TDC: ',TDC
      PRINT*,'TOT INJ:',TOTALPART,' / TRACKED:',NP,' / MISSED:',OOB,
     & ' / TOT TRACKED & MISSED=',NP+OOB
      PRINT*
C
C
  800 FORMAT('X=',I4,2X,'Y=',I4,2X,'Z=',I4)
  900  FORMAT('STARTING POINT OF POLLUTION: ','PX=',I3,2X,'PY=',I3,
     & 2X,'PZ=',I3)
C
      RETURN
      END
C
C
C---------------------------------------------------------------
C     NORMAL RANDOM NUMBER FUNCTION GENERATOR
C---------------------------------------------------------------
C
        FUNCTION RVNORMAL(SEED)
        IMPLICIT DOUBLE PRECISION (A-H,O-Z)
        DATA S,T / 0.449871,-0.386595 /
        DATA A,B / 0.19600,0.25472 /
        INTEGER SEED
C
  100   U=RANDM(SEED)
        V=RANDM(SEED)
        V=1.7156D0*(V-0.5D0)
        X=U-S
        Y=ABS(V)-T
        Q=X*X+Y*(A*Y-B*X)
C
        IF(V**2.GT.-4*LOG(U)*U**2) GOTO 100
        IF(Q.GT.0.27846) GOTO 100
        IF(Q.LT.0.27597) RVNORMAL=V/U
        RETURN
        END
```

```
C
C
C------------------------------------------------------------
C      RANDOM NUMBER FUNCTION  (0-1 EQUAL PROBABLE)
C------------------------------------------------------------
C
      FUNCTION RANDM(IDUM)
      INTEGER IDUM,IM1,IM2,IMM1,IA1,IQ1,IQ2,IR1,NTAB,NDIV
      DOUBLE PRECISION RANDM,AM,EPS,RNMX
      PARAMETER (IM1=2147483563,IM2=2147483399,AM=1.D0/IM1,IMM1=IM1-1,
     *      IA1=40014,IA2=40692,IQ1=53668,IQ2=52774,IR1=12211,
     *      NTAB=32,NDIV=1+IMM1/NTAB,EPS=1.2E-7,RNMX=1.D0-EPS)
      INTEGER IDUM2,J,K,IV(NTAB),IY
      SAVE IV,IY,IDUM2
      DATA IDUM2/123456789/,IV/NTAB*0/,IY/0/
      IF (IDUM.LE.0)THEN
         IDUM=MAX(-IDUM,1)
         IDUM2=IDUM
      DO 11 J=NTAB+8,1,-1
            K=IDUM/IQ1
            IDUM=IA1*(IDUM-K*IQ1)-K*IR1
            IF (IDUM.LT.0) IDUM=IDUM+IM1
            IF (J.LE.NTAB) IV(J)=IDUM
 11   CONTINUE
      IY=IV(1)
      ENDIF
      K=IDUM/IQ1
      IDUM=IA1*(IDUM-K*IQ1)-K*IR1
      IF (IDUM.LT.0) IDUM=IDUM+IM1
      K=IDUM2/IQ2
      IDUM2=IA2*(IDUM2-K*IQ2)
      IF (IDUM2.LT.0) IDUM2=IDUM+IM2
      J=1+IY/NDIV
      IY=IV(J)-IDUM2
      IV(J)=IDUM
      IF (IY.LT.1) IY=IY+IMM1
      RANDM=MIN(AM*IY,RNMX)
      RETURN
      END
C
C
C
C************************************************************
C      SUBROUTINE LANDFL: LANDFILL'S SHAPE AND BOUNDARIES
C************************************************************
C
      SUBROUTINE LANDF
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON /PARAM/ P0,P1,EP,DX,DY,DZ,NX,NY,NZ,NSEED
      COMMON /LANDFILL/ LFXI,LFXE,LFYI,LFYE,LFAR,LFC
      INTEGER LFC(100000)
C
      NN=NX*NY
C
      DO I=1,NN
        LFC(I)=0
      ENDDO
C
C      --> RECTAGULAR LANDFILL <--
C      LANDFILL (COORDINATIONS IN METERS/D TO GET DIMENSIONLESS NUMBERS)
      LFXI=INT(10/DX)              !LANDFILL'S X INITIAL BOUNDARY LIMIT
      LFXE=INT(60/DX)             !LANDFILL'S X ENDING BOUNDARY LIMIT
      LFYI=INT(140/DY)            !LANDFILL'S Y INITIAL BOUNDARY LIMIT
      LFYE=INT(260/DY)            !LANDFILL'S Y ENDING BOUNDARY LIMIT
      LFAR=(LFXE-LFXI-1)*(LFYE-LFYI-1) !LF'S DIMENSIONLESS AREA (No OF
CELLS)
C
      DO J=1,NY
```

```
            DO I=1,NX
              IP=(J-1)*NX+I
              IF(J.GE.LFYI.AND.J.LE.LFYE.AND.I.GE.LFXI.AND.I.LT.LFXE)THEN
                 LFC(IP)=1
              ENDIF
            ENDDO
         ENDDO
C
         RETURN
         END
C
C
C************************************************************
C     SUBROUTINE RANDORIGIN: CREATING RANDOM ORIGIN POINT OF POLLUTION
C************************************************************
C
         SUBROUTINE RANDORIGIN(RPX,RPY,ORPOS)
         IMPLICIT DOUBLE PRECISION (A-H,O-Z)
         COMMON /PARAM/ P0,P1,EP,DX,DY,DZ,NX,NY,NZ,NSEED
         COMMON /LANDFILL/ LFXI,LFXE,LFYI,LFYE,LFAR,LFC
         INTEGER ORPOS,LFC(100000)
C
         XL=ABS(LFXE-LFXI)
         YL=ABS(LFYE-LFYI)
         RPX=XL*RANDM(NSEED)+LFXI
         RPY=YL*RANDM(NSEED)+LFYI
         PX=INT(RPX)
         PY=INT(RPY)
         PZ=1
         IF(RPY-PY.GE.0.5)PY=PY+1        !COUNTS ON CENTRAL Y
         IF(RPX-PX.GE.0.5)PX=PX+1        !COUNTS ON CENTRAL X
C
         ORPOS=(PY-1)*NX+PX   ! INITIAL CUBIC ELEMENT POSITION OF PARTICLES
C
         WRITE(39,*)PX,PY
C
         RETURN
         END
C
C
C
C************************************************************
C     SUBROUTINE WNDFS: WELLS' DISTANCE FROM SOURCE (NORMALIZED)
C************************************************************
C
         SUBROUTINE WNDFS(SIGMA,AT,DFS)
         IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
         IF(SIGMA.EQ.0.D0)THEN
           IF(AT.EQ.0.001D0)DFS=3.0D0
           IF(AT.EQ.0.01D0)DFS=2.25D0
           IF(AT.EQ.0.02D0)DFS=1.50D0
           IF(AT.EQ.0.05D0)DFS=0.50D0
           IF(AT.EQ.0.1D0)DFS=0.125D0
           IF(AT.EQ.0.2D0)DFS=0.030D0
           IF(AT.EQ.0.5D0)DFS=0.015D0
         ENDIF
C
         IF(SIGMA.EQ.0.25D0)THEN
           IF(AT.EQ.0.001D0)DFS=1.75D0
           IF(AT.EQ.0.01D0)DFS=1.50D0
           IF(AT.EQ.0.02D0)DFS=1.00D0
           IF(AT.EQ.0.05D0)DFS=0.50D0
           IF(AT.EQ.0.1D0)DFS=0.125D0
           IF(AT.EQ.0.2D0)DFS=0.30D0
           IF(AT.EQ.0.5D0)DFS=0.015D0
         ENDIF
C
```

```
      IF(SIGMA.EQ.0.50D0)THEN
        IF(AT.EQ.0.001D0)DFS=1.75D0
        IF(AT.EQ.0.01D0)DFS=1.50D0
        IF(AT.EQ.0.02D0)DFS=0.50D0
        IF(AT.EQ.0.05D0)DFS=0.50D0
        IF(AT.EQ.0.1D0)DFS=0.125D0
        IF(AT.EQ.0.2D0)DFS=0.030D0
        IF(AT.EQ.0.5D0)DFS=0.015D0
      ENDIF
C
      IF(SIGMA.EQ.0.75D0)THEN
        IF(AT.EQ.0.001D0)DFS=1.75D0
        IF(AT.EQ.0.01D0)DFS=1.25D0
        IF(AT.EQ.0.02D0)DFS=0.50D0
        IF(AT.EQ.0.05D0)DFS=0.25D0
        IF(AT.EQ.0.1D0)DFS=0.125D0
        IF(AT.EQ.0.2D0)DFS=0.030D0
        IF(AT.EQ.0.5D0)DFS=0.015D0
      ENDIF
C
      IF(SIGMA.EQ.1.D0)THEN
        IF(AT.EQ.0.001D0)DFS=1.75D0
        IF(AT.EQ.0.01D0)DFS=1.25D0
        IF(AT.EQ.0.02D0)DFS=0.50D0
        IF(AT.EQ.0.05D0)DFS=0.125D0
        IF(AT.EQ.0.1D0)DFS=0.0625D0
        IF(AT.EQ.0.2D0)DFS=0.030D0
        IF(AT.EQ.0.5D0)DFS=0.015D0
      ENDIF
C
      IF(SIGMA.EQ.1.5D0)THEN
        IF(AT.EQ.0.001D0)DFS=1.25D0
        IF(AT.EQ.0.01D0)DFS=1.00D0
        IF(AT.EQ.0.02D0)DFS=0.50D0
        IF(AT.EQ.0.05D0)DFS=0.125D0
        IF(AT.EQ.0.1D0)DFS=0.0625D0
        IF(AT.EQ.0.2D0)DFS=0.015D0
        IF(AT.EQ.0.5D0)DFS=0.015D0
      ENDIF
C
      IF(SIGMA.EQ.2.0D0)THEN
        IF(AT.EQ.0.001D0)DFS=0.75D0
        IF(AT.EQ.0.01D0)DFS=0.50D0
        IF(AT.EQ.0.02D0)DFS=0.25D0
        IF(AT.EQ.0.05D0)DFS=0.125D0
        IF(AT.EQ.0.1D0)DFS=0.0625D0
        IF(AT.EQ.0.2D0)DFS=0.015D0
        IF(AT.EQ.0.5D0)DFS=0.015D0
      ENDIF
C
      RETURN
      END
C
C
C
C***************************************************************
C     SUBROUTINE POLVOL: ESTIMATING THE POLLUTED VOLUME
C***************************************************************
      SUBROUTINE POLVOL(VOL)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
      PARAMETER (IMEM=1024000)
      COMMON /PARAM/ P0,P1,EP,DX,DY,DZ,NX,NY,NZ,NSEED
      COMMON /POLLUTION/ C,OOB
      INTEGER C(IMEM)
C
      NXNY=NX*NY
      VOL=0
```

```
      DO 50 K=1,NZ
        DO 50 J=1,NY
          DO 50 I=1,NX
            IP=(K-1)*NXNY+(J-1)*NX+I
            IF(C(IP).GT.28)VOL=VOL+1
   50 CONTINUE
C
      VOL=VOL+OOB     !PARTICLES OUT OF BOUNDARIES INCLUDED (1 CELL/PAR)
C
      RETURN
      END
C
C
C
C************************************************************
C     CALCULATING THE VELOCITY FIELD
C************************************************************
C
      SUBROUTINE VEL(RK,P,VELX,VELY,VELZ)
C
C     VELOCITIES ARE CALCULATED IN A SHIFTED GRID, EQUAL TO 1/2 IN RELATION
C     TO THE INITIAL GRID WHERE K AND H ARE CALCULATED. THIS MEANS THAT
C     VX(I+1/2,J,K), VY(I,J+1/2,K), VZ(I,J,K+1/2). CALCULATIONS OF VELOCITY
C     ONTO OTHER POINTS OF SIMULATION AREA MUST ACCOUNT FOR THIS SHIFT.
C     VELOCITIES ON INITIAL GRID NODES ARE LINEARLY INTERPOLATED,
C     BETWEEN I+1,I AND J+1,J.
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      PARAMETER (IMEM=1024000)
C
      DOUBLE PRECISION P(IMEM),RK(IMEM),VELX(IMEM),VELY(IMEM),VELZ(IMEM)
      DOUBLE PRECISION VELXI(IMEM),VELYI(IMEM),VELZI(IMEM)
      INTEGER TS,TEND,TPRD
C
      COMMON /PARAM/ P0,P1,EP,DX,DY,DZ,NX,NY,NZ,NSEED
      COMMON /TIME/ TS,TEND,TPRD,NSIM
C
C     INITIALIZATION OF MATRICES AND PARAMETERS
      DO I=1,IMEM
      VELXI(I)=0.D0
      VELYI(I)=0.D0
      VELZI(I)=0.D0
      VELX(I)=0.D0
      VELY(I)=0.D0
      VELZ(I)=0.D0
      ENDDO
C
      NXNY=NX*NY
C
C     CALCULATING
      DO 810 K=1,NZ
      DO 810 J=1,NY
      DO 810 I=1,NX
      IP=(K-1)*NXNY+(J-1)*NX+I
C
C     VELOCITY ON X AXIS (I+1/2)
      IF(I.GE.1.AND.I.LE.NX-1)THEN                ! CALCULATING grad(H)
        GRADHX=(P(IP+1)-P(IP))/DX
        RKPX=2.D0*RK(IP+1)*RK(IP)/(RK(IP+1)+RK(IP))
        VELXI(IP)=RKPX*GRADHX/EP                  ! CALCULATING VELOCITY
      ENDIF
C
      IF(I.EQ.NX) VELXI(IP)=VELXI((K-1)*NXNY+(J-1)*NX+NX-1)
C
C     VELOCITY ON Y AXIS (J+1/2)
      IF(J.GE.1.AND.J.LE.NY-1)THEN                ! CALCULATING grad(H)
        GRADHY=(P(IP+NX)-P(IP))/DY
        RKPY=2.D0*RK(IP+NX)*RK(IP)/(RK(IP+NX)+RK(IP))
```

```
            VELYI(IP)=RKPY*GRADHY/EP                 ! CALCULATING VELOCITY
          ENDIF
C
          IF(J.EQ.NY) VELYI(IP)=VELYI((K-1)*NXNY+(J-1-1)*NX+I)
C
C         VELOCITY ON Z AXIS  (K+1/2)
          IF(K.GT.1.AND.K.LT.NZ)THEN                 ! CALCULATING grad(H)
            GRADHZ=(P(IP+NXNY)-P(IP))/DZ
            RKPZ=2.D0*RK(IP+NXNY)*RK(IP)/(RK(IP+NXNY)+RK(IP))
            VELZI(IP)=RKPZ*GRADHZ/EP                  ! CALCULATING VELOCITY
          ENDIF
C
          IF(K.EQ.NZ) VELZI(IP)=VELZ((K-1-1)*NXNY+(J-1)*NX+I)
C
    810 CONTINUE
C
C         LINEARLY INTERPOLATING VELOCITIES ON (I,J)
C         VELOCITY ON X AXIS [(I+1/2)+(I-1/2)]/2
          DO 820 K=1,NZ
           DO 820 J=1,NY
             DO 820 I=2,NX-1
               IP=(K-1)*NXNY+(J-1)*NX+I
               IB=(K-1)*NXNY+(J-1)*NX+I-1
               VELX(IP)=(VELXI(IP)+VELXI(IB))/2.D0
    820 CONTINUE
C
C         VELOCITY ON Y AXIS [(J+1/2)+(J-1/2)]/2
          DO 830 K=1,NZ
           DO 830 J=2,NY-1
             DO 830 I=1,NX
               IP=(K-1)*NXNY+(J-1)*NX+I
               IB=(K-1)*NXNY+(J-1-1)*NX+I
               VELY(IP)=(VELYI(IP)+VELYI(IB))/2.D0
    830 CONTINUE
C
C         VELOCITY ON (NX,J) SIDE
          DO J=1,NY
             IP=(J-1)*NX+1
             IE=(J-1)*NX+NX
             VELX(IP)=VELXI(IP)
             VELX(IE)=VELXI(IE)
          ENDDO
C
C         VELOCITY ON (I,NY) SIDE
          DO I=1,NX
             IE=(NY-1)*NX+I
             VELY(I)=VELYI(I)
             VELX(IE)=VELXI(IE)
          ENDDO
C
C
C         REMOVING DIMENSIONS (VELOCITY IN DX/TS M/DAY UNITS)
          DO 850 K=1,NZ
           DO 850 J=1,NY
             DO 850 I=1,NX
                IP=(K-1)*NXNY+(J-1)*NX+I
                VELX(IP)=VELX(IP)/(DX/TS)
                VELY(IP)=VELY(IP)/(DY/TS)
                VELZ(IP)=VELZ(IP)/(DZ/TS)
    850 CONTINUE
C
C
          RETURN
          END
C
C
C
C
```

```
C***********************************************************
C        3D HYBRID VELOCITY INTERPOLATION SCEME SUBROUTINES
C***********************************************************
C
C
      SUBROUTINE VCL(XPR,YPR,ZPR,VLX,VLY,VLZ)
C
C***********************************************************
C     LINEAR VELOCITY INTERPOLATION
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      PARAMETER (IMEM=1024000)
C
      DOUBLE PRECISION VELX(IMEM),VELY(IMEM),VELZ(IMEM)
C
      COMMON /VELOCITY/ VELX,VELY,VELZ
      COMMON /PARAM/ P0,P1,EP,DX,DY,DZ,NX,NY,NZ,NSEED
C
C
      NXNY=NX*NY
      VLX=0.D0
      VLY=0.D0
      VLZ=0.D0
      I=INT(XPR)
      J=INT(YPR)
      K=INT(ZPR)
C
      FX=XPR-INT(XPR)
      FY=YPR-INT(YPR)
C
C     ---------------- X-AXIS -----------------------------------
      IF(INT(XPR).GE.1.AND.INT(XPR).LE.NX-1)THEN
         VLX=(DX-FX)*VELX((K-1)*NXNY+(J-1)*NX+I)+
     &         FX*VELX((K-1)*NXNY+(J-1)*NX+I+1)
      ENDIF
C
      IF(INT(XPR).EQ.NX)VLX=VELX((K-1)*NXNY+(J-1)*NX+NX)
C
C
C     ---------------- Y-AXIS -----------------------------------
      IF(INT(YPR).GE.1.AND.INT(YPR).LE.NY-1)THEN
         VLY=(DY-FY)*VELY((K-1)*NXNY+(J-1)*NX+I)+
     &         FY*VELY((K-1)*NXNY+(J-1+1)*NX+I)
       ENDIF
C
      IF(INT(YPR).EQ.NY)VLY=VELY((K-1)*NXNY+(NY-1)*NX+I)
C
C
      RETURN
      END
C
C
C
C***********************************************************
C
      SUBROUTINE VCB(XPR,YPR,ZPR,VBX,VBY,VBZ)
C
C***********************************************************
C     BILINEAR VELOCITY INTERPOLATION
C
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      PARAMETER (IMEM=1024000)
C
      DOUBLE PRECISION VELX(IMEM),VELY(IMEM),VELZ(IMEM)
C
      COMMON /VELOCITY/ VELX,VELY,VELZ
      COMMON /PARAM/ P0,P1,EP,DX,DY,DZ,NX,NY,NZ,NSEED
```

```
C
C
      NXNY=NX*NY
      VBX=0.D0
      VBY=0.D0
      VBZ=0.D0
      I=INT(XPR)
      J=INT(YPR)
      K=INT(ZPR)
C
      FX=XPR-INT(XPR)
      FY=YPR-INT(YPR)
C
C
C     ---------------- X-AXIS -----------------------------------
      IF(INT(XPR).GE.1.AND.INT(XPR).LE.NX-1.AND.INT(YPR).LE.NY-1)THEN
         BVX1=(DX-FX)*(DY-FY)*VELX((K-1)*NXNY+(J-1)*NX+I)
         BVX2=FX*(DY-FY)*VELX((K-1)*NXNY+(J-1)*NX+I+1)
         BVX3=(DX-FX)*FY*VELX((K-1)*NXNY+(J-1+1)*NX+I)
         BVX4=FX*FY*VELX((K-1)*NXNY+(J-1+1)*NX+I+1)
         VBX=BVX1+BVX2+BVX3+BVX4
      ENDIF
C
      IF(INT(XPR).EQ.NX)VBX=VELX((K-1)*NXNY+(J-1)*NX+NX)
C
C     ---------------- Y-AXIS -----------------------------------
      IF(INT(YPR).GE.1.AND.INT(YPR).LE.NY-1.AND.INT(XPR).LE.NX-1)THEN
         BVY1=(DX-FX)*(DY-FY)*VELY((K-1)*NXNY+(J-1)*NX+I)
         BVY2=FX*(DY-FY)*VELY((K-1)*NXNY+(J-1)*NX+I+1)
         BVY3=(DX-FX)*FY*VELY((K-1)*NXNY+(J-1+1)*NX+I)
         BVY4=FX*FY*VELY((K-1)*NXNY+(J-1+1)*NX+I+1)
         VBY=BVY1+BVY2+BVY3+BVY4
      ENDIF
C
      IF(INT(YPR).EQ.NY)VBY=VELX((K-1)*NXNY+(NY-1)*NX+I)
C
C
      RETURN
      END
```

A-3 Flow Numerical Solution

(T.Sarris, personal communication, developed by A.J. Desbarats)

```
C***************************************************************
C      SOLVING THE FLOW PROBLEM
C***************************************************************
C
      SUBROUTINE FLOW3D(RK,P,ICON,DMAX)
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      PARAMETER (IMEM=1024000)
      DOUBLE PRECISION P(IMEM),B(IMEM),F(IMEM),S(IMEM),A(IMEM),D(IMEM),
     &                 RK(IMEM)
C
      COMMON /PARAM/ P0,P1,EP,DX,DY,DZ,NX,NY,NZ,NSEED
C
C---- ---------------------------------------------------------
C      SET CONSTANTS AND INITIALIZE VECTORS
C---- ---------------------------------------------------------
      NNNN=NX*NY*NZ
      NXNY=NX*NY
      TX=2.D0*DZ*(DY/DX)
      TY=2.D0*DZ*(DX/DY)
      TZ=2.D0*DX*(DY/DZ)
      DO 5 I=1,NNNN
      A(I)=0.D0
      B(I)=0.D0
      F(I)=0.D0
      S(I)=0.D0
      D(I)=0.D0
 5    CONTINUE
C
C---- ----------------------------------------------------------
C      SET UP DIAGONAL VECTORS FOR K+1 AND K-1
C---- ----------------------------------------------------------
      IF(NZ.EQ.1)GO TO 14
      NZ1=NZ-1
      DO 10 IK=1,NZ1
      DO 10 IJ=1,NY
      DO 10 II=1,NX
      IP=(IK-1)*NXNY+(IJ-1)*NX+II
      S(IP)=-1.D0*TZ*RK(IP)*RK(IP+NXNY)/(RK(IP)+RK(IP+NXNY))
 10   CONTINUE
C
C---- ----------------------------------------------------------
C      SET UP DIAGONAL VECTORS FOR J+1 AND J-1
C---- ----------------------------------------------------------
 14   IF(NY.EQ.1) GO TO 19
      NY1=NY-1
      DO 15 IK=1,NZ
      DO 15 IJ=1,NY1
      DO 15 II=1,NX
      IP=(IK-1)*NXNY+(IJ-1)*NX+II
      F(IP)=-1.D0*TY*RK(IP)*RK(IP+NX)/(RK(IP)+RK(IP+NX))
 15   CONTINUE
C
C---- -----------------------------------------------------------
C      SET UP DIAGONAL VECTORS FOR I+1 AND I-1
C---- -----------------------------------------------------------
 19   NX1=NX-1
      DO 20 IK=1,NZ
      DO 20 IJ=1,NY
      DO 20 II=1,NX1
```

```
      IP=(IK-1)*NXNY+(IJ-1)*NX+II
      B(IP)=-1.D0*TX*RK(IP)*RK(IP+1)/(RK(IP)+RK(IP+1))
 20   CONTINUE
C
C---- -----------------------------------------------------------
C      SET UP MAIN DIAGONAL AND RHS VECTOR
C---- -----------------------------------------------------------
      DO 25 IK=1,NZ
      DO 25 IJ=1,NY
      IP=(IK-1)*NXNY+(IJ-1)*NX+1
      TBOUND=TX*RK(IP)
      PBOUND=P0
      A(IP)=TBOUND
      D(IP)=TBOUND*PBOUND
      DO 26 II=1,NX
      IP=(IK-1)*NXNY+(IJ-1)*NX+II
      ZIP=0.D0
      GIP=0.D0
      CIP=0.D0
      IF(IP.GT.NXNY)ZIP=S(IP-NXNY)
      IF(IP.GT.NX)GIP=F(IP-NX)
      IF(IP.GT.1)CIP=B(IP-1)
      A(IP)=A(IP)-S(IP)-ZIP-F(IP)-GIP-CIP-B(IP)
 26   CONTINUE
      TBOUND=TX*RK(IP)
      PBOUND=P1
      A(IP)=A(IP)+TBOUND
      D(IP)=TBOUND*PBOUND
 25   CONTINUE
C
C      SOLVE HEPTADIAGONAL LINEAR SYSTEM OF EQUATIONS
C      USING A LINE SUCCESSIVE OVER RELAXATION (LSOR) METHOD.
C
      CALL LSOR(A,B,F,S,D,P,ICON,DMAX)
C
      RETURN
      END
C
C
C
C***************************************************************
      SUBROUTINE LSOR(A,B,F,S,D,P,ICON,DMAX)
C***************************************************************
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DOUBLE PRECISION AZL(500),BZL(500),CZL(500),DZL(500),UZL(500),
     &   UM(500),A(1),B(1),F(1),S(1),D(1),P(1)
      INTEGER SNSIM
C
      COMMON /SOLVE/ OMEGA,TOL,TOL1,MITER,SNSIM
      COMMON /PARAM/ P0,P1,EP,DX,DY,DZ,NX,NY,NZ,NSEED
C
      NXNY=NX*NY
      IDEBUG=1
      IOCODE=9
      ICON=0
      NITER=0
      MFLAG=MITER-50
      DMAX=1.D0
      RHO1=0.D0
      THETA=0.D0
C
C---- ---------------------------------------------------------
C      ITERATE ON SOLUTION
C---- ---------------------------------------------------------
C
 11   CONTINUE
C
```

```
      TW=1.D0-OMEGA
      DMAX0=DMAX
      THETA0=THETA
      IOCODE=9
      IF(NITER.GE.MITER)THEN
        WRITE(IOCODE,3000)NITER,TOL,DMAX
        PRINT 3000,NITER,TOL,DMAX
        PRINT*,'******************************************************
     &*********'
        PRINT*
        PRINT*
        RETURN
      ENDIF
C
      NITER=NITER+1
      DMAX=0.D0
C
      DO 20 K=1,NZ
      DO 20 J=1,NY
C
C---- -------------------------------------------------------
C      SOLVE TRIDIAGONAL SYSTEM FOR BLOCK (J,K)
C---- -------------------------------------------------------
      DO 15 I=1,NX
      IP=(K-1)*NXNY+(J-1)*NX+I
      UM(I)=P(IP)
      AZL(I)=A(IP)
      DZL(I)=D(IP)
      BZL(I)=B(IP)
      CIP=0.D0
      IF(IP.GT.1)CIP=B(IP-1)
      CZL(I)=CIP
      IF(NY.EQ.1)GO TO 14
      JM=J-1
      JP=J+1
      IF(J.EQ.1)JM=1
      IF(J.EQ.NY)JP=NY
      IPM=(K-1)*NXNY+(JM-1)*NX+I
      IPP=(K-1)*NXNY+(JP-1)*NX+I
      GIP=0.D0
      IF(IP.GT.NX)GIP=F(IP-NX)
      DZL(I)=DZL(I)-GIP*P(IPM)-F(IP)*P(IPP)
 14   IF(NZ.EQ.1)GO TO 15
      KM=K-1
      KP=K+1
      IF(K.EQ.1)KM=1
      IF(K.EQ.NZ)KP=NZ
      IPM=(KM-1)*NXNY+(J-1)*NX+I
      IPP=(KP-1)*NXNY+(J-1)*NX+I
      ZIP=0.D0
      IF(IP.GT.NXNY)ZIP=S(IP-NXNY)
      DZL(I)=DZL(I)-ZIP*P(IPM)-S(IP)*P(IPP)
 15   CONTINUE
C
C---- ------------------------------------------------------
C      CALL TRIDIAGONAL SYSTEM SOLVER
C---- ------------------------------------------------------
      CALL THOMAS(AZL,BZL,CZL,DZL,UZL,NX)
C
C---- ------------------------------------------------------
C      UPDATE SOLUTION
C---- ------------------------------------------------------
      DO 16 I=1,NX
      GSLSOR=UZL(I)
      IPX=(K-1)*NXNY+(J-1)*NX+I
      P(IPX)=TW*UM(I)+OMEGA*GSLSOR
      ARG=P(IPX)-UM(I)
      DM=ABS(ARG)
```

```
      IF(DM.GT.DMAX)DMAX=DM
 16   CONTINUE
C
 20   CONTINUE
C
C---- --------------------------------------------------------
C      UPDATE ACCELERATION PARAMETER OMEGA
C---- --------------------------------------------------------
      IF(TOL1.EQ.0.D0)GO TO 25
      THETA=DMAX/DMAX0
      DELTA=THETA-THETA0
      ARG=DELTA
      ARG=ABS(ARG)
      IF(ARG.GT.TOL1)GO TO 25
      OM=OMEGA-1.D0
      RHO1=(THETA+OM)*(THETA+OM)/(THETA*OMEGA*OMEGA)
      IF(RHO1.GE.1.D0)GO TO 25
      ARG=1.D0-RHO1
      OMEGA=2.D0/(1.D0+SQRT(ARG))
      IF(NITER.GE.MFLAG)OMEGA=0.5D0
C
C---- ---------------------------------------------------------
C      TEST FOR CONVERGENCE
C---- ---------------------------------------------------------
 25   IF(DMAX.GT.TOL)GO TO 11
      IF(IDEBUG.NE.1)GO TO 300
      WRITE(IOCODE,4000)NITER,OMEGA,DMAX,THETA,RHO1
      PRINT*,'      Flow Field Solved!!!'
      PRINT*
 300  CONTINUE
      ICON=1
C
C     COUNTER : NUMBER OF FLOW FIELD SOLUTION
      SNSIM=SNSIM+1
C
 4000 FORMAT(T5,'CONVERGENCE(LSOR) REACHED AFTER ',I4,
     +' ITERATIONS',5X,'OMEGA = ',F6.3/
     +T5,'DMAX = ',F10.6,5X,'THETA = ',F10.6,5X,'RHO1 = ',F10.6/)
 3000 FORMAT(T15,'Convergence (LSOR) was NOT reached IN',I5,
     +' ITERATIONS'/T15,'TOL= ',F10.7,10X,'DMAX = ',F15.7)
C
      RETURN
      END
C
C
C************************************************************
      SUBROUTINE THOMAS(A,B,C,D,X,N)
C************************************************************
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DOUBLE PRECISION A(1),B(1),C(1),D(1),X(1),Q(500),G(500)
C
      WI=A(1)
      G(1)=D(1)/WI
      DO 10 I=2,N
      Q(I-1)=B(I-1)/WI
      WI=A(I)-C(I)*Q(I-1)
      G(I)=(D(I)-C(I)*G(I-1))/WI
 10   CONTINUE
      X(N)=G(N)
      DO 20 I=2,N
      J=N-I+1
      X(J)=G(J)-Q(J)*X(J+1)
 20   CONTINUE
      RETURN
      END
```

A-4 Flow Numerical Solution and STUBA Subroutine

(A.Mantoglou, personal communication)

```
C****************************************************************
C-      TURNING BANDS FIELD GENERATOR
C****************************************************************
C
      SUBROUTINE TUBA(NXDIM,NYDIM,DXX,DYY,FKM,FKV,CRL,TUBARK)
C-----------------------------------------------------------------------------
C
C      Main program module for TUBA, Version 2.11d
C
C-----------------------------------------------------------------------------
C
C      INCLUDE FILE FOR TUBA VERSION 2.11d
C
C      COMMON /TBAPAR/ ICOVF,IPAA,LINES,FMAX,NHAR,NMAX,UN,FX,FY,
C
C     1 XO,YO,TBMX,KS,IP,NX,NY,XMAX,YMAX,DX,DY,NXY, AM,AN,AV,CLX,CLY,
C
C     1 IDFP,IURN, DS,UD,KD,NR,CK,FM,FA, A1,A3,A5,KT,DT,SG,B0,B1,B2,
C
C     1 NF,IPF,SAJ,IULP,MSK,IMSEX
C
C-----------------------------------------------------------------------------
C
C      LOGICAL UNIT IDENTIFIERS
C
C      IN = standard input  - terminal  ( generally, this will be unit 5 )
C
C      IT = standard output - terminal  ( generally, this will be unit 6 )
C
C      IL = listing file unit
C
C      IO = output  data unit
C
C      L1 = used for reading (x,y) points, mask file data, then for storing
C
C      the (x,y) generation points in direct access file for gridded fields
C
C      L2 = used for areal average processes - stores line process data for
C
C      each line in direct access file (to reduce memory requirements)
C
C-----------------------------------------------------------------------------
C
      PARAMETER   (IN=5,IT=6,IL=77,IO=20,L1=21,L2=22,LGTH=1000000)
      COMPLEX      C(LGTH/2)
      DOUBLE PRECISION TUBARK(1000000),DXX,DYY,FKM,FKV,CRL
      REAL         A(LGTH),TBKK(1000000)
C       INTEGER XDIM,YDIM
      EQUIVALENCE  (A,C)
      INCLUDE 'tuba211d.inc'
      COMMON /KFIELD/ TBKK
      COMMON  /PGPARS/ PCL,IPG
      COMMON  /ADRSES/LXY,LPP,LPA,LZ1,LZZ,LZM,LSS,LCC,LFF,LTT,LDZ,
     1                 LS1,LS2,LC1,LC2

      XMAX=DXX*NXDIM
      YMAX=DYY*NYDIM
      NX=NXDIM
```

```
      NY=NYDIM
      AM=FKM
      AN=0.0
      AV=FKV*FKV
      CLX=CRL
      CLY=CRL

      KS=2
      IP=2
      LINES=160
C
C     READ INPUT AND OUTPUT PARAMETERS
      CALL RDINPT(IN,IT,IL,L1,A(1),A(1),MODEL,NLINE,NSIM)
C
C     CALCULATE INTERNAL PARAMETERS
      CALL INTPAR(A(1))
C
C     CREATE THE <NAME>.INP CARD FILE
      CALL LSTINP(IL)
C
C     CALCULATE "ADDRESSES" OF ARRAY POINTERS
      CALL ADDRES(IT,IL,LGTH)
C
C     CALCULATE (X,Y) POINT PROJECTIONS ONTO THE TBM LINES
      CALL CALXYP(IT,L1,A(LXY),A(LZM),A(LSS),A(LCC),A(LPP))
C
C     CALCULATION OF LINE PROCESS ARRAY DATA
      CALL CALINP(IT,L2,A(LPA),A(LSS),A(LCC),A(LS1),A(LC1),A(LFF))
C
C     BEGIN SIMULATING THE RANDOM FIELD(S)
      DO 20 ISIM=1,NSIM
C        WRITE(IT,*)
        IF(NSIM.GT.1) CALL PROGSS(' SIMULATION NUMBER ...',
     1                IT,ISIM,NSIM,5)
        PCLSAV = PCL
        IPGSAV = IPG
        CALL RESEED(ISIM,NUSEED)
        DO 10 L=1,NLINE
          IF(MODEL.LE.3)  CALL SPCTRL(L,L2,A(LPA),A(LZ1),C(LDZ/2+1),
     1                                A(LS1),A(LC1),A(LS2),A(LC2))
          IF(MODEL.EQ.4)  CALL MOVAVG(A(LTT),A(LZ1),A(LFF))
          IF(MODEL.EQ.5)  CALL WNRLVY(A(LZ1))
          CALL PROJCT(L,IT,L1,A(LXY),A(LPP),A(LSS),A(LCC),A(LZZ),
     1                        A(LZM),A(LZ1))
10      CONTINUE
        CALL OUTPUT(IT,IL,IO,ISIM,NSIM,A(LXY),A(LZZ),A(LZM),NUSEED)
        PCL = PCLSAV
20    CONTINUE
C
C      OPEN(34,FILE='TBKK.TXT',STATUS='UNKNOWN')
      DO 30 J=1,NY
        DO 30 I=1,NX
         IP=(J-1)*NX+I
         TUBARK(IP)=TBKK(IP)
 30   CONTINUE
C
       CLOSE(77)
C
      RETURN
      END
C
C
      BLOCK DATA
C---------------------------------------------------------------------------
-
C     INITIALIZE DATA FOR VARIABLES IN LABELED COMMON STATEMENTS
C
      INCLUDE 'tuba211d.inc'
```

```
C
Comt  COMMON    /SEEDS/ needed by URNITMB
      COMMON    /SEEDS/ ML,MM,MK,L,M,K
C
Comt  COMMON   /ADRSES/ needed by ADDRES, MAIN
      COMMON   /ADRSES/LXY,LPP,LPA,LZ1,LZZ,LZM,LSS,LCC,LFF,LTT,LDZ,
     1                  LS1,LS2,LC1,LC2
C
Comt  COMMON   /IRSGRD/ needed by DEFPAR, FLDPAR
      COMMON   /IRSGRD/ GXMIN,GYMIN
C
Comt  DATA    L, M, K and ML, MM, MK needed by URNITMB
      DATA    L, M, K  /089347405, 301467177, 240420681/
      DATA    ML,MM,MK /65539, 33554433, 36243609/
C
Comt  DATA    LS1,LS2 ... needed by ADRSES
      DATA    LS1,LS2,LC1,LC2 /1,1,1,1/,   MSK /0/
C
Comt  DATA    FM,FA,AM .. needed by INTPAR
      DATA    FM,FA,AM,AN,AV,CLX,CLY /1.0, 0.0, 0.0, 0.0, 1.0, 1.0, 1.0/
C
Comt  DATA    GXMIN,GYMIN needed by FLDPAR
      DATA    GXMIN,GYMIN /1.E+15,1.E+15/
C
      END
C
C
      SUBROUTINE ADDRES(IT,IL,LGTH)
C-----------------------------------------------------------------------
-
C     CALCULATE ADDRESSES OF ARRAY POINTERS
C
C     LXY,LPP,LPA, ETC. ARE THE "ADDRESSES" OF THE XY,PP,PA ARRAYS IN
C     THE ONE DIMENSIONAL ARRAY A.  IF SIMULATING AT ARBITRARY (X,Y)
C     LOCATIONS (KS=1),  THESE COORDINATES (NXY OF THEM)  ARE STORED
C     AT THE BEGINNING OF ARRAY A.  IF A MASK FILE IS USED, IT IS ALSO
C     (MUTUALLY EXCLUSIVE OPTIONS)  STORED AT THE BEGINNING OF ARRAY A.
C
      INCLUDE 'tuba211d.inc'
      CHARACTER  BITES*10
      COMMON /ADRSES/LXY,LPP,LPA,LZ1,LZZ,LZM,LSS,LCC,LFF,LTT,LDZ,
     1                LS1,LS2,LC1,LC2
Comt  SEE BLOCK DATA MODULE
Comt  DATA    LS1,LS2,LC1,LC2 /1,1,1,1/
C
      IGS = 0
      KSS = MIN(2,KS)
      IF(KS.GT.1) NXY = NX*NY
      IF(KS.EQ.3) IGS = NX+NY
      LXY = 1
      LZM = 1 + IGS
      LPP = (2-KSS)*(2*NXY) + 1 + MIN(MSK,1)*NXY + IGS
      LPA = LPP + 2*(KSS-1)*NX
      LZ1 = LPA + NHAR
      LZZ = LZ1 + MAX(NMAX,NHAR)
      LSS = LZZ + NXY
      LCC = LSS + LINES
      LFF = LCC + LINES
      LTT = LFF + KD
      LDZ = LTT + NR
      LRQ = LDZ + 2*NHAR
C
C     THESE ARRAYS ARE FOR SHINOZUKA AND JAN METHOD
      IF(ICOVF.LE.3 .AND. ISAJ.EQ.1) THEN
        LS1 = LTT + NR
        LC1 = LS1 + NHAR
        LS2 = LC1 + NHAR
        LC2 = LS2 + NHAR
```

```
          LRQ = LC2 + NHAR
        END IF
C
C       DIRECT ACCESS FILES USE AN ADDITIONAL 8 BYTES PER RECORD
C       BXY = BYTES FOR (X,Y) DATA; BAA = BYTES FOR AREAL AVERAGE DATA
        BXY = ( 4*(2*NXY) + 8*NY )
        BAA = ( 4*NHAR*LINES + 8*LINES ) * (IPAA-1)
        FDS = ( BXY + BAA ) * 1.E-06
        BITES = ' Megabytes'
        IF(FDS.LT.1) THEN
          BITES = ' Kilobytes'
          FDS = 1000 * FDS
        END IF
C        WRITE(IT,10) LGTH,LRQ,LGTH-LRQ,FDS,BITES
        WRITE(IL,10) LGTH,LRQ,LGTH-LRQ,FDS,BITES
10      FORMAT(/' Number Of Elements Allocated In A Array =',I9,
     1  /' Total Storage Required For Computations =',I9,
     1  /' No Of Elements In Excess of Reqirements =',I9,/' Free',
     1   ' Disk Space Needed For Computations =',F9.3,A,/)
C
        IF(LRQ.LT.0 .AND. IDFP.EQ.2) WRITE(IT,15)
15      FORMAT(' ***** err, integer overflow - you may be specifying',
     1      /'       the Turning Band line parameters improperly.',
     2      /'       Recheck  Turning Band parameter input values')
C
C       The following should NEVER occur
        IF(LRQ.LT.0 .AND. IDFP.EQ.1) WRITE(IT,16)
16      FORMAT(' ***** err, integer overflow - contact code author',
     1 /'       send email message to:  dazimme@somnet.sandia.gov')
C
        IF(LRQ.GT.LGTH) WRITE(IT,20)
20      FORMAT(' ***** err, Insufficient Storage (Dimension of A Array)',
     1      /'            Increase Parameter LGTH in main program')
C
        IF(LRQ.GT.LGTH) STOP
C
        RETURN
        END
C
C
        SUBROUTINE CALINP(IT,L2,PA,SS,CC,S1,C1,FF)
C---------------------------------------------------------------------------
--
C       CALCULATION OF ARRAY DATA NEEDED FOR LINE PROCESS GENERATION
C
        REAL    PA(*), SS(*), CC(*), S1(*), C1(*), FF(*)
        INCLUDE 'tuba211d.inc'
        COMMON   /PGPARS/ PCL,IPG
        CHARACTER  LPMA*47,LPSM*43,LPTB*43,LPSP*47
        DATA    LPMA /' Calculating Line Process Data ... (MA Process)'/
        DATA    LPSM /' Calculating Line Process Data ... Harmonic'/
        DATA    LPTB /' Calculating Line Process Data ... Line  No'/
        DATA    LPSP /' Calculating Line Process Data ... ( Spectral )'/

C       NO ARRAY DATA NEEDED FOR NON-STATIONARY GENERALIZED COVARIANCE MODELS
C       GC MODEL LINE PROCESS PARAMETERS CALCULATED IN SUBROUTINE INTPAR
        IF(ICOVF.EQ.5) RETURN
Comt  WRITE(IT,*)'Calculating Line Process Data ... (GC Models)'

C       MOVING AVERAGE GENERATION OF THE LINE PROCESS
        IF(IULP.EQ.2) THEN
C         USER-DEFINED MOVING AVERAGE ALGORITHM GOES HERE
C         THE FF ARRAY CONTAINS THE MOVING AVERAGE WEIGHTS
C         SEE SECTIONS 2.4 AND 5.4 OF THE USER'S MANUAL
Comt      WRITE(IT,*)' Calculating Line Process Data ... (MA Process)'
          IF(IPF.GE.2) WRITE(IT,'(A)') LPMA
          CK = 1.0
          RETURN
```

```
        END IF

C       MOVING AVERAGE GENERATION OF THE LINE PROCESS (TELIS COVARIANCE)
        IF(ICOVF.EQ.4) THEN
Comt      WRITE(IT,*)' Calculating Line Process Data ... (MA Process)'
          IF(IPF.GE.2) WRITE(IT,'(A)') LPMA
          DO 10 K=1,KD
            XT = DS*FLOAT(K-1)
            FF(K) = (1.-XT)*EXP(-XT)
10        CONTINUE
          CX = 1.-EXP(-2.*DS)
          CK = SQRT(12.*CX*CX/(CX-DS*EXP(-2.*DS)))
          RETURN
        END IF

C       SPECTRAL GENERATION OF THE LINE PROCESS  (SAJ AND FFT METHODS)
        AX = FX/CLX
        AY = FY/CLY
        DOM = FMAX/FLOAT(NHAR)
        DLM = 0.1*DOM
C        IF(IPF.EQ.1) WRITE(IT,'(A)') LPSP
        IF(IPAA.EQ.2) GO TO 33

C       line generation for POINT processes ...
        DO 20 M=1,NHAR
Comt      CALL PROGSS(' Calculating Line Process Data ... Harmonic',
          IF(IPF.GE.2) CALL PROGSS(LPSM,IT,M,NHAR,20)
          OM = (FLOAT(M)-0.5)*DOM
          SPEC = SPDF(OM,ICOVF)*DOM
C         This if block pertains only to the Shinozuka and Jan method
          IF(ISAJ.EQ.1) THEN
            OMM = OM + URN55()*DLM
            C1(M) = COS(OMM*UN)
            S1(M) = SIN(OMM*UN)
            SPEC  = 2.0*SQRT(SPEC)
          END IF
          PA(M) = SPEC
20      CONTINUE
        RETURN

C       line generation for AREAL AVERAGE processes ...
33      LREC = 4*NHAR
        OPEN(UNIT=L2,STATUS='SCRATCH',ACCESS='DIRECT',RECL=LREC,
     1      FORM='UNFORMATTED')
        DO 40 L=1,LINES
          IF(IPF.GE.2) CALL PROGSS(LPTB,IT,L,LINES,10)
C           IF(IPF.EQ.2) CALL PROGSS(LPTB,IT,L,LINES,10)
comt      IF(IPF.EQ.3) CALL PROGSS(' Turning Band Line ...',IT,L,LINES,10)
comt      PCLSAV = PCL
comt      IPGSAV = IPG
          DO 30 M=1,NHAR
Comt        CALL PROGSS(' Calculating Line Process Data ... Harmonic',
comt        IF(IPF*IPGSAV.EQ.3) CALL PROGSS(LPSM,IT,M,NHAR,20)
            OM = (FLOAT(M)-0.5)*DOM
            SPEC = SPDF(OM,ICOVF)*DOM
C           This if block pertains only to the Shinozuka and Jan method
            IF(ISAJ.EQ.1) THEN
              OMM = OM + URN55()*DLM
              C1(M) = COS(OMM*UN)
              S1(M) = SIN(OMM*UN)
              SPEC  = 2.0*SQRT(SPEC)
            END IF
            AC = CC(L)
            AS = SS(L)
            IF(ICOVF.EQ.0) AASD = WTUSR(OM,AC,AS,AX,AY)*SPEC
            IF(ICOVF.EQ.1) AASD = WTEXP(OM,AC,AS,AX,AY)*SPEC
            IF(ISAJ .EQ.1) AASD = 2.*SQRT(AASD)
            PA(M) = AASD
```

```
30        CONTINUE
          WRITE(UNIT=L2,REC=L) (PA(M),M=1,NHAR)
comt      PCL = PCLSAV
40      CONTINUE

        RETURN
        END



        SUBROUTINE CALXYC(K,GS,X,Y)
C----------------------------------------------------------------------------
--
C       CALCULATE (x,y) COORDINATES FOR GRIDDED OUTPUT

        REAL    GS(*)
        INCLUDE 'tuba211d.inc'

C       KS = 1   OUTPUT AT SPECIFIED (X,Y) LOCATIONS
C       KS = 2   OUTPUT ONTO A BLOCK OR POINT CENTERED  REGULARLY  SPACED GRID
C       KS = 3   OUTPUT ONTO A BLOCK OR POINT CENTERED IRREGULARLY SPACED GRID
C       IP = 1   POINT CENTERED GRID,   IP = 2  BLOCK CENTERED GRID

C       DECODE I AND J INDICES FROM SINGLE INDEX REFERENCE
        J = K/NX + 1
        IF(MOD(K,NX).EQ.0)  J = J - 1
        I = K - (J-1)*NX
        V = 1.0/FLOAT(IP)
        IF(KS.EQ.2) X = (I-V)*DX
        IF(KS.EQ.2) Y = (J-V)*DY
        IF(KS.EQ.3) THEN
          X = 0
          Y = 0
          DO 10 II=1,I-1
10        X = X + GS(II)
          X = X + (1-V)*GS(I)
          DO 20 JJ=1,J-1
20        Y = Y + GS(NX+JJ)
          Y = Y + (1-V)*GS(NX+J)
        END IF

        RETURN
        END



        SUBROUTINE CALXYP(IT,IU,GS,ZM,SS,CC,PP)
C----------------------------------------------------------------------------
--
C       CALCULATE (X,Y) POINT PROJECTIONS ONTO THE TBM LINES

        PARAMETER  (PI=3.1415926)
        REAL        CC(*), SS(*), GS(*), ZM(*), PP(2,*)
        INCLUDE 'tuba211d.inc'
        CHARACTER PPCS*43
        DATA      PPCS /' Calculating Projection Points ... Point No'/

C       CALCULATE SINES AND COSINES OF TBM LINE ANGLES
        DTHA = PI/FLOAT(LINES)
        TNOT = URN55() * 2.0*PI
        DO 10 L=1,LINES
          THETA = FLOAT(L)*DTHA + TNOT
          CC(L) = COS(THETA)
          SS(L) = SIN(THETA)
10      CONTINUE

C       NORMALIZED PROJECTON POINTS FOR KS=1 OBTAINED IN SUBROUTINE PROJCT
        IF(KS.EQ.1) THEN
```

```
        WRITE(IT,*)'Projection Points Not Calculated -> Read as Input'
        WRITE(IT,*)'Projection Points = (x,y) Field Generation Points'
        IF(IULP.EQ.2 .OR. ICOVF.GE.4) WRITE(IT,*)
        RETURN
      END IF

C     CALCULATE AND STORE THE NORMALIZED (X,Y) PROJECTION POINTS FOR GRIDS
      LREC = 2*(4*NX)
      OPEN(UNIT=IU,STATUS='SCRATCH',ACCESS='DIRECT',RECL=LREC,
     1     FORM='UNFORMATTED')
C      IF(IPF.EQ.1) WRITE(IT,*)'Calculating Projection Points ...'
      DO 40 I=1,NY
        DO 30 J=1,NX
          K = (I-1)*NX + J
Comt      CALL PROGSS(' Calculating Projection Points ... Point No',
          IF(IPF.EQ.2) CALL PROGSS(PPCS,IT,K,NXY,20)
          IF(IPF.EQ.3) CALL PROGSS(PPCS,IT,K,NXY, 5)
          IF(MSK.GT.0 .AND. ZM(K).EQ.0)  GO TO 30
          CALL CALXYC(K,GS,X,Y)
          PP(1,J) = X
          PP(2,J) = Y
30      CONTINUE
        WRITE(UNIT=IU,REC=I) ((PP(K,J),K=1,2),J=1,NX)
40    CONTINUE
C      WRITE(IT,*)

      RETURN
      END



      SUBROUTINE COMENT(ID,CMT,NC)
C-----------------------------------------------------------------------
--
C     RETURN COMMENT FOR THE <NAME>.INP FILE

C     TUBA CREATES A CARD FILE "ON THE FLY"  (ie. WHILE IT IS BEING RUN
C     INTERACTIVELY).  THE CARD FILE PROVIDES A RECORD OF WHAT OPTIONS AND
C     PARAMETERS WERE USED AND LISTS THE SAMPLE STATISTICS OF EACH OUTPUT
C     FIELD.  THE CARD FILE CAN ALSO BE USED FOR BATCH PROCESSING.

      CHARACTER   COMTS(37)*42, CMT*(*)
      INTEGER     NCHRS(37)
      DATA   COMTS( 1) /'1=(x,y) Locations, 2=Even Grid, 3=Uneven  '/
      DATA   COMTS( 2) /'Input Filename for (x,y) Locations        '/
      DATA   COMTS( 3) /'1=Point Centered,  2=Block Centered       '/
      DATA   COMTS( 4) /'Maximum X and Y Field Dimensions          '/
      DATA   COMTS( 5) /'Number of Nodes-X and Nodes-Y             '/
      DATA   COMTS( 6) /'1=Normal, 2=exp(X), 3=10**(X)             '/
      DATA   COMTS( 7) /'0=User,1=Exp,2=Gauss,3=Besl,4=Telis,5=GC  '/
      DATA   COMTS( 8) /'1=Point Process, 2=Areal Average Process  '/
      DATA   COMTS( 9) /'X and Y Dimensions of Averaging Area      '/
      DATA   COMTS(10) /'Desired Mean, Nugget and Sill             '/
      DATA   COMTS(11) /'X and Y Direction Correlation Lengths     '/
      DATA   COMTS(12) /'Generalized Covariance Model Coefficients '/
      DATA   COMTS(13) /'Line Process by: 1=Spectral, 2=Moving Avg '/
      DATA   COMTS(14) /'1=Default TBM Parameters, 2=Enter Manually'/
      DATA   COMTS(15) /'Number of Turning Band Lines              '/
      DATA   COMTS(16) /'TBM Line Discretization Distance          '/
      DATA   COMTS(17) /'Nbr of Harmonics for Discretizing Spectrum'/
      DATA   COMTS(18) /'Max Frequency for Truncation of Spectrum  '/
      DATA   COMTS(19) /'Discretization Distance for MA Process    '/
      DATA   COMTS(20) /'Discretization Distance for Weiner Process'/
      DATA   COMTS(21) /'Field ORIGIN Relative to TBM Origin       '/
      DATA   COMTS(22) /'Output Data Filename                      '/
      DATA   COMTS(23) /'1=Output Only Z, 2=Output X,Y, and Z      '/
      DATA   COMTS(24) /'1=Unformatted, 2=Formatted Output         '/
      DATA   COMTS(25) /'Output Format for Writing Data to Disk    '/
```

```
      DATA   COMTS(26) /'1=Single Write Statement, 2=Line at a Time'/
      DATA   COMTS(27) /'1=First Row to Last, 2=Last Row to First  '/
      DATA   COMTS(28) /'1=Marsaglia URNG, 2=Machine Indep URNG    '/
      DATA   COMTS(29) /'Seed(s) for Random Number Generator       '/
      DATA   COMTS(30) /'Number of Realizations to be Simulated    '/
      DATA   COMTS(31) /'Maximum Turning Band Line Length          '/
      DATA   COMTS(32) /'Mask Filename                             '/
      DATA   COMTS(33) /'Input Filename for grid-block widths      '/
      DATA   COMTS(34) /'1=Single file output, 2=Multiple files    '/
      DATA   COMTS(35) /'1=Minimal, 2=Med, 3=Frequent screen output'/
      DATA   COMTS(36) /'0=do not scale, 1=match T-stats exactly   '/
      DATA   COMTS(37) /'Mean, Nugget, Sill for Gen Cov Model      '/

      DATA   NCHRS     / 40, 34, 35, 32, 29, 29, 40, 40, 36, 29, 37,
     1                   41, 41, 42, 28, 32, 42, 40, 38, 42, 35, 20,
     1                   36, 33, 38, 42, 40, 38, 35, 38, 32, 13, 36,
     1                   38, 42, 39, 36/

      CMT = COMTS(ID)
      NC  = NCHRS(ID)

      RETURN
      END



      SUBROUTINE COVPAR(IN,IT,IL,MODEL)
C-----------------------------------------------------------------------------
--
C     QUERY FOR COVARIANCE PARAMETERS OF THE RANDOM FIELD

      INCLUDE 'tuba211d.inc'

C      WRITE(IT,10)
C 10    FORMAT(//' ++++++++++++   COVARIANCE  PARAMETERS   ++++++++++++'/)

C      WRITE(IT,*)'Select Type Of Covariance Model:'
C      WRITE(IT,*)'(0) - User Specified'
C      WRITE(IT,*)'(1) - Exponential Model'
C      WRITE(IT,*)'(2) - Gaussian Covariance'
C      WRITE(IT,*)'(3) - Bessel Type Covariance'
C      WRITE(IT,*)'(4) - Telis Covariance Function'
C      WRITE(IT,*)'(5) - Generalized Covariance Model'
C      WRITE(IT,*)
C      CALL RDINTG(IN,IT,IL,ICOVF,1,7)
      ICOVF=2
      MODEL = ICOVF

      IPAA = 1
C     AREAL AVERAGE PROCESS DATA FOR USER DEFINED OR EXPONENTIAL MODELS
      IF(ICOVF.LE.1) THEN
        WRITE(IT,*)'(1) - Point Process'
        WRITE(IT,*)'(2) - Areal Average Process'
        WRITE(IT,*)
        CALL RDINTG(IN,IT,IL,IPAA,1,8)
        IF(IPAA.EQ.2) THEN
          WRITE(IT,*)'Enter X And Y Dimensions Of Averaging Rectangle'
          WRITE(IT,*)
          CALL RDREAL(IN,IT,IL,FX,2,9)
        END IF
      END IF

      IF(ICOVF.EQ.5) THEN
        WRITE(IT,*)'Enter Gen. Covariance Parameters  A1,A3,A5'
        WRITE(IT,*)'     K(r) = A1*r + A3*r**3 + A5*r**5'
        WRITE(IT,*)'( A1,A5.GE.0, A3.GE.-(10/3)*SQRT(A1*A5) )  '
        WRITE(IT,*)
        CALL RDREAL(IN,IT,IL,A1,3,12)
```

```
          RETURN
        END IF

C        WRITE(IT,*)'Enter Mean And Variance Parameters: If You Will Have'
C        WRITE(IT,*)'The Field(s) Exponentiated, Enter The Desired Mean &'
C        WRITE(IT,*)'Variance BEFORE Exponentiation (Variance=Nugget+Sill)'
C        WRITE(IT,*)
C        WRITE(IT,*)'Enter The Mean, Nugget And Sill For Covariance Model'
C        WRITE(IT,*)
C        CALL RDREAL(IN,IT,IL,AM,3,10)
        IF(AN.LT.0 .OR. AV.LT.0) THEN
          STOP '***** ERR, nugget and sill must be > or = 0'
        END IF

C        WRITE(IT,*)'Enter The X and Y Direction Correlation Lengths'
C        WRITE(IT,*)'    ( Make These Equal For Isotropic Fields )'
C        WRITE(IT,*)
C        CALL RDREAL(IN,IT,IL,CLX,2,11)

        RETURN
        END
C
C
        SUBROUTINE DEFPAR(NLINE,XY)
C-----------------------------------------------------------------------
--
C       CALCULATE DEFAULT TURNING BAND PARAMETERS

        PARAMETER  (PI=3.141592654D0)
        REAL        DLK(4),XY(*)
        INTEGER     NHR(4)
        INCLUDE 'tuba211d.inc'
        COMMON /IRSGRD/ GXMIN,GYMIN

        DATA        NHR /2048, 1024,  4096, 0 /
        DATA        DLK /0.05, 0.10, 0.025, 0./

C       CALCULATE DEFAULT TBM ORIGIN AND MAXIMUM TBM LINE LENGTH
        CALL ORGMAX(XY)

C       SET DEFAULT NUMBER OF TBM LINES (BOTH NEEDED BECAUSE OF COMMON)
C       THERE IS NO LONGER A  "DEFAULT"  NUMBER OF TBM LINES ...
Comt    LINES = 16
Comt    NLINE = 16

C       SPECTRAL AND MOVING AVERAGE METHOD  LINE PARAMETERS
        IF(ICOVF.LE.4) THEN
          ISAJ = 0
          NHAR = NHR(ICOVF)
          UN = 0.0625
          DS = 0.05*AMIN1(CLX,CLY)
        END IF

C       BLOCK OR CELL SPACING FOR GRIDDED OUTPUT
        IF(KS.EQ.2) THEN
          K = 2 - IP
          DX = XMAX / MAX(NX-K,1)
          DY = YMAX / MAX(NY-K,1)
        ELSE IF(KS.EQ.3) THEN
          DX = GXMIN
          DY = GYMIN
        END IF

C       GENERALIZED COVARIANCE MODEL DEFAULT LINE DISCRETIZATION DISTANCE
C       DX,DY SET IN ORGMAX FOR THE CASE OF KS=1
        IF(ICOVF.EQ.5) THEN
          UN = AMIN1(DX,DY)
          DT = 0.2*UN
```

```
      END IF

C     UN = NORMALIZED LINE DISCRETIZATION DISTANCE = 2*PI/FMAX (FFT METHOD)
C     FOR STATIONARY MODELS, UN IS SET EQUAL TO 0.0625 (16 PTS/CORR LGTH)
C     IF(UN.GT.DX  .OR.  UN.GT.DY) THEN UN IS DECREASED APPROPRIATELY.
C     ALSO MAKE SURE MA PROCESS PARAMETER DS IS SMALL ENOUGH.
      IF(KS.GT.1 .AND. ICOVF.LE.4) THEN
        CM = AMAX1(CLX,CLY)
        DC = AMIN1(CLX/16.,CLY/16.)
        DN = AMIN1(.99*DX/CLX,.99*DY/CLY,DC/CM)
        UN = AMIN1(UN,DN)
        DS = AMIN1(DS,UN*AMIN1(CLX,CLY)/10)
      END IF

C     IF THE SPECTRAL METHOD IS USED .AND. UN IS DECREASED, THEN THE
C     FREQUENCY SPACING DELK MAY BE GREATER THAN THE ALLOWABLE MAXIMUM
C    (SEE DLK IN DATA STATEMENT).  WHEN THIS HAPPENS, NHAR IS INCREASED
C    (BY A FACTOR OF 2 FOR THE FFT) TO OBTAIN A SMALLER DELK.

      FMAX = 2.*PI/UN
      IF(UN.LT.0.0625 .AND. ICOVF.LE.3) THEN
16      IF(FMAX/FLOAT(NHAR).GT.DLK(ICOVF)) THEN
          NHAR = 2*NHAR
          GO TO 16
        END IF
      END IF

      RETURN
      END



      SUBROUTINE FFT(F,NPT,IFB)
C-----------------------------------------------------------------------
--
C     ONE DIMENSIONAL FAST FOURIER TRANSFORM ROUTINE  (FORWARD AND INVERSE)
C
C     THIS ROUTINE, MODIFIED BY D. A. (TONY) ZIMMERMAN AT NEW MEXICO TECH
C     AND VERIFIED WITH IMSL ROUTINES, WAS TAKEN FROM PAGE 108 OF:
C
C              RAFAEL .C GONZALEZ AND PAUL WINTZ,  1987.
C                   ``DIGITAL IMAGE PROCESSING''
C                 ADDISON-WESLEY PUBLISHING COMPANY
C
C     F   = COMPLEX SEQUENCE TO BE TRANSFORMED (INPUT)
C     F   = COMPLEX TRANSFORMED ARRAY ON OUTPUT
C     NPT = NUMBER POINTS IN F TO BE TRANSFORMED
C     IFB = -1 FOR FORWARD TRANSFORM   ( EXP(-i*2PIux/NPT) )
C     IFB = +1 FOR INVERSE TRANSFORM   ( EXP(+i*2PIux/NPT) )
C-----------------------------------------------------------------------
--
C     NOTE: THE INPUT SEQUENCE MUST BE OF LENGTH EQUAL TO 2**N FOR SOME N
C-----------------------------------------------------------------------
--
      PARAMETER  (PI=3.141592654D0)
      COMPLEX     F(*),U,W,T

      IF(IFB.GT.0) THEN
        DO 10 K=1,NPT
10      F(K) = CONJG(F(K))
      END IF

      LN = ALOG(FLOAT(NPT))/ALOG(2.0)
      N  = 2**LN
      NV2 = N/2
      NM1 = N-1

      J = 1
```

```
      DO 3 I=1,NM1
        IF(I.GE.J) GO TO 1
        T = F(J)
        F(J) = F(I)
        F(I) = T
1       K = NV2
2       IF(K.GE.J) GO TO 3
        J = J-K
        K = K/2
        GO TO 2
3       J = J+K

      DO 5 L=1,LN
        LE  = 2**L
        LE1 = LE/2
        U = CMPLX(1.0,0.0)
        A = PI/LE1
        W = CMPLX(COS(A),-SIN(A))
        DO 5 J=1,LE1
          DO 4 I=J,N,LE
            IP = I+LE1
            T  = F(IP)*U
            F(IP) = F(I)-T
4           F(I)  = F(I)+T
5         U = U*W

      IF(IFB.GT.0) THEN
        DO 20 K=1,NPT
20      F(K) = CONJG(F(K))
      END IF

      RETURN
      END



      SUBROUTINE FFTGEN(L,L2,PA,Z1,DZ)
C------------------------------------------------------------------------
--
C     GENERATION OF THE LINE PROCESS VIA FAST FOURIER TRANSFORM

      REAL     PA(*),Z1(*)
      COMPLEX  DZ(*),i
      INCLUDE 'tuba211d.inc'

C     THE IMAGINARY PART YIELDS AN INDEPENDENT REALIZATION
      IF(MOD(L,2).EQ.0)  GO TO 30

      i = (0.,1.)
      IF(IPAA.EQ.2) READ(UNIT=L2,REC=L) (PA(M),M=1,NHAR)

      DO 10 M=1,NHAR
        DELF = PA(M)
        SQDF = SQRT(6.*DELF)
        A = SQDF * URN55()
        B = SQDF * URN55()
        DZ(M) = A - i*B
10    CONTINUE

      CALL FFT(DZ,NHAR,-1)

      DO 20 M=1,NHAR
20    Z1(M) = 2.0*REAL(DZ(M))

      RETURN

30    DO 40 M=1,NHAR
40    Z1(M) = 2.0*AIMAG(DZ(M))
```

```
      RETURN
      END



      SUBROUTINE FILPAR(IN,IT,IL)
C-------------------------------------------------------------------------
--
C     QUERY FOR OUTPUT FILE PARAMETERS

      CHARACTER       FMT*35,FNAM*35
      INCLUDE 'tuba211d.inc'
      COMMON /OTPTS1/ FMT,FNAM
      COMMON /OTPTS2/ IFO,IMO,IRO,ILN

C      WRITE(IT,5)
C 5     FORMAT(//' +++++++++++++  OUTPUT FILE PARAMETERS  +++++++++++++'/)

C      WRITE(IT,*)'Enter A Filename For The Output File(s)'
C      WRITE(IT,*)
C      CALL RDCHAR(IN,IT,IL,FNAM,22)
       FNAM='TUBA.TXT'

      IF(KS.EQ.1) THEN
        WRITE(IT,*)'(1) - Output Only The  Field Values, Z'
        WRITE(IT,*)'(2) - Output The (X,Y) Locations And Z'
        WRITE(IT,*)
        CALL RDINTG(IN,IT,IL,IOF,1,23)
      END IF

C      WRITE(IT,*)'(1) - Unformatted Output'
C      WRITE(IT,*)'(2) -   Formatted Output'
C      WRITE(IT,*)
C      CALL RDINTG(IN,IT,IL,IFM,1,24)
       IFM=1

      IF(IFM.EQ.2) THEN
        IF(KS.EQ.1) WRITE(IT,10) '"(2F12.2,1PE12.5)"'
        IF(KS.GT.1) WRITE(IT,10) '"(10F12.5)"'
10      FORMAT(' Enter Output Format, e.g., ',A)
        WRITE(IT,*)'   (include the parentheses)'
        WRITE(IT,*)
        CALL RDCHAR(IN,IT,IL,FMT,25)
      END IF

      IF(KS.GT.1) THEN
C        WRITE(IT,*)'(1) - Write Out Matrix With One WRITE Statement'
C        WRITE(IT,*)'(2) - Write Out Matrix One Line (Row) At A Time'
C        WRITE(IT,*)
C        CALL RDINTG(IN,IT,IL,IMO,1,26)
        IMO=2
        IMO = 2 - IMO
        IRO = 1
        IF(IMO.EQ.0 .AND. IFM.EQ.2) THEN
          WRITE(IT,*)' Output the Rows of the Matrix via ...'
          WRITE(IT,*)'(1) - First Row --> Last  Row'
          WRITE(IT,*)'(2) - Last  Row --> First Row'
          WRITE(IT,*)
          CALL RDINTG(IN,IT,IL,IRO,1,27)
        END IF
      END IF

C     IOF AND IFO ARE PARAMETERS CONTROLLING OUTPUT FORMAT
      KSS = MIN(KS,2)
      IOF = MAX(IOF*(2-KSS),1)
      IFO = IOF*2 - IFM + 1

```

```
      RETURN
      END




      SUBROUTINE FLDPAR(IN,IT,IL,IU,XY,GS,ZM)
C----------------------------------------------------------------------------
--
C     QUERY FOR OUTPUT FIELD PARAMETERS

      CHARACTER    FMT*35,FNAM*35, DATAF*35, MASKF*35
      REAL         XY(2,*),GS(*),ZM(*)
      INCLUDE 'tuba211d.inc'
      COMMON /IRSGRD/ GXMIN,GYMIN
      COMMON /OTPTS1/ FMT,FNAM
      COMMON /OTPTS2/ IFO,IMO,IRO,ILN

C      WRITE(IT,5)
C 5     FORMAT(//' ++++++++++++  OUTPUT FIELD  PARAMETERS  ++++++++++++'/)

C      WRITE(IT,*)'(1) - Simulate Only At Specified (x,y) Locations'
C      WRITE(IT,*)'(2) - Simulate Onto A Regularly Spaced Grid'
C      WRITE(IT,*)'(3) - Simulate Onto An Unevenly Spaced Grid'
C      WRITE(IT,*)
C      CALL RDINTG(IN,IT,IL,KS,1,1)


      IF(KS.EQ.1) THEN
        WRITE(IT,*)'Enter The Filename For Reading (X,Y) Locations'
        WRITE(IT,*)
        CALL RDCHAR(IN,IT,IL,DATAF,2)
        OPEN(UNIT=IU,FILE=DATAF,STATUS='OLD')
        I = 0
10      I = I + 1
        READ(IU,*,END=11)  XY(1,I), XY(2,I)
        GO TO 10
11      NXY = I-1
        WRITE(IT,20) NXY
20      FORMAT(' >>>>> ',I8,' Data Pairs Read'/)
        CLOSE(UNIT=IU)
      END IF

      IF(KS.GT.1)  THEN
C        WRITE(IT,*)'(1) - Point Centered Grid'
C        WRITE(IT,*)'(2) - Block Centered Grid'
C        WRITE(IT,*)
C        CALL RDINTG(IN,IT,IL,IP,1,3)


C        WRITE(IT,*)'Enter The Maximum X And Y Field Dimensions'
C        WRITE(IT,*)
C        CALL RDREAL(IN,IT,IL,XMAX,2,4)

C        WRITE(IT,*)'Enter The Number Of Nodes In The X And Y Directions'
C        WRITE(IT,*)
C        CALL RDINTG(IN,IT,IL,NX,2,5)

        IF(KS.EQ.3) THEN
          WRITE(IT,*)'Enter The Filename For Reading Grid-Block Widths'
          WRITE(IT,*)
          CALL RDCHAR(IN,IT,IL,DATAF,33)
          OPEN(UNIT=IU,FILE=DATAF,STATUS='OLD')
          READ(IU,*) (GS(I),I=1,NX-2+IP)
          READ(IU,*) (GS(NX+I),I=1,NY-2+IP)
          CLOSE(UNIT=IU)
          DO 30 I=1,NX
30        IF(GS(I).LT.GXMIN) GXMIN = GS(I)
```

```
            DO 32 I=1,NY
 32         IF(GS(NX+I).LT.GYMIN) GYMIN = GS(NX+I)
          END IF

C          WRITE(IT,*)'Enter mask filename or type NONE or <cr>'
C          WRITE(IT,*)
C          CALL RDCHAR(IN,IT,IL,MASKF,32)
C          IF(MASKF.EQ.' ')  MASKF = 'none'
          MASKF = 'none'
          NONE = INDEX(MASKF,'NONE') + INDEX(MASKF,'none')
          IF(NONE.EQ.0) THEN
            OPEN(UNIT=IU,FILE=MASKF,STATUS='OLD')
            READ(IU,*) (ZM(I),I=1,NX*NY)
            CLOSE(UNIT=IU)
            DO 40 I=1,NX*NY
 40         IF(ZM(I).NE.0) MSK = MSK + 1
          END IF
        END IF

C        WRITE(IT,*)'(1) - Generate a Field f(x) Whose pdf is Gaussian'
C        WRITE(IT,*)'(2) - Generate a Lognormal Field K(x) =  exp(f(x))'
C        WRITE(IT,*)'(3) - Generate a Lognormal Field K(x) = 10**(f(x))'
C        WRITE(IT,*)
C        CALL RDINTG(IN,IT,IL,ILN,1,6)
         ILN=1
        RETURN
        END



        SUBROUTINE FSCALE(XY,ZZ,ZM,ILN,BAR,VAR,SSQ,PTS)
C----------------------------------------------------------------------------
--
C       DO FINAL SCALING, ADD IN THE MEAN, NUGGET & CALCULATE MEAN AND
VARIANCE

        REAL     ZZ(*), ZM(*), XY(2,*)
        INCLUDE 'tuba211d.inc'

        SUM = 0.0
        SSQ = 0.0
        HNUG = SQRT(3.0*AN)
        SDEV = SQRT(AV)
        SQLN = SQRT(FLOAT(LINES))
        DO 10 K=1,NXY
          IF(MSK.EQ.0 .OR. (MSK.GT.0 .AND. ZM(K).NE.0)) THEN
            ZZ(K) = SDEV*ZZ(K)/SQLN
            ZZ(K) = ZZ(K) + AM
            IF(AN.GT.0) ZZ(K) = ZZ(K) + URNAB(-HNUG,+HNUG)
            SUM  = SUM + ZZ(K)
            SSQ  = SSQ + ZZ(K)*ZZ(K)
          END IF
 10     CONTINUE
        PTS = FLOAT(MSK)
        IF(PTS.EQ.0) PTS = FLOAT(NXY)
        BAR = SUM / PTS
        VAR =(SSQ-PTS*BAR*BAR) / (PTS-1.)

C       FROM THIS POINT ON WE CAN SIMPLY CHECK IF ZZ(K).NE.0 (.NE.EXACT ZERO)
C       RATHER THAN CHECKING THE MSK FLAG AND ZM ARRAY  (IF MASK OPTION USED)

C       USE THE FORMULA ON PAGE 10 OF THE MANUAL (THE FORMULA THAT'S LABELED
C      "DO NOT USE") TO SCALE THE FIELD TO MATCH THE DESIRED MEAN & VARIANCE.
C       READ SECTION 2.1.2 OF MANUAL BEFORE INVOKING THIS OPTION.
C       BAR LEFT IN FORMULAS BELOW FOR CLARITY.  AN=NUGGET, AV=SILL
        IF(IMSEX.EQ.1) THEN
          DO 30 I=1,NXY
 30       IF(ZZ(I).NE.0) ZZ(I) = ZZ(I) - BAR
```

```
          BAR = 0.
          SFAC  = SQRT(AN+AV) / SQRT(VAR-BAR*BAR)
          DO 40 I=1,NXY
40        IF(ZZ(I).NE.0) ZZ(I) = SFAC * (ZZ(I)-BAR) + AM
          BAR = AM
          VAR = AN + AV
        END IF
comt    if you don't believe BAR=AM, VAR=AN+AV, uncomment the following lines
comt    SUM = 0.
comt    SSQ = 0.
comt    DO 50 K=1,NXY
comt      IF(ZZ(K).NE.0) THEN
comt        SUM  = SUM + ZZ(K)
comt        SSQ  = SSQ + ZZ(K)*ZZ(K)
comt      END IF
50      CONTINUE
comt    BAR = SUM / PTS
comt    VAR =(SSQ-PTS*BAR*BAR) / (PTS-1.)

comt    EXPONENTIATE THE FIELD IF REQUESTED ...
        IF(ILN.EQ.2) THEN
          DO 60 K=1,NXY
60        IF(ZZ(K).NE.0) ZZ(K) = EXP(ZZ(K))
        ELSE IF(ILN.EQ.3) THEN
          DO 70 K=1,NXY
70        IF(ZZ(K).NE.0) ZZ(K) = 10.**ZZ(K)
        END IF

        RETURN
        END




        SUBROUTINE INTPAR(XY)
C-------------------------------------------------------------------------
--
C       CALCULATE INTERNAL PARAMETERS

        PARAMETER  (PI=3.141592654)
        REAL         XY(*)
        INCLUDE 'tuba211d.inc'
Comt    SEE BLOCK DATA MODULE
Comt    DATA    FM,FA,AM,AV,CLX,CLY /1.0, 0.0, 0.0, 1.0, 1.0, 1.0/

C       NORMALIZE DISTANCE FROM TBM ORIGIN TO OUTPUT FIELD ORIGIN
        XO = XO / CLX
        YO = YO / CLY

C       DX AND DY DEPEND ON WHETHER GRID IS POINT OR BLOCK CENTERED
        IF(KS.EQ.2) THEN
          K = 2 - IP
          DX = XMAX / MAX(NX-K,1)
          DY = YMAX / MAX(NY-K,1)
        END IF

C       NORMALIZE LINE DISCRETIZATION DISTANCE (UN) FOR STATIONARY MODELS
        IF(IDFP.NE.1 .AND. ICOVF.LE.4)  UN = UN / AMAX1(CLX,CLY)

C       NORMALIZE MAX DISCRETIZATION DISTANCE ALONG ANY TBM LINE, THEN
C       ESTIMATE NMAX = THE NUMBER OF POINTS ALONG THE LONGEST TBM LINE
        IF(ICOVF.LE.4) THEN
          TBMX = TBMX / AMIN1(CLX,CLY)
          NMAX = TBMX / UN + 1
        END IF

C       FOR FFT GENERATION ALGORITHM, LINE PROCESS LENGTH = UN*NHAR/2.
C       IF THAT IS LESS THAN TBMX, NHAR MUST BE INCREASED.
```

```
      IF(ICOVF.LE.3 .AND. ISAJ.EQ.0) THEN
16      IF(UN*NHAR/2.0 .LT. TBMX) THEN
          NHAR = 2*NHAR
          GO TO 16
        END IF
      END IF

C     CALCULATE PARAMETERS NEEDED FOR THE MOVING AVERAGE PROCESS
      IF(ICOVF.EQ.4 .OR. IULP.EQ.2) THEN
        DS = DS/AMIN1(CLX,CLY)
        UD = UN/DS
C       FOR USER DEFINED MA PROCESS, CLN MUST BE REPLACED WITH  A NUMBER
C       REPRESENTING THE NBR CORR LGTHS THE MA WEIGHTING FCN IS NON-ZERO
Comt    IF(ICOVF.EQ.0) KD = CLN/DS + 1
        IF(ICOVF.EQ.4) KD = 5.0/DS + 1
        NR = NMAX*UD + KD
        IF(DS.GT.UN) FM =  UD
        IF(DS.GT.UN) FA = 0.5
      END IF

C     GENERALIZED COVARIANCE PARAMETERS
      IF(ICOVF.EQ.5) THEN
        NMAX = TBMX/UN + 1
        KT = AMAX1(UN/DT,1.)
        DT = UN / FLOAT(KT)
        SG = SQRT( 24.*DT )
        B0 = SQRT(A1*PI/2.)
        B2 = SQRT(A5*PI*15./16.)
        B1 =      A3*PI* 3./4.
        B1 = SQRT(B1*B1 + 2.*B0*B2)
      END IF

      RETURN
      END




      SUBROUTINE LSTINP(IL)
C-----------------------------------------------------------------------------
--
C     LIST INPUT VALUES & INTERNAL PARAMETERS USED IN LINE PROCESS
GENERATION
C
C     AS INPUT IS READ, IT IS WRITTEN (AND ANNOTATED) ON UNIT IL.  NOW
REWIND
C     IL, REREAD THOSE LINES AND STORE THEM IN THE "INTERNAL FILE" BUF.
THEN
C     OPEN IL WITH THE DATA FILENAME AND EXTENSION ".INP" & DUMP BUF INTO
IT.
C-----------------------------------------------------------------------------
--
      INTEGER       NC(32)
      CHARACTER     FMT*35,FNAM*35,LSTF*35,REC*80,BUF(32)*80
      INCLUDE 'tuba211d.inc'
      COMMON /OTPTS1/ FMT,FNAM
      COMMON /OTPTS2/ IFO,IMO,IRO,ILN

C     READ THE ANNOTATED INPUT PARAMETERS FROM SCRATCH FILE (UNIT IL)
C     AND WRITE THEM TO THE INTERNAL FILE "BUF"
      REWIND IL
      DO 10 K=1,32
        READ(IL,5,END=11) REC
5       FORMAT(A)
        WRITE(BUF(K),5) REC
        NC(K) = NCHR(REC)
10    CONTINUE
11    NREC = K-1
```

```
C      OPEN THE <NAME>.INP LISTING FILE; REUSE LOGICAL UNIT IL AND
C      WRITE THE ANNOTATED INPUT PARAMETERS TO THIS LIST FILE
       CLOSE(UNIT=IL,STATUS='DELETE')
       IDOT = INDEX(FNAM,'.')
       IF(IDOT.EQ.0)  IDOT = NCHR(FNAM) + 1
       LSTF = FNAM(1:IDOT-1) // '.inp'
       OPEN(UNIT=IL,FILE=LSTF,STATUS='UNKNOWN',FORM='FORMATTED')
       DO 15 K=1,NREC
15     WRITE(IL,5) BUF(K)(1:NC(K))

C      LIST OTHER INTERNAL PARAMETERS ...
       TBMAXX = TBMX * AMIN1(CLX,CLY)
       UNLAST =  UN  * AMAX1(CLX,CLY)
       WRITE(IL,20) XO*CLX,YO*CLY,LINES,TBMAXX,UNLAST
20     FORMAT(/' FIELD ORIGIN relative to the TBM origin =',2G13.6,
     1        /' The Number of Turning Band Lines Equals =',I9,
     1        /' The Maximum  Turning Band  Line  Length =',G13.6,
     1        /' Turning Band Line Discretization Length =',G13.4)

       IF(ICOVF.LE.3 .AND. IULP.NE.2 .AND. ISAJ.EQ.0) NMAX = NHAR
       IF(ICOVF.EQ.4 .OR.  IULP.EQ.2) WRITE(IL,30) DS*AMIN1(CLX,CLY)
30     FORMAT(' Discretization Distance for  MA Process =',G13.4)
       IF(ICOVF.GE.4 .OR.  IULP.EQ.2) WRITE(IL,32) NMAX
32     FORMAT(' Number of Output Points Along each Line =',I9)

       IF(ICOVF.EQ.5 .AND. (A3.NE.0 .OR. A5.NE.0) ) WRITE(IL,35) DT
35     FORMAT(' Discretization Distance for  WL Process =',G13.4)

       IF(ICOVF.LE.3 .AND. IULP.LE.1) WRITE(IL,40) FMAX,NHAR,FMAX/NHAR
40     FORMAT(' The Maximum Frequency  for the Spectrum =',G13.6,
     1       /' Number  of  Harmonics  for the Spectrum =',I9,
     1       /' Frequency  Spacing in  Spectral  Domain =',G13.5)

       IF(KS.EQ.1) WRITE(IL,*)
       IF(KS.EQ.2) THEN
         WRITE(IL,45) DX,DY
45       FORMAT(' The Spatial Discretizations, DELX, DELY =',2G13.4)
         SMPLS = (XMAX/CLX)/2.0*(YMAX/CLY)/2.0
         IF(ICOVF.LE.4) WRITE(IL,50) CLX/DX,CLY/DY,SMPLS
50       FORMAT( ' No Points/correlation Length in X,Y Dir =',F9.1,
     1  3X,F9.1/' Approximate No. of  Independent Samples =',F9.1)
       END IF

       RETURN
       END




       SUBROUTINE MOVAVG(TT,Z1,FF)
C-----------------------------------------------------------------------
--
C      MOVING AVERAGE SIMULATION OF THE LINE PROCESS  (FOR TELIS COVARIANCE)

       REAL      TT(*), Z1(*), FF(*)
       INCLUDE 'tuba211d.inc'

C      FM, FA, NR, UD AND KD  ARE ALL CALCULATED IN SUBROUTINE INTPAR.
C      CK IS FOR MOVING AVERAGE PROCESS ASSOCIATED WITH TELIS COV FCN.
C      CK IS SET TO 1.0 IN SUBROUTINE CALINP FOR USER-DEFINED MOVING
AVERAGES.

       DO 10 K=1,NR
10     TT(K) = URN55()

       DO 30 N=1,NMAX
         Z1(N) = 0.0
```

```
           IOFF =(N-1)*UD + 0.5
           DO 20 K=1,KD
             IADR  = IOFF + FLOAT(K)*FM + FA
             Z1(N) = Z1(N) + FF(K)*TT(IADR)
 20        CONTINUE
           Z1(N) = CK*Z1(N)
 30      CONTINUE

         RETURN
         END




         FUNCTION NCHR(BUF)
C----------------------------------------------------------------------
--
C        DETERMINE THE NUMBER OF CHARACTERS IN THE CHARACTER ARRAY BUF

         CHARACTER  BUF*(*)

         LGTH = LEN(BUF)
         DO 10 K=LGTH,1,-1
 10      IF(BUF(K:K).NE.' ') GO TO 20
 20      NCHR = K

         RETURN
         END




         SUBROUTINE OPNFIL(IT,IL,IO,LREC,ISIM,NSIM,BAR,VAR,SSQ,PTS,
        1                  MODEL,ISEED)
C----------------------------------------------------------------------
--
C        OPEN DATA OUTPUT FILE AND LIST THE RANDOM FIELD STATISTICS

         CHARACTER  FMT*35,FNAM*35
         CHARACTER  FNAME*25,EXT*5,IFM*5,FRM*11
         INCLUDE 'tuba211d.inc'
         COMMON    /OTPTS1/ FMT,FNAM
         COMMON    /OTPTS2/ IFO,IMO,IRO,ILN
         DATA       SMBAR,SMSSQ,SMPTS /0.0,0.0,0.0/

         NC = NCHR(FNAM)
         FNAME(1:NC) = FNAM(1:NC)
         FNAME(NC+1:25) = ' '

C        APPEND SIMULATION NUMBER TO FILENAME IF MULTIPLE FILES REQUESTED
         IF(NF.GT.1) THEN
           IDOT = INDEX(FNAM,'.')
           IF(IDOT.EQ.0) IDOT = NC + 1
           NDIG = ALOG10( FLOAT(NSIM) ) + 1
           WRITE(IFM,10) NDIG
 10        FORMAT(2H(I,I1,1H))
           WRITE(EXT,IFM) ISIM
           DO 15 I=1,NDIG-1
 15        IF(EXT(I:I).EQ.' ')  EXT(I:I) = '0'
           FNAME = FNAM(1:IDOT-1) // '.' // EXT(1:NDIG)
           NC = IDOT + NDIG
         END IF

         IF(NF.GT.1 .OR. ISIM.EQ.1) THEN
           CLOSE(UNIT=IO)
           IF(MOD(IFO,2).EQ.0)  FRM = 'UNFORMATTED'
           IF(MOD(IFO,2).NE.0)  FRM =   'FORMATTED'
Comt       RECL cannot be used for unformatted files with Lahey Fortran
```

```
Comt      OPEN(UNIT=IO,FILE=FNAME,STATUS='UNKNOWN',FORM=FRM,RECL=LREC)
          OPEN(UNIT=IO,FILE=FNAME,STATUS='UNKNOWN',FORM=FRM)
        END IF

C       LIST NEW RANDOM SEED FOR MULTIPLE SIMULATION RUN
        IF(NSIM.GT.1) WRITE(IL,18) ISIM,FNAME(1:NC),ISEED
18      FORMAT(/24X,' Simulation Nmbr =',I9,
     1         /24X,' Output Filename =',1X,A,
     1         /24X,' New Random Seed =',I12)

C       LIST THE STATISTICS FOR THE SAMPLE DATA TO LIST FILE AND TERMINAL
        WRITE(IL,20)  BAR,VAR
20      FORMAT( 24X,' The Sample Mean =',G13.5,
     1         /24X,' Sample Variance =',G13.5)
        IF(IPF.NE.1) WRITE(IT,*)
        IF(IPF.NE.1 .AND. NSIM.GT.1) WRITE(IT,28) ISIM
28      FORMAT(' Simulation Nmbr =',I8)
        WRITE(IT,30) BAR,VAR
30      FORMAT('       The Sample Mean =',G13.5,
     1       /'       Sample Variance =',G13.5/)

        SMBAR = SMBAR + BAR
        SMSSQ = SMSSQ + SSQ
        SMPTS = SMPTS + PTS

C       LIST ENSEMBLE STATISTICS IF THIS IS THE LAST REALIZATION
        IF(NSIM.GT.1 .AND. ISIM.EQ.NSIM) THEN
          ENBAR = SMBAR/FLOAT(NSIM)
          ENVAR = (SMSSQ-SMPTS*ENBAR*ENBAR)/(SMPTS-1.)
          WRITE(IL,40) ENBAR,ENVAR
40        FORMAT(/22X,' THE ENSEMBLE STATISTICS ...' ,
     1           /22X,' The Ensemble Mean =',G13.5,
     1           /22X,' Ensemble Variance =',G13.5)
          WRITE(IT,50) ENBAR,ENVAR
50        FORMAT(//' THE ENSEMBLE STATISTICS ...',
     1            /'       The Ensemble Mean = ',G13.5,
     1            /'       Ensemble Variance = ',G13.5)
        END IF

        RETURN
        END




        SUBROUTINE ORGMAX(XY)
C-----------------------------------------------------------------------------
--
C       CALCULATE DEFAULT TBM ORIGIN AND MAXIMUM DISTANCE ALONG ANY TBM LINE

        REAL    XY(2,*)
        INCLUDE 'tuba211d.inc'

C       FOR OUTPUT AT ARBITRARY LOCATIONS (KS=1):
C       SET DEFAULT TBM ORIGIN EQUAL TO THE MINIMUM (X,Y) COORDINATE
        IF(KS.EQ.1) THEN
          X14 = -1.E-15
          X23 = +1.E+15
          Y12 = -1.E-15
          Y34 = +1.E+15
          DO 10 I=1,NXY
            X14 = AMAX1(XY(1,I),X14)
            X23 = AMIN1(XY(1,I),X23)
            Y12 = AMAX1(XY(2,I),Y12)
            Y34 = AMIN1(XY(2,I),Y34)
10        CONTINUE
          XO = X23
          YO = Y34
```

```
        DXX = X14 - XO
        DYY = Y12 - YO
        TBMX = SQRT(DXX*DXX + DYY*DYY)
C       ------------------------------------------------------------------
--
C       THE REMAINDER OF THIS IF-BLOCK PERTAINS ONLY TO THE CASE OF GENER-
C       ATING AT ARBITRARY LOCATIONS (KS=1) USING GENERALIZED COVARIANCE.
C       The following is used to calculate DX and DY and ASSUMES a uniform
C       distribution of the "finite element" grid points (i.e., the (x,y)
C       arbitrary locations for generating the field).  DX and DY are only
C       needed for this case (KS=1) in subroutine DEFPAR where the DEFAULT
C       TBM line discretization length (UN) is calculated.  The calculated
C       value of UN is only APPROXIMATED and should be checked for adequacy
C       (e.g., UN should be .LE. the minimum spacing between any two field
C       generation points). ASSUMPTIONS: (1) NY/NX=DYY/DXX, (2) NX*NY = NXY
C       ------------------------------------------------------------------
--
        NX = SQRT( FLOAT(NXY)*DXX/DYY )
        NY = NXY/NX
        DX = 0.2*DXX/FLOAT(NX)
        DY = 0.2*DYY/FLOAT(NY)
      END IF

C     FOR GRIDDED OUTPUT (KS=2,3):
C     SET DEFAULT TBM ORIGIN AND FIND THE MAXIMUM DISTANCE FROM
C     THE TBM ORIGIN TO THE FAR CORNER OF THE GRID
      IF(KS.GT.1) THEN
        XO  = 0.0
        YO  = 0.0
        TBMX = SQRT(XMAX*XMAX + YMAX*YMAX)
      END IF

      RETURN
      END




      SUBROUTINE OUTPUT(IT,IL,IO,ISIM,NSIM,XY,ZZ,ZM,NEWS)
C-----------------------------------------------------------------------
--
C     FINISH FIELD GENERATION, THEN WRITE FIELD TO OUTPUT FILE

      CHARACTER   FMT*35,FNAM*35
      REAL        ZZ(*), ZM(*), XY(2,*),TBKK(1000000)
      INCLUDE 'tuba211d.inc'
      COMMON /OTPTS1/ FMT,FNAM
      COMMON /OTPTS2/ IFO,IMO,IRO,ILN
      COMMON /KFIELD/ TBKK

C     DO THE FINAL SCALING, ADD IN THE MEAN, AND CALCULATE STATISTICS
      CALL FSCALE(XY,ZZ,ZM,ILN,BAR,VAR,SSQ,PTS)

C     OPEN OUTPUT FILE AND LIST RANDOM FIELD SAMPLE STATISTICS
C     LREC = BYTE LENGTH OF UNFORMATTED RECORDS
      LREC = 256
      IF(MOD(IFO,2).EQ.0) THEN
        LREC = 4*NX
        IF(IMO.EQ.1) LREC = 4*NXY
      END IF
      CALL OPNFIL(IT,IL,IO,LREC,ISIM,NSIM,BAR,VAR,SSQ,PTS,ICOVF,NEWS)

C     IFO,IMO AND IRO ARE INTERNAL PARAMETERS CONTROLLING OUTPUT FORMAT;
C     THESE ARE CALCULATED IN SUBROUTINE FILPAR.
C     IFO EVEN,ODD -> UNFORMATTED,FORMATTED RESPECTIVELY
C     IMO = 0  ->  WRITE MATRIX OUT LINE BY LINE
C     IMO = 1  ->  WRITE MATRIX OUT WITH ONE WRITE STATEMENT

```

```
C        OPEN(35,FILE='K_TUBA.TXT',STATUS='UNKNOWN')

      IF(IMO.EQ.1 .OR. KS.EQ.1) THEN
        IF(IFO.EQ.1) WRITE(IO,FMT) (ZZ(K),K=1,NXY)
        IF(IFO.EQ.2) WRITE(IO)     (ZZ(K),K=1,NXY)
        IF(IFO.EQ.3) WRITE(IO,FMT) (XY(1,K),XY(2,K),ZZ(K),K=1,NXY)
        IF(IFO.EQ.4) WRITE(IO)     (XY(1,K),XY(2,K),ZZ(K),K=1,NXY)
      ELSE
        JST =(IRO-1)*NY + (2-IRO)
        JND =(2-IRO)*NY + (IRO-1)
        JNC = 3 - 2*IRO
        DO 20 J=JST,JND,JNC
           DO 20 I=1,NX
             IP=(J-1)*NX+I
             TBKK(IP)=ZZ(IP)
C             WRITE(35,*) I,J,1,TBKK(IP)
C             PRINT*,I,J,ZZ(IP)
20      CONTINUE
      END IF

      RETURN
      END



      SUBROUTINE PROGSS(MSG,LU,K,KMAX,INC)
C-------------------------------------------------------------------------
C     REPORT COMPUTATION PROGRESS

      CHARACTER  MSG*(*)
      COMMON    /PGPARS/ PCL,IPG

      IF(K.EQ.1) THEN
        PCL = 100./FLOAT(KMAX)
        WRITE(LU,10) MSG,K,INT(PCL)
        IPG = 1
        RETURN
      END IF

      PCT = 100 * FLOAT(K)/FLOAT(KMAX)
      IPC = INT(PCT)
      DIF = PCT - PCL

      IPR = 0
      IF(INC.EQ.0) THEN
        IPR = 1
      ELSE IF(KMAX.LE.99) THEN
        IF(DIF.GT.INC) IPR = 1
      ELSE
        IF(MOD(IPC,INC).EQ.0 .AND. DIF.GE.2) IPR = 1
      END IF
      IF(K.EQ.KMAX) IPR = 1

      IPG =  0
      IF(IPR.EQ.1) THEN
        IPG = 1
        PCT = AMIN1(PCT,99.9)
        PCL = PCT
        IF(PCT.EQ.99.9) PCL = 0.0
        WRITE(LU,10) MSG,K,INT(PCT)
10      FORMAT(A,I8,' ... ( ',I2,' % ) ')
      END IF

      RETURN
      END
```

```
      SUBROUTINE PROJCT(L,IT,IU,XY,PP,SS,CC,ZZ,ZM,Z1)
C-----------------------------------------------------------------------
--
C     ADD PROJECTIONS FROM THE LTH TBM LINE ONTO OUTPUT FIELD

      REAL     XY(2,*), PP(2,*), SS(*), CC(*), ZZ(*), ZM(*), Z1(*)
      INTEGER  INC(3)
      INCLUDE 'tuba211d.inc'
      COMMON   /PGPARS/ PCL,IPG
      CHARACTER PLPD*43,TBLIN*22
      DATA      INC /20,5,0/
      DATA      TBLIN /' Turning Band Line ...'/
      DATA      PLPD  /' Projecting  Line Process Data ... Point No'/

C     ZERO OUT THE OUTPUT FIELD IF ON TURNING BAND LINE NO 1
      IF(L.EQ.1) THEN
        DO 10 K=1,NXY
10      ZZ(K) = 0.0
      END IF

C     FOR OUTPUT AT ARBITRARY (X,Y) LOCATIONS ...
      IF(KS.EQ.1) THEN
        CALL PROGSS(TBLIN,IT,L,LINES,INC(IPF))
        PCLSAV = PCL
        IPGSAV = IPG
        DO 20 K=1,NXY
Comt      CALL PROGSS(' Projecting  Line Process Data ... Point No',
          IF(IPF*IPGSAV.GE.2) CALL PROGSS(PLPD,IT,K,NXY,INC(IPF-1))
          CALL PROJSB(XY,K,L,K,CC,SS,ZZ,Z1)
20      CONTINUE
        PCL = PCLSAV
        GO TO 50
      END IF

C     FOR OUTPUT ONTO REGULAR OR IRREGULARLY-SPACED GRIDS ...
C      CALL PROGSS(TBLIN,IT,L,LINES,INC(IPF))
      PCLSAV = PCL
      IPGSAV = IPG
      DO 40 I=1,NY
        READ(UNIT=IU,REC=I) ((PP(K,J),K=1,2),J=1,NX)
        DO 30 J=1,NX
          K = (I-1)*NX + J
Comt      CALL PROGSS(' Projecting  Line Process Data ... Point No',
          IF(IPF*IPGSAV.GE.2) CALL PROGSS(PLPD,IT,K,NXY,INC(IPF-1))
          IF(MSK.GT.0 .AND. ZM(K).EQ.0)  GO TO 30
          CALL PROJSB(PP,J,L,K,CC,SS,ZZ,Z1)
30      CONTINUE
40    CONTINUE
      PCL = PCLSAV

50    IF(IPF*IPGSAV.GT.1) WRITE(IT,*)
      RETURN
      END



      SUBROUTINE PROJSB(A2,J,L,K,CC,SS,ZZ,Z1)
C-----------------------------------------------------------------------
--
C     DO THE PROJECTION FOR BOTH GRIDDED AND NON-GRIDDED FIELDS

      REAL    A2(2,*), CC(*), SS(*), ZZ(*), Z1(*)
      INCLUDE 'tuba211d.inc'

      XP = A2(1,J)/CLX + XO
      YP = A2(2,J)/CLY + YO
      XD = ABS( XP*CC(L) + YP*SS(L) )
      N1 = INT(XD/UN)+1
```

```
      ZZ(K) = ZZ(K) + Z1(N1)
      RETURN
      END



      SUBROUTINE RDINPT(IN,IT,IL,IU,XY,ZM,MODEL,NLINE,NSIM)
C-----------------------------------------------------------------------
--
C     CONTROL MODULE FOR READING INPUT PARAMETERS

      REAL    XY(*),ZM(*)
      INCLUDE 'tuba211d.inc'

C      WRITE(IT,10)
 10   FORMAT(//' +++++++++   Program "TUBA (version 2.11d)"  +++++++++',
     1       //'         A Code For Simulating 2D Random Fields',
     1        /'              Via The Turning Bands Method'/)

C     OPEN TEMPORARY FILE (LATER DELETED)
      OPEN(UNIT=IL,STATUS='SCRATCH')

C     QUERY FOR OUTPUT FIELD  PARAMETERS
      CALL FLDPAR(IN,IT,IL,IU,XY,XY,ZM)

C     QUERY FOR  COVARIANCE  PARAMETERS
      CALL COVPAR(IN,IT,IL,MODEL)

C     QUERY FOR TURNING BANDS PARAMETERS
      CALL TBMPAR(IN,IT,IL,NLINE,XY)

C     MODEL REFERS TO THE LINE PROCESS GENERATION METHOD
C     WHEREAS ICOVF REFERS THE THE COVARIANCE MODEL TYPE
C     NEXT LINE IS NEEDED IN THE MAIN MODULE (FOR A USER-DEFINED MA PROCESS)
      IF(IULP.EQ.2)  MODEL = 4

C     QUERY FOR  OUTPUT FILE  PARAMETERS
      CALL FILPAR(IN,IT,IL)

C     QUERY  FOR  SIMULATION  PARAMETERS
      CALL SIMPAR(IN,IT,IL,NSIM)

      RETURN
      END



      SUBROUTINE RDINTG(IN,IT,IL,IV,NV,ID)
C-----------------------------------------------------------------------
--
C     READ AND REFLECT INTEGER INPUT DATA

      CHARACTER  CMT*42, BUF*(*)
      INTEGER    IV(*)
      REAL       RV(*)

      READ (IN,*) (IV(I),I=1,NV)
      WRITE(IT,*)'>>>>> ',(IV(I),I=1,NV)
      WRITE(IT,*)' '

      CALL COMENT(ID,CMT,NC)
      IF(NV.EQ.1) WRITE(IL,11)  IV(1),       CMT(1:NC)
      IF(NV.EQ.2) WRITE(IL,12)  IV(1),IV(2), CMT(1:NC)
11    FORMAT(2X, I12,T36,A)
12    FORMAT(2X,2I12,T36,A)

      RETURN
```

```
      ENTRY RDREAL(IN,IT,IL,RV,NV,ID)
C-----------------------------------------
C     READ AND REFLECT REAL INPUT DATA

      READ (IN,*) (RV(I),I=1,NV)
      WRITE(IT,*)'>>>>> ',(RV(I),I=1,NV)
      WRITE(IT,*)' '

      CALL COMENT(ID,CMT,NC)
      IF(NV.EQ.1) WRITE(IL,21)  RV(1),            CMT(1:NC)
      IF(NV.EQ.2) WRITE(IL,22)  RV(1),RV(2),      CMT(1:NC)
      IF(NV.EQ.3) WRITE(IL,23)  RV(1),RV(2),RV(3),CMT(1:NC)
21    FORMAT(2X, G13.5,T36,A)
22    FORMAT(2X,2G13.5,T36,A)
23    FORMAT(1PE11.3,2E11.3,T36,A)

      RETURN

      ENTRY RDCHAR(IN,IT,IL,BUF,ID)
C-----------------------------------------
C     READ AND REFLECT CHARACTER VARIABLES

      READ(IN,30) BUF
30    FORMAT(A)
      NB = NCHR(BUF)
      IF(NB.EQ.0) BUF = ' '
      IF(NB.EQ.0) NB = 1
      WRITE(IT,*)'>>>>> ',BUF(1:NB)
      WRITE(IT,*)' '

      CALL COMENT(ID,CMT,NC)
      WRITE(IL,35) BUF(1:NB),CMT(1:NC)
35    FORMAT(A,T36,A)

      RETURN
      END



      SUBROUTINE SIMPAR(IN,IT,IL,NSIM)
C---------------------------------------------------------------------------
--
C     READ SIMULATION PARAMETERS

      SAVE        ISEED,JSEED
      CHARACTER  BUF*32
      INCLUDE 'tuba211d.inc'

C      WRITE(IT,10)
C 10    FORMAT(//' +++++++++++++  SIMULATION PARAMETERS  ++++++++++++++'/)

C      WRITE(IT,*)'(1) - Marsaglia and Bray  Random Number Generator'
C      WRITE(IT,*)'(2) - Machine Independent Random Number Generator'
C      WRITE(IT,*)
C      CALL RDINTG(IN,IT,IL,IURN,1,28)
       IURN=1

C      WRITE(IT,*)'Enter Integer Seed(s) To Initialize The Generator'
      IF(IURN.EQ.2) WRITE(IT,20)
20    FORMAT('( Seed For This Generator Must Be 8 Digits Long )')
      WRITE(IT,*)
Comt  CALL RDINTG(IN,IT,IL,ISEED,1,29)
C      CALL RDCHAR(IN,IT,IL,BUF,29)
C      READ(BUF,*,END=21) ISEED,JSEED
C      GO TO 30
      ISEED=1
21    JSEED = ISEED
30    IF(IURN.EQ.1)  DUMY = UNITMB(ISEED)
```

```
      IF(IURN.EQ.2)  DUMY = UNITSS(IT,ISEED)

C      WRITE(IT,*)'Enter The Number Of Realizations To Be Simulated'
C      WRITE(IT,*)
C      CALL RDINTG(IN,IT,IL,NSIM,1,30)
       NSIM=1

      IF(NSIM.GT.1) THEN
        WRITE(IT,*)'(1) - All Realizations Written To One File'
        WRITE(IT,*)'(2) - A Separate File For Each Realization'
        WRITE(IT,*)'       (e.g., file.1, file.2  ...  file.99)'
        WRITE(IT,*)
        CALL RDINTG(IN,IT,IL,NF,1,34)
      END IF

C      WRITE(IT,*)'(0) - Do NOT  Artifically Scale The Realizations'
C      WRITE(IT,*)'(1) - Scale Data To Match Mean and Variance Exactly'
C      WRITE(IT,*)'          Please Read Section 2.1.2 Of The Manual'
C      WRITE(IT,*)'                Before Choosing This Option'
C      WRITE(IT,*)
C      CALL RDINTG(IN,IT,IL,IMSEX,1,36)
       IMSEX=0

      IF(IMSEX.EQ.1 .AND. ICOVF.EQ.5) THEN
        WRITE(*,*)'GC Model: Enter Desired Mean, Nugget and Sill'
        WRITE(IT,*)
        CALL RDREAL(IN,IT,IL,AM,3,37)
      END IF

C      WRITE(IT,*)'Specify The Level Of Status Reporting To The Screen'
C      WRITE(IT,*)'(1) - Minimal (e.g., For Many Realizations)'
C      WRITE(IT,*)'(2) - More Frequent (e.g., For Many TBM Lines)'
C      WRITE(IT,*)'(3) - Very Frequent (e.g., For Very Large Fields)'
C      WRITE(IT,*)
C      CALL RDINTG(IN,IT,IL,IPF,1,35)
       IPF=1

      RETURN

      ENTRY RESEED(ISIM,NUSEED)
C-------------------------------------
C     RESEED THE RANDOM NUMBER GENERATOR

      IF(ISIM.EQ.1) THEN
        NUSEED = ISEED
        IF(JSEED.EQ.ISEED) RETURN
        IF(IURN.EQ.1) DUMY = UNITMB(JSEED)
        IF(IURN.EQ.2) DUMY = UNITSS(IT,JSEED)
        RETURN
      END IF

      NUSEED = 1.E+08*(URN55()+0.5)
      IF(IURN.EQ.1) DUMY = UNITMB(NUSEED)
      IF(IURN.EQ.2) THEN
36      IF(ALOG10(FLOAT(NUSEED)) .LT. 7) THEN
          NUSEED = 10*NUSEED
          GO TO 36
        END IF
        DUMY = UNITSS(IT,NUSEED)
      END IF

      RETURN
      END



      SUBROUTINE SPCTRL(L,L2,PA,Z1,DZ,S1,C1,S2,C2)
C-----------------------------------------------------------------------
```

```
--
C      SPECTRAL SIMULATION OF THE LINE PROCESSES

       PARAMETER  (TUPI=6.2831853)
       COMPLEX     DZ(*)
       REAL        PA(*),Z1(*),S1(*),C1(*),S2(*),C2(*)
       INCLUDE 'tuba211d.inc'

C      GENERATE LINE PROCESS USING THE FFT METHOD
       IF(ISAJ.EQ.0) CALL FFTGEN(L,L2,PA,Z1,DZ)
       IF(ISAJ.EQ.0) RETURN

C      GENERATE LINE PROCESS USING THE METHOD OF SHINOZUKA AND JAN
       DO 10 M=1,NHAR
         THETA = URN55() * TUPI
         C2(M) = COS(THETA)
         S2(M) = SIN(THETA)
10     CONTINUE
       IF(IPAA.EQ.2) READ(UNIT=L2,REC=L) (PA(M),M=1,NHAR)

C      PA(M) = 2.0 * SQRT(SPECTRL DENSITY * DELTA OMEGA)
C      C2SAV ETC IS FOR TRIG IDENTITIES - THE COS(OMEGA'*ZETA+PHI) TERM IS
C      CALCULATED BY  CONSIDERING  ZETA = N*DELTA-ZETA AND TRIG IDENTITIES
       DO 30 N=1,NMAX
         Z1(N) = 0.0
         DO 20 M=1,NHAR
           Z1(N) = Z1(N)+ PA(M) * C2(M)
           C2SAV = C2(M)
           S2SAV = S2(M)
           C2(M) = C2SAV*C1(M) - S2SAV*S1(M)
           S2(M) = S2SAV*C1(M) + C2SAV*S1(M)
20       CONTINUE
30     CONTINUE

       RETURN
       END



       FUNCTION SPDF(FRQ,ICOVF)
C-----------------------------------------------------------------------
--
C      CALCULATE NORMALIZED 1D SPECTRAL DENSITY FUNCTION FOR POINT PROCESSES
C      HAVING 2D COVARIANCE FUNCTIONS OF: USER-SPECIFIED (ICOVF=0),
C      EXPONENTIAL (ICOVF=1), GAUSSIAN (ICOVF=2), BESSEL (ICOVF=3)

       DATA   SOME,THING /0.,1./

       IF(ICOVF.EQ.0) THEN
C        USER DEFINED SPECTRUM GOES HERE
         SPDF = SOME + THING
         RETURN
       END IF

C      EXPLANATION OF ANCIENT FORTRAN: (COMPUTED GO TO)
C      IF(ICOVF.EQ. 1,2,3)  THEN GO TO  (10,20,30)

       GO TO (10,20,30) ICOVF

10     DENOM =(1.+FRQ*FRQ)**1.5
       SPDF  = 0.5*FRQ/DENOM
       RETURN

20     XARG = 0.25*FRQ*FRQ
       SPDF = 0.25*FRQ*EXP(-XARG)
       RETURN

30     DENOM = (1.+FRQ*FRQ)**2.0
```

```
      SPDF  = 1.0*FRQ/DENOM
      RETURN
      END



      SUBROUTINE TBMPAR(IN,IT,IL,NLINE,XY)
C-----------------------------------------------------------------------
--
C     QUERY FOR TURNING BANDS LINE PARAMETERS

      PARAMETER  (PI=3.1415926)
      REAL         XY(*)
      INCLUDE 'tuba211d.inc'

C      WRITE(IT,10)
C 10    FORMAT(//' ++++++++++++  TURNING BANDS PARAMETERS  ++++++++++++'/)

C      WRITE(IT,*)'Enter The Number Of Turning Band Lines'
C      WRITE(IT,*)'         ( Use At Least 16 )'
C      WRITE(IT,*)
C      CALL RDINTG(IN,IT,IL,LINES,1,15)
      NLINE = LINES

      IF(ICOVF.EQ.0) THEN
        WRITE(IT,*)'(1) - Line Process By A Spectral Method'
             WRITE(IT,*)'(2) - Line Process By A Moving Average Method'
        WRITE(IT,*)
        CALL RDINTG(IN,IT,IL,IULP,1,13)
      ELSE
C        WRITE(IT,*)'For The Remaining Turning Band Parameters:'
C        WRITE(IT,*)'(1) - Use Default Turning Band Parameters'
C        WRITE(IT,*)'(2) - Enter The TBM Parameters Manually'
C        WRITE(IT,*)
C        CALL RDINTG(IN,IT,IL,IDFP,1,14)
         IDFP=1
        IF(IDFP.EQ.1) CALL DEFPAR(NLINE,XY)
        IF(IDFP.EQ.1) RETURN
      END IF

      WRITE(IT,*)'Enter The TBM Line Discretization Distance'
      WRITE(IT,*)'  (e.g., Smaller Than The Grid Spacing)'
      IF(ICOVF.NE.5) THEN
        WRITE(IT,*)'(e.g., 1/16th the Correlation Length)'
      END IF
      WRITE(IT,*)
      CALL RDREAL(IN,IT,IL,UN,1,16)

      IF(ICOVF.LE.3 .AND. IULP.NE.2) THEN
        WRITE(IT,*)'Enter NBR Of Harmonics For Discretizing Spectrum'
        WRITE(IT,*)
        CALL RDINTG(IN,IT,IL,NHAR,1,17)
C       SAJ METHOD BY DEFAULT, FFT METHOD IF NHAR=2**N FOR SOME N
        ISAJ = 1
        HMCS = NHAR
16      IF(HMCS/2 .GT. 1) THEN
          HMCS = HMCS/2
          GO TO 16
        END IF
        IF(HMCS.EQ.2) THEN
          FMAX = 2.*PI/(UN/AMAX1(CLX,CLY))
          ISAJ = 0
        END IF
        IF(ISAJ.EQ.1) THEN
          WRITE(IT,*)'Enter Max Frequency For Truncation Of Spectrum'
          WRITE(IT,*)
          CALL RDREAL(IN,IT,IL,FMAX,1,18)
        END IF
```

```
      END IF

      IF(ICOVF.EQ.4 .OR. IULP.EQ.2)  THEN
        WRITE(IT,*)'Enter Discretization Distance for the MA Process'
        WRITE(IT,*)'   (Suggest 1/20th Of The Correlation Length)'
        WRITE(IT,*)'(and No Larger Than 1/10th TBM Line Disc. Dist.)'
        WRITE(IT,*)
        CALL RDREAL(IN,IT,IL,DS,1,19)
      END IF

      DT = UN
      IF(ICOVF.EQ.5 .AND. (A3.NE.0 .OR. A5.NE.0) ) THEN
        WRITE(IT,*)'Enter Discretization Distance for Weiner Process'
        WRITE(IT,*)'(Suggest 1/5th Of The TBM Discretized Distance)'
        WRITE(IT,*)
      CALL RDREAL(IN,IT,IL,DT,1,20)
      END IF

      WRITE(IT,*)'Enter (Xo,Yo) Field Origin Relative To TBM Origin'
      WRITE(IT,*)
      CALL RDREAL(IN,IT,IL,XO,2,21)

      WRITE(IT,*)'Enter the Maximum Turning Band Line Length'
      WRITE(IT,*)
      CALL RDREAL(IN,IT,IL,TBMX,1,31)

      RETURN
      END



      FUNCTION UNITMB(ISEED)
C-----------------------------------------------------------------------------
--
C     URN01 generates UNIFORM RANDOM NUMBERS on the interval [0,1] using the
C     algorithm of Marsaglia and Bray presented in (pages 567 & 597) of:
C
C          "The Handbook of Random Number Generation and Testing
C                     with TESTRAND computer code"
C                   E. J. Dudewicz  and  T. G. Rally
C                  American Sciences Press, Inc. 1981.
C
C     This generator was "recommended for practical use"  (page 134)  by the
C     above authors.  This generator passed the very sensitive and
exhaustive
C     tests described in the above reference.
C-----------------------------------------------------------------------------
--
C     NOTE !!!  Compile with "integer overflow check" turned OFF
C-----------------------------------------------------------------------------
--
C     This version of Marsaglia's code was arranged by D. A. Zimmerman
C     at New Mexico Tech, Geoscience Dept., Hydrology Program, August, 1987.
C-----------------------------------------------------------------------------
--
C     DUMY = URNIT(ISEED)               ! Initialize Random Number
Generator
C     DO 10 I=1,N                       ! Generate N Uniformly Distributed
C 10  X(I) = URN01()                    ! Random Numbers On Interval [0,1]
C-----------------------------------------------------------------------------
--
      INTEGER      N1(64), N2(64), N(128), MS(6)
      EQUIVALENCE (N(1),N1), (N(65),N2), (MS(1),ML)
      COMMON      /SEEDS/ ML,MM,MK,L,M,K
C***  SEE BLOCK DATA MODULE
C***  DATA         L, M, K  /089347405, 301467177, 240420681/
C***  DATA         ML,MM,MK /65539, 33554433, 36243609/

```

```
      DATA         N1/  880431333,  845941495,  233211304, 1989552121,
     1      465185814,  280672924,  294923811,  969688974,  798989604,
     1      379880543,  130022074, 1958997525, 1074191695,  680854387,
     1      751282651, 1208899767,  695831691, 1667008051, 1682546364,
     1     1984522335,  287570376, 1137852001, 1597983496, 2015817872,
     1     1479672206, 1468443024, 1657203843,  326324124,  680973716,
     1     1451006002, 1251441372,  241092947, 1815086916, 1807193097,
     1      770906592,  725422944, 1822111098,  470585328,  939566271,
     1     1084841038, 1988336409,  229735215, 1763201387, 2072973152,
     1     1143606610,  548108569,  544252510, 1980873641, 1195919839,
     1     2089487851, 1406149582, 1839198022, 2106705200,  189238196,
     1     1170370207, 1304402631, 1936129483,  810953177,  706509560,
     1      476957499, 1307077413,  824336639, 1487297852, 1591453718/

      DATA         N2/ 1348888685,  155452792,  265840413, 1440038626,
     1      770186799, 1152058296, 1726999383, 1389732859, 1838014251,
     1     1751063044,  102451305,  212848938, 1046489181,  976388856,
     1     1797117421,  461971124,  259337424,  492056652, 1152625277,
     1     1087711027,  344810019, 1477716555,  809152324, 1766452264,
     1     1687482934, 1077592551, 1906112218,  328744821, 1380339247,
     1      339750038, 1993648985, 1054008271, 2006727977, 1618648061,
     1     1300903972,  168650429, 1734500183,  906733794,  614096451,
     1     1092917209, 1180334545,  577024776, 1406305431,  648073629,
     1      973807028,  883884075, 1562357277, 1705648154, 1377603620,
     1     1845151798,  220566094,  768813055,  571717967,  218994012,
     1      212872559, 1824677815, 1573937649,  450149130,  284847256,
     1     2062965934,   47834840, 1766553923, 1580332201,  182920702/

      I = MOD(ISEED,6) + 1
      MS(I) = ISEED
      RETURN

C     ENTRY URN01()
      ENTRY URNMB()
C---------------------------------------------------------------------
C     URN01 RETURNS  UNIFORMLY DISTRIBUTED RANDOM NUMBERS ON  [0.,1.]

      L = ML * L
      M = MM * M
      K = MK * K
      J = 1.0 + IABS(L) / 16777216
C     URN01 = 0.5 + FLOAT( N(J)+L+M ) * 0.23283064E-09
      URNMB =       FLOAT( N(J)+L+M ) * 0.23283064E-09
      N(J) = K

      RETURN
      END



      FUNCTION UNITSS(LU,ISEED)
C----------------------------------------------------------------------------
--
C     URN01 generates UNIFORM RANDOM NUMBERS on the interval [0,1]
C
C     Reference: C. G. Swain and M. S. Swain  1980.   "A Uniform
C                Random  Number  Generator That  Is Reproducible,
C                HARDWARE-INDEPENDENT, And Fast"  J. Chem. Inf.
C                Comput. Sci.  Vol 20.  pp 56-58.
C
C     According to E. J. Dudewicz, Dept. Statistics, Ohio State University,
C     in "Modern and Easy Generation of Random Numbers / Testing of Random
C     Number Generators with TESTRAND", 10th IMACS World Congress On System
C     Simulation and Scientific Computation, August 8-13, 1982, Montreal,
C     Canada, Proceedings, Volume 2, page 133, this generator  failed the
C     sensitive Chi-square on Chi-square test performed by the TESTRAND
code.
C----------------------------------------------------------------------------
```

```
--
C     This version of Swain & Swain's code was arranged by D. A. Zimmerman
C     at New Mexico Tech, Geoscience Dept., Hydrology Program,   June, 1986.
C-----------------------------------------------------------------------------
--
C     DUMY = URNIT(12345678)              ! INITIALIZE URNG:  ISEED=12345678
C     DO 10 K=1,N                         ! GENERATE N UNIFORMLY DISTRIBUTED
C 10  X(K) = URN01()                      ! RANDOM NUMBERS ON INTERVAL [0,1]
C-----------------------------------------------------------------------------
--
      PARAMETER (K1=35260417, K2=72619094, K3=86952743)
      INTEGER    M(0:3)
      DATA       M /0,K1,K2,K3 /

      SEED = FLOAT(ISEED)
      IPWR = ALOG10(SEED)

      IF(IPWR.NE.7) THEN
        WRITE(LU,*)' ***** URN GENERATOR SEED MUST BE 8 DIGITS LONG'
        WRITE(LU,*)'       PROGRAM EXECUTION HALTED'
        STOP
      END IF

      M(1) = K1
      M(2) = K2
      M(3) = K3

      I = MOD(ISEED,3) + 1
      M(I) = ISEED

      RETURN

C     ENTRY URN01()
      ENTRY URNSS()
C------------------------------------------------------------------
C     URN01 RETURNS UNIFORMLY DISTRIBUTED RANDOM NUMBERS ON [0.,1.]

      M(0) = M(1) + M(2) + M(3)

      IF(M(2) .LT.  50000000)  M(0) = M(0) + 1357
      IF(M(0) .GE. 100000000)  M(0) = M(0) - 100000000
      IF(M(0) .GE. 100000000)  M(0) = M(0) - 100000000

      M(1) = M(2)
      M(2) = M(3)
      M(3) = M(0)

C     URN01 = 1.0E-08 * M(0)
      URNSS = 1.0E-08 * M(0) - 0.5

      RETURN
      END




      FUNCTION URNAB(A,B)
C-------------------------------------------------------------------
C     URNAB returns uniformly distributed random numbers on [A,B]

comt  URNAB = A + (B-A) * URN01()
      URNAB = A + (B-A) * ( URN55() + 0.5 )

      RETURN
      END
```

```
      FUNCTION URN55()
C----------------------------------------------------------------------------
--
C     RETURN UNIFORMLY DISTRIBUTED RANDOM NUMBER ON INTERVAL [-.5,+.5]

      INCLUDE 'tuba211d.inc'

C     IURN = 1  MARSAGLIA AND BRAY RANDOM NUMBER GENERATOR  (RECOMMENDED)
C     IURN = 2  SWAIN AND SWAIN MACHINE INDEPENDENT RANDOM NUMBER GENERATOR

      IF(IURN.EQ.1) URN55 = URNMB()
      IF(IURN.EQ.2) URN55 = URNSS()

      RETURN
      END




      SUBROUTINE WNRLVY(Z1)
C----------------------------------------------------------------------------
--
C     NON STATIONARY CASE: WIENER-LEVY SIMULATION OF LINE PROCESS

      REAL     Z1(*)
      INCLUDE 'tuba211d.inc'

      Z1(1) = 0.0
      W1  = 0.0
      AI1 = 0.0
      BI1 = 0.0
      TT  = 0.0
      DO 20 N=2,NMAX
        DO 10 K=1,KT
          TT = TT+DT
          W2  = W1 + SG * URN55()
          AI1 = AI1 + 0.5*(W2+W1)*DT
          BI1 = BI1 + 0.5*(W1*(TT-DT)+TT*W2)*DT
          W1  = W2
10      CONTINUE
        Z1(N) = B0*W1 + (B1+B2*TT)*AI1 - B2*BI1
20    CONTINUE

      RETURN
      END




      FUNCTION WTEXP(OM,ACL,ASL,AL1,AL2)
C----------------------------------------------------------------------------
--
C     CALCULATE SPECTRAL DENSITY WEIGHTS FOR EXPONENTIAL AREAL AVERAGE
PROCESS

      AS = SIN(AL1*OM*ACL/2.)
      BS = SIN(AL2*OM*ASL/2.)

      IF(ACL.NE.0. .AND. ASL.NE.0.) THEN
        AL12 = AL1*AL1*AL2*AL2
        OMOM = OM*OM*OM*OM
        A1B1 = ACL*ACL*ASL*ASL
        ASBS = AS*AS*BS*BS
        ALOA = AL12*OMOM*A1B1
        WTEXP = ASBS*(16./ALOA)
      END IF

```

```
      IF(ACL.EQ.0.) WTEXP = BS*BS*(4./(AL2*AL2*ASL*ASL*OM*OM))
      IF(ASL.EQ.0.) WTEXP = AS*AS*(4./(AL1*AL1*ACL*ACL*OM*OM))

      RETURN
      END




      FUNCTION WTUSR(OM,ACL,ASL,AL1,AL2)
C-------------------------------------------------------------------------
--
C     RETURN SPECTRAL DENSITY WEIGHTS FOR USER-DEFINED AREAL AVERAGE PROCESS

      DATA    SOME,THING /0.,1./

C     SEE CHAPTERS 2 AND 5 OF THE DOCUMENTATION
      WTUSR = SOME + THING

      RETURN

```

APPENDIX B

Tables of Simulation Results

In this Appendix all simulation results are presented. There are two subsections. At the first numerical results of detection probability of an instantaneous groundwater pollution originating from a point source are presented. At the second subsection results of detection probability of a precipitation triggered pollution originating from a point source are presented. Results presented concern different field heterogeneities $\left(\sigma^2_{\ln K}\right)$, transeverse dispersion oefficients $\left(a_T\right)$, sampling frequencies and remedial action delay times. Abbreviations reffered into Tables are reading as:

nws:	normalized wells space
ndfs:	normalized distance from source
ndfs(max):	normalized distance from source where detection probability is maximum
$P_d\left(ED\right)$:	Detection probability if sampling is performed Every Day
$P_d\left(1M\right)$:	Detection probability if sampling is performed Monthly
$P_d\left(2M\right)$:	Detection probability if sampling is performed Bimonthly
$P_d\left(3M\right)$:	Detection probability if sampling is performed Quarterly
$P_d\left(4M\right)$:	Detection probability if sampling is performed Every 4Months
$P_d\left(6M\right)$:	Detection probability if sampling is performed Biannually
$P_d\left(12M\right)$:	Detection probability if sampling is performed Annually
RADTi:	*Remedial Action Delay Times*
NAV:	*Not Applicable Value (a computational problem during simulation returned a non valid number)*

B.1 Instantaneous Pollution

Table B.1: Detection probability in case of $\sigma^2_{\ln K} = 0.0$ and $\sigma^2_{\ln K} = 0.5$, for different sampling frequencies

		σ^2_{lnK}	0.00								0.50							
σ_r(m)	nws	No Wells	nfds(max)	P_d (ED)	P_d (1M)	P_d (2M)	P_d (3M)	P_d (4M)	P_d (6M)	P_d (12M)	nfds(max)	P_d (ED)	P_d (1M)	P_d (2M)	P_d (3M)	P_d (4M)	P_d (6M)	P_d (12M)
0.001	**1.00**	**1**	3.00	4.2	4.2	4.2	4.2	4.1	3.9	3.0	1.75	4.5	4.5	4.4	4.5	4.3	4.2	3.1
	0.50	**2**	3.00	8.5	8.2	8.2	8.0	7.9	7.6	6.1	1.75	8.1	8.1	8.0	7.8	7.8	7.4	5.6
	0.33	**3**	3.00	13.3	13.2	13.1	13.1	12.8	12.4	10.1	1.75	11.5	11.4	11.3	11.3	11.0	10.6	7.8
	0.25	**4**	3.00	16.9	16.8	16.5	16.4	16.1	16.0	12.4	1.75	14.5	14.2	14.1	14.0	13.8	13.2	9.2
	0.17	**6**	3.00	25.3	24.8	24.6	24.3	24.0	23.3	18.3	1.75	21.0	20.7	20.6	20.3	20.2	19.3	14.1
	0.12	**8**	3.00	33.0	32.6	32.3	32.2	31.8	31.5	24.4	1.75	28.1	27.7	27.5	27.2	26.6	25.7	18.2
	0.08	**12**	3.00	49.1	48.8	48.4	48.0	47.4	46.6	36.3	1.75	42.0	41.5	41.1	40.8	40.3	38.3	28.1
	0.05	**20**	3.00	82.7	81.8	81.0	80.4	79.6	77.8	61.0	1.75	64.2	63.7	63.2	62.7	62.0	59.8	44.4
0.010	**1.00**	**1**	2.25	6.0	5.7	5.6	5.5	5.4	5.4	4.9	1.50	5.4	5.2	5.2	5.2	5.1	5.0	4.5
	0.50	**2**	2.25	12.0	11.6	11.3	11.3	10.8	10.8	10.2	1.50	10.9	10.6	10.5	10.3	10.2	10.0	8.9
	0.33	**3**	2.25	18.9	18.2	17.8	17.5	17.1	16.9	15.9	1.50	15.1	14.5	14.3	14.1	13.9	13.6	11.8
	0.25	**4**	2.25	23.9	23.3	23.0	22.8	22.5	22.1	20.4	1.50	20.7	20.2	19.9	19.6	19.3	18.9	16.6
	0.17	**6**	2.25	35.4	34.3	33.6	33.4	32.7	32.3	29.8	1.50	30.7	29.5	29.0	28.6	28.2	27.5	24.1
	0.12	**8**	2.25	47.2	45.5	44.8	44.2	43.3	42.8	39.9	1.50	41.5	39.7	38.9	38.3	37.9	37.1	32.7
	0.08	**12**	2.25	70.5	68.5	67.4	66.7	65.8	64.8	59.5	1.50	57.0	55.5	54.5	53.5	53.1	51.8	46.7
	0.05	**20**	2.25	99.6	99.5	99.4	99.4	99.3	99.3	95.1	1.50	77.2	75.9	75.0	74.2	73.5	72.7	66.8
0.02	**1.00**	**1**	1.50	5.8	5.6	5.5	5.4	5.3	5.2	4.5	0.50	5.9	5.9	5.9	5.7	5.7	5.6	4.5
	0.50	**2**	1.50	11.7	11.1	10.7	10.4	10.3	10.0	8.8	0.50	11.6	11.2	11.1	11.0	10.9	10.8	8.8
	0.33	**3**	1.50	18.2	17.5	17.0	16.7	16.3	15.9	14.0	0.50	16.9	16.6	16.4	15.9	16.0	15.5	12.8
	0.25	**4**	1.50	23.5	22.2	21.9	21.5	21.2	20.8	19.2	0.50	22.1	21.2	20.9	20.7	20.4	20.1	17.0
	0.17	**6**	1.50	34.6	32.9	31.8	31.2	31.0	30.2	27.4	0.50	33.2	32.4	32.0	31.7	31.2	30.8	25.8
	0.12	**8**	1.50	46.3	43.9	43.0	42.1	41.5	40.2	36.5	0.50	43.6	42.0	41.5	40.9	40.7	39.5	33.8
	0.08	**12**	1.50	69.0	65.6	64.5	63.2	62.4	60.3	55.0	0.50	61.9	60.0	59.2	58.7	58.0	57.0	48.6
	0.05	**20**	1.50	99.4	99.3	99.0	98.7	98.5	97.1	89.4	0.50	84.4	83.0	82.2	81.9	81.6	80.8	71.8
0.05	**1.00**	**1**	0.50	5.8	5.5	5.2	5.3	5.1	4.9	4.4	0.50	5.6	5.0	4.7	4.5	4.2	4.0	3.0
	0.50	**2**	0.50	11.6	10.8	10.4	10.4	10.2	9.7	8.2	0.50	10.8	9.6	9.2	8.8	8.6	8.2	5.9
	0.33	**3**	0.50	18.2	17.3	16.7	16.3	16.3	15.6	13.9	0.50	14.9	13.6	12.9	12.6	12.0	11.5	8.9
	0.25	**4**	0.50	23.5	22.3	21.3	21.2	20.8	20.0	17.6	0.50	19.8	17.8	17.1	16.4	15.8	14.7	11.5
	0.17	**6**	0.50	34.1	31.9	31.0	30.6	30.2	29.0	25.3	0.50	29.9	27.0	25.5	24.7	24.0	22.8	17.0
	0.12	**8**	0.50	45.8	43.2	42.2	41.3	40.5	39.4	34.7	0.50	39.1	35.1	33.7	33.0	31.5	29.7	23.4
	0.08	**12**	0.50	69.0	65.1	63.0	61.9	60.7	59.0	52.3	0.50	55.7	50.2	48.0	46.2	44.4	41.8	33.2
	0.05	**20**	0.50	99.4	98.9	98.1	97.4	96.5	94.9	84.7	0.50	78.2	73.4	70.9	69.2	67.4	64.5	51.7
0.10	**1.00**	**1**	0.125	5.7	5.3	5.1	4.9	5.0	4.7	4.4	0.125	6.4	5.9	5.6	5.3	5.2	4.8	4.0
	0.50	**2**	0.125	11.3	10.4	10.1	9.8	9.7	9.5	8.2	0.125	10.3	9.2	9.0	8.5	8.7	8.1	6.7
	0.33	**3**	0.125	18.1	16.9	16.4	15.9	16.0	15.3	13.9	0.125	16.2	14.9	14.4	13.9	13.5	12.9	10.3
	0.25	**4**	0.125	23.2	21.7	21.1	20.8	20.4	19.8	17.2	0.125	20.0	18.0	17.2	16.5	16.4	15.3	12.7
	0.17	**6**	0.125	33.9	31.8	30.9	30.0	29.5	28.6	25.1	0.125	30.3	28.0	27.1	26.0	25.7	24.3	19.9
	0.12	**8**	0.125	45.8	42.6	41.4	40.7	39.9	38.8	34.1	0.125	42.2	38.4	37.1	35.9	36.0	33.8	27.6
	0.08	**12**	0.125	67.9	63.7	62.0	60.5	59.8	57.5	51.1	0.125	62.2	56.4	54.6	52.3	51.8	48.7	39.8
	0.05	**20**	0.125	99.1	97.3	96.0	95.1	93.9	92.3	83.6	0.125	87.0	81.9	79.9	77.9	76.5	73.2	60.7
0.20	**1.00**	**1**	0.030	4.7	4.1	3.8	3.6	3.6	3.3	2.7	0.030	4.8	4.2	4.1	4.0	3.9	3.7	2.7
	0.50	**2**	0.030	8.4	7.4	7.0	6.7	6.5	6.3	4.8	0.030	7.9	6.8	6.4	6.1	5.9	5.4	3.9
	0.33	**3**	0.030	14.3	12.3	11.6	10.9	11.0	10.1	8.1	0.030	12.9	11.2	10.9	10.6	10.4	9.8	7.2
	0.25	**4**	0.030	18.0	15.2	14.4	13.7	13.6	12.5	9.4	0.030	15.3	13.5	12.9	12.3	12.0	11.5	8.0
	0.17	**6**	0.030	26.1	22.5	21.2	20.5	19.5	19.2	14.6	0.030	24.1	20.2	19.2	18.6	17.9	16.7	11.7
	0.12	**8**	0.030	36.1	30.7	29.1	27.9	27.5	26.1	20.0	0.030	32.5	28.5	27.1	25.9	25.4	23.2	16.2
	0.08	**12**	0.030	53.9	46.0	44.3	42.1	42.0	39.1	30.2	0.030	48.3	42.3	40.5	39.2	37.9	35.9	25.3
	0.05	**20**	0.030	80.8	70.9	68.2	65.9	64.8	62.1	47.7	0.030	69.6	61.7	59.7	58.0	56.6	53.3	37.4
0.50	**1.00**	**1**	0.015	2.4	2.2	1.9	1.9	1.9	1.7	0.1	0.015	3.0	2.6	2.4	2.2	2.1	1.8	0.9
	0.50	**2**	0.015	4.9	4.1	3.9	3.7	3.7	3.4	0.3	0.015	4.5	3.7	3.4	3.3	3.2	2.5	1.0
	0.33	**3**	0.015	7.3	6.2	5.8	5.6	5.5	5.0	0.4	0.015	7.8	6.9	6.6	6.2	5.9	4.9	1.8
	0.25	**4**	0.015	8.6	7.2	6.8	6.7	6.5	6.0	0.8	0.015	7.8	6.6	6.1	6.0	5.7	4.9	1.5
	0.17	**6**	0.015	13.7	11.5	11.1	10.7	10.5	9.8	0.8	0.015	13.5	10.9	10.5	10.0	9.3	7.8	2.8
	0.12	**8**	0.015	18.2	15.1	14.4	13.7	13.5	12.5	1.3	0.015	18.0	15.1	14.4	13.7	13.0	10.6	3.4
	0.08	**12**	0.015	27.6	23.9	22.5	22.2	21.3	19.8	2.4	0.015	27.5	22.6	21.3	20.5	19.5	16.1	5.6
	0.05	**20**	0.015	40.5	36.7	35.0	34.2	33.4	31.0	3.1	0.015	38.2	34.0	32.8	31.7	30.0	25.4	8.7

Table B.2: Detection probability in case of $\sigma^2_{\ln K} = 1.0$ and $\sigma^2_{\ln K} = 1.5$, for different sampling frequencies

		σ^2_{lnK}					1.00								1.50			
αr(m)	nws	No WeLLs	nfds(max)	Pd (ED)	Pd (1M)	Pd (2M)	Pd (3M)	Pd (4M)	Pd (6M)	Pd (12M)	nfds(max)	Pd (ED)	Pd (1M)	Pd (2M)	Pd (3M)	Pd (4M)	Pd (6M)	Pd (12M)
0.001	1.00	1	1.75	3.8	3.8	3.8	3.7	3.7	3.6	2.7	1.25	3.9	3.8	3.8	3.8	3.7	3.3	2.5
	0.50	2	1.75	7.1	7.0	6.9	6.8	6.8	6.5	5.0	1.25	7.2	7.2	7.1	7.0	6.7	6.4	4.8
	0.33	3	1.75	9.8	9.7	9.6	9.5	9.4	9.1	6.9	1.25	9.4	9.3	9.2	9.1	8.8	8.0	6.1
	0.25	4	1.75	14.0	13.8	13.5	13.4	13.0	12.4	9.5	1.25	13.3	13.2	13.1	12.7	12.7	11.5	8.2
	0.17	6	1.75	20.6	20.3	20.1	19.8	19.6	18.5	14.2	1.25	20.9	20.7	20.4	19.9	19.5	18.1	13.7
	0.12	8	1.75	26.5	26.1	25.9	25.5	25.4	24.1	17.6	1.25	25.7	25.3	24.8	24.4	23.5	21.9	16.2
	0.08	12	1.75	39.9	39.3	38.8	38.5	37.6	36.2	27.8	1.25	35.6	35.2	34.9	34.3	33.8	31.0	23.0
	0.05	20	1.75	57.2	56.4	55.9	55.2	54.8	52.5	41.5	1.25	54.9	54.4	54.0	52.8	52.3	48.1	36.0
0.010	1.00	1	1.25	5.7	5.3	5.2	5.2	5.1	5.0	4.0	1.00	5.0	4.7	4.7	4.6	4.6	4.3	3.4
	0.50	2	1.25	9.5	9.1	8.8	8.7	8.5	8.2	6.9	1.00	9.0	8.6	8.3	8.2	7.9	7.8	6.1
	0.33	3	1.25	14.7	14.0	13.6	13.4	13.2	12.8	10.4	1.00	13.5	12.9	12.7	12.4	12.2	11.4	9.1
	0.25	4	1.25	18.1	17.5	17.1	16.7	16.5	16.0	13.1	1.00	16.9	16.3	15.8	15.7	15.4	14.6	11.6
	0.17	6	1.25	27.4	26.3	25.6	25.0	24.5	23.8	19.9	1.00	24.2	23.0	22.4	21.9	21.4	20.7	16.1
	0.12	8	1.25	35.7	34.4	33.6	32.9	32.6	31.3	25.6	1.00	33.2	31.8	30.9	30.7	30.0	28.7	22.4
	0.08	12	1.25	50.4	48.4	47.8	46.7	46.2	45.2	37.5	1.00	45.8	44.4	43.4	43.0	42.3	40.1	32.5
	0.05	20	1.25	68.8	66.7	65.7	64.7	64.3	62.4	53.6	1.00	61.6	59.9	59.0	58.8	57.7	56.2	46.7
0.02	1.00	1	0.50	6.3	5.9	5.7	5.7	5.6	5.3	4.5	0.50	5.7	5.4	5.4	5.3	5.2	4.6	3.9
	0.50	2	0.50	10.1	9.7	9.6	9.5	9.3	8.9	7.3	0.50	9.7	9.3	9.2	9.0	8.9	8.3	6.8
	0.33	3	0.50	17.0	16.2	15.9	15.7	15.5	14.8	12.0	0.50	14.8	14.0	13.6	13.5	13.0	12.2	10.0
	0.25	4	0.50	20.5	19.7	19.3	19.2	18.9	18.6	15.4	0.50	18.9	18.2	17.8	17.4	17.2	16.2	12.7
	0.17	6	0.50	28.5	27.5	26.9	26.6	26.0	25.0	20.7	0.50	28.1	26.9	26.6	26.3	25.8	24.5	20.0
	0.12	8	0.50	42.1	40.8	39.9	39.3	38.6	37.0	29.9	0.50	36.7	35.3	34.3	33.8	33.2	31.6	25.2
	0.08	12	0.50	57.5	55.6	54.7	53.9	53.5	52.2	44.1	0.50	50.0	48.4	47.5	46.8	46.2	43.6	35.5
	0.05	20	0.50	77.0	75.5	74.6	74.2	73.5	72.0	61.9	0.50	69.1	67.1	66.2	65.5	64.8	62.7	52.8
0.05	1.00	1	0.13	5.7	5.6	5.5	5.4	5.1	5.0	3.7	0.13	5.5	5.2	5.1	4.9	4.8	4.6	3.8
	0.50	2	0.13	11.6	11.2	11.1	10.9	10.7	10.4	8.4	0.13	11.3	10.7	10.4	10.4	10.0	9.7	8.1
	0.33	3	0.13	17.0	16.5	16.2	16.0	15.4	14.8	11.9	0.13	14.9	14.5	14.2	13.9	13.8	13.2	11.2
	0.25	4	0.13	22.0	21.3	21.0	20.7	20.4	19.6	16.9	0.13	19.3	18.4	17.9	17.6	17.4	16.5	13.6
	0.17	6	0.13	33.3	31.9	31.2	30.8	30.2	29.2	23.7	0.13	31.8	30.4	29.5	29.6	28.3	27.4	22.8
	0.12	8	0.13	43.5	42.1	41.5	40.9	40.3	39.0	32.7	0.13	40.1	38.6	37.8	37.4	36.9	35.1	29.2
	0.08	12	0.13	61.8	59.7	59.1	58.3	57.5	55.8	47.1	0.13	57.6	55.4	54.4	53.7	52.7	50.5	41.7
	0.05	20	0.13	86.3	84.7	84.2	83.1	82.9	80.6	68.7	0.13	81.6	79.6	78.3	78.0	76.8	74.0	63.3
0.10	1.00	1	0.063	5.4	5.1	5.1	4.8	4.8	4.6	3.7	0.063	6.1	5.6	5.4	5.3	5.1	4.8	3.8
	0.50	2	0.063	11.1	10.2	9.9	9.7	9.5	9.0	7.3	0.063	10.3	9.5	9.1	8.8	8.5	8.1	6.3
	0.33	3	0.063	17.1	15.9	15.8	15.2	14.9	14.1	10.9	0.063	15.8	14.3	13.9	13.6	13.2	12.4	9.9
	0.25	4	0.063	21.6	20.4	19.9	19.6	19.0	18.1	14.3	0.063	19.9	18.6	18.1	17.5	17.1	16.0	11.9
	0.17	6	0.063	31.6	29.4	28.5	27.6	27.1	25.5	19.7	0.063	29.7	27.1	26.3	25.2	24.6	23.0	18.1
	0.12	8	0.063	43.2	40.0	38.6	37.8	36.8	34.8	27.6	0.063	40.0	36.5	35.3	34.0	33.4	31.5	25.0
	0.08	12	0.063	60.8	56.5	54.8	53.7	52.5	49.5	38.8	0.063	57.6	54.2	52.4	51.0	49.8	46.2	35.5
	0.05	20	0.063	86.2	82.7	81.0	79.5	78.5	74.9	59.3	0.063	80.8	76.9	75.5	73.8	72.4	68.7	53.2
0.20	1.00	1	0.030	4.0	3.4	3.2	3.0	3.0	2.7	1.7	0.015	4.1	3.4	3.1	2.9	2.8	2.5	1.5
	0.50	2	0.030	7.7	6.5	6.2	6.1	5.6	5.2	3.5	0.015	8.4	7.3	7.0	6.8	6.4	5.8	4.0
	0.33	3	0.030	12.8	11.2	10.6	10.3	10.0	9.2	5.9	0.015	12.1	10.6	9.8	9.4	8.8	8.2	5.3
	0.25	4	0.030	16.6	14.5	13.9	13.2	13.1	11.8	8.2	0.015	15.2	13.3	12.7	12.1	11.5	10.4	7.2
	0.17	6	0.030	22.0	19.2	18.0	17.8	16.7	15.6	10.0	0.015	23.3	20.1	19.2	18.1	17.1	15.6	10.5
	0.12	8	0.030	31.1	26.6	25.3	24.5	23.2	21.3	14.7	0.015	31.3	27.7	25.9	25.4	23.7	21.6	14.4
	0.08	12	0.030	44.7	38.6	37.0	35.8	34.3	31.7	21.0	0.015	46.2	40.4	38.4	37.3	35.0	31.7	21.5
	0.05	20	0.030	64.6	57.8	55.6	53.6	52.7	48.0	32.8	0.015	65.3	58.8	56.8	54.8	52.1	47.6	32.9
0.50	1.00	1	0.015	2.2	2.0	1.9	1.6	1.5	1.2	0.4	0.015	1.9	1.4	1.4	1.3	1.2	0.9	0.4
	0.50	2	0.015	4.2	3.6	3.4	3.2	3.0	2.4	0.7	0.015	4.4	3.7	3.4	3.2	2.9	2.1	1.2
	0.33	3	0.015	7.7	6.7	6.4	5.8	5.4	4.1	1.6	0.015	6.4	5.4	5.1	4.7	4.4	3.3	1.7
	0.25	4	0.015	9.0	7.5	7.0	6.5	6.1	4.8	2.1	0.015	8.2	7.1	6.8	6.3	5.6	4.6	2.4
	0.17	6	0.015	12.7	10.9	10.4	9.7	9.3	7.2	2.7	0.015	12.5	10.6	9.9	9.1	8.4	6.2	3.3
	0.12	8	0.015	18.1	15.6	14.4	13.4	12.2	9.5	4.0	0.015	16.5	14.3	13.2	12.2	11.0	8.6	4.2
	0.08	12	0.015	25.3	21.6	20.5	19.0	17.8	14.0	5.7	0.015	24.9	21.0	19.9	18.0	16.3	13.0	6.4
	0.05	20	0.015	36.9	32.9	31.5	29.8	28.0	22.3	9.2	0.015	34.6	30.8	29.6	27.4	24.9	20.4	9.9

Table B.3 Detection probability in case of $\sigma^2_{\ln K} = 2.0$, for different sampling frequencies

		$\sigma^2_{\ln K}$					2.00			
α_T(m)	nws	No WelLs	nfds(max)	P_d (ED)	P_d (1M)	P_d (2M)	P_d (3M)	P_d (4M)	P_d (6M)	P_d (12M)
0.001	1.00	1	0.75	3.4	3.4	3.3	3.3	3.1	2.8	1.7
	0.50	2	0.75	6.8	6.7	6.7	6.4	6.0	5.6	3.9
	0.33	3	0.75	9.2	9.1	8.8	8.5	8.2	7.2	5.1
	0.25	4	0.75	11.9	11.8	11.5	11.0	10.6	9.7	6.7
	0.17	6	0.75	19.3	18.9	18.6	18.1	17.3	15.6	11.1
	0.12	8	0.75	24.3	23.9	23.4	22.6	21.6	19.6	14.3
	0.08	12	0.75	34.2	33.6	32.8	31.8	30.4	27.6	19.5
	0.05	20	0.75	53.1	52.3	51.6	49.9	47.6	43.4	30.6
0.010	1.00	1	0.50	5.3	5.1	5.1	5.1	4.8	4.7	3.3
	0.50	2	0.50	8.0	7.9	7.8	7.7	7.6	7.1	5.8
	0.33	3	0.50	14.2	13.9	13.8	13.6	13.1	12.4	9.7
	0.25	4	0.50	16.8	16.5	16.2	16.0	15.8	14.9	12.0
	0.17	6	0.50	23.8	23.2	22.7	22.5	22.1	20.9	16.9
	0.12	8	0.50	32.3	31.6	31.1	30.7	30.0	28.4	22.8
	0.08	12	0.50	46.8	45.8	45.2	44.4	43.6	40.9	33.6
	0.05	20	0.50	64.7	63.4	62.7	62.1	61.1	58.2	47.5
0.02	1.00	1	0.25	5.0	4.9	4.8	4.7	4.7	4.6	3.8
	0.50	2	0.25	10.4	10.0	9.7	9.5	9.4	8.9	7.1
	0.33	3	0.25	13.5	13.0	12.9	12.7	12.4	12.0	9.7
	0.25	4	0.25	17.7	17.2	16.7	16.7	16.2	15.4	12.3
	0.17	6	0.25	28.0	27.1	26.7	26.0	25.7	24.4	19.8
	0.12	8	0.25	36.7	35.3	34.5	34.3	33.3	31.6	25.4
	0.08	12	0.25	50.6	49.1	48.1	47.6	46.2	44.0	35.5
	0.05	20	0.25	71.7	70.2	69.0	68.6	67.0	64.6	54.4
0.05	1.00	1	0.13	5.1	4.9	4.7	4.6	4.4	4.1	3.0
	0.50	2	0.13	10.6	9.9	9.6	9.4	9.1	8.4	7.0
	0.33	3	0.13	14.0	13.4	13.0	12.6	12.4	11.5	9.0
	0.25	4	0.13	19.9	19.2	18.9	18.7	18.1	17.6	13.9
	0.17	6	0.13	29.8	28.3	27.8	27.0	26.5	24.7	20.3
	0.12	8	0.13	40.4	38.3	37.5	37.1	36.1	34.3	27.0
	0.08	12	0.13	56.4	54.2	53.1	52.2	51.2	48.2	39.1
	0.05	20	0.13	76.9	74.8	73.9	73.1	71.7	68.9	56.9
0.10	1.00	1	0.063	4.9	4.6	4.4	4.1	4.1	3.9	3.1
	0.50	2	0.063	10.3	9.6	9.3	9.0	8.6	8.1	6.4
	0.33	3	0.063	14.7	13.7	13.0	12.4	12.2	11.5	8.4
	0.25	4	0.063	19.2	17.9	17.3	16.6	15.8	14.6	10.5
	0.17	6	0.063	28.9	26.6	25.7	25.0	24.0	22.7	17.2
	0.12	8	0.063	37.5	34.7	33.2	32.4	31.2	29.2	22.7
	0.08	12	0.063	54.5	50.4	48.9	47.1	45.6	42.7	32.5
	0.05	20	0.063	74.7	71.1	69.4	67.8	65.9	61.9	47.9
0.20	1.00	1	0.015	3.8	3.5	3.4	3.2	3.0	2.7	1.9
	0.50	2	0.015	7.8	6.8	6.3	6.0	5.6	5.2	3.8
	0.33	3	0.015	12.2	10.4	10.0	9.4	8.9	7.9	5.1
	0.25	4	0.015	15.5	13.2	12.4	11.8	11.0	9.6	6.0
	0.17	6	0.015	22.0	19.0	17.8	16.6	15.8	14.3	9.7
	0.12	8	0.015	29.2	24.8	23.4	22.2	21.2	18.6	12.6
	0.08	12	0.015	44.0	38.2	36.2	34.8	33.0	29.4	18.6
	0.05	20	0.015	62.3	55.6	53.0	50.9	48.6	43.4	29.9
0.50	1.00	1	0.015	2.1	1.8	1.7	1.5	1.4	1.0	0.7
	0.50	2	0.015	4.6	3.8	3.2	2.9	2.7	2.2	1.4
	0.33	3	0.015	6.8	5.4	4.9	4.4	4.0	3.1	1.8
	0.25	4	0.015	8.9	7.8	7.3	6.5	6.0	4.3	1.7
	0.17	6	0.015	12.0	10.0	8.9	8.0	7.3	5.6	3.4
	0.12	8	0.015	16.6	13.9	12.5	11.8	10.6	8.4	4.6
	0.08	12	0.015	25.4	22.1	20.5	19.2	17.5	13.5	6.0
	0.05	20	0.015	34.7	30.6	28.9	26.8	24.6	19.3	9.9

Table B.4: Detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area L for various RADTi in case of $\sigma^2_{\ln K} = 0.0$ assuming daily (ED) and monthly (1M) sampling frequencies

	$\sigma^2_{\ln K}$									0.00										
α_T(m)	now	nfds(max)	P_d (ED)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L	P_d (1M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	**1**	3.00	4.2	9495	0.03	0.02	0.02	0.03	0.03	0.03	0.02	4.2	9513	0.03	0.02	0.02	0.03	0.03	0.03	0.02
	2	3.00	8.5	9529	0.03	0.03	0.03	0.03	0.03	0.03	0.02	8.2	9542	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	3	3.00	13.3	9524	0.03	0.02	0.03	0.03	0.03	0.03	0.02	13.2	9540	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	4	3.00	16.9	9562	0.03	0.03	0.03	0.03	0.03	0.03	0.02	16.8	9578	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	6	3.00	25.3	9530	0.03	0.03	0.03	0.03	0.03	0.03	0.02	24.8	9541	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	8	3.00	33.0	9520	0.03	0.03	0.03	0.03	0.03	0.03	0.02	32.6	9534	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	12	3.00	49.1	9524	0.03	0.03	0.03	0.03	0.03	0.03	0.02	48.8	9538	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	20	3.00	82.7	9524	0.03	0.03	0.03	0.03	0.03	0.03	0.02	81.8	9539	0.03	0.03	0.03	0.03	0.03	0.03	0.02
0.01	**1**	2.25	6.0	7173	0.18	0.13	0.13	0.13	0.13	0.14	0.14	5.7	7187	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	2	2.25	12.0	7196	0.18	0.13	0.13	0.13	0.13	0.14	0.14	11.6	7214	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	3	2.25	18.9	7196	0.18	0.13	0.13	0.13	0.13	0.14	0.14	18.2	7213	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	4	2.25	23.9	7222	0.18	0.13	0.13	0.13	0.13	0.14	0.14	23.3	7238	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	6	2.25	35.4	7201	0.18	0.13	0.13	0.13	0.13	0.14	0.14	34.3	7218	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	8	2.25	47.2	7196	0.18	0.13	0.13	0.13	0.13	0.14	0.14	45.5	7211	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	12	2.25	70.5	7193	0.18	0.13	0.13	0.13	0.13	0.14	0.14	68.5	7209	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	20	2.25	99.6	7176	0.18	0.13	0.13	0.13	0.13	0.14	0.14	99.5	7195	0.18	0.13	0.13	0.13	0.13	0.14	0.14
0.02	**1**	1.50	5.8	4929	0.31	0.16	0.17	0.17	0.17	0.18	0.19	5.6	4940	0.31	0.16	0.17	0.17	0.17	0.18	0.19
	2	1.50	11.7	4938	0.31	0.16	0.17	0.17	0.17	0.18	0.19	11.1	4959	0.31	0.16	0.17	0.17	0.17	0.18	0.19
	3	1.50	18.2	4942	0.31	0.16	0.17	0.17	0.17	0.18	0.19	17.5	4962	0.31	0.16	0.17	0.17	0.17	0.18	0.19
	4	1.50	23.5	4969	0.31	0.16	0.17	0.17	0.17	0.18	0.19	22.2	4988	0.31	0.16	0.17	0.17	0.17	0.18	0.19
	6	1.50	34.6	4948	0.31	0.16	0.17	0.17	0.17	0.18	0.19	32.9	4965	0.31	0.16	0.17	0.17	0.17	0.18	0.19
	8	1.50	46.3	4941	0.31	0.16	0.17	0.17	0.17	0.18	0.19	43.9	4961	0.31	0.16	0.17	0.17	0.17	0.18	0.19
	12	1.50	69.0	4939	0.31	0.16	0.17	0.17	0.17	0.18	0.19	65.6	4955	0.31	0.16	0.17	0.17	0.17	0.18	0.19
	20	1.50	99.4	4929	0.31	0.16	0.17	0.17	0.17	0.18	0.19	99.3	4954	0.31	0.16	0.17	0.17	0.17	0.18	0.19
0.05	**1**	0.50	5.8	1898	0.63	0.16	0.16	0.17	0.18	0.21	0.23	5.5	1909	0.63	0.16	0.16	0.17	0.18	0.21	0.23
	2	0.50	11.6	1919	0.63	0.16	0.17	0.17	0.18	0.21	0.23	10.8	1937	0.63	0.16	0.17	0.17	0.18	0.21	0.23
	3	0.50	18.2	1929	0.63	0.16	0.17	0.17	0.18	0.21	0.23	17.3	1943	0.63	0.16	0.17	0.17	0.19	0.21	0.23
	4	0.50	23.5	1959	0.63	0.16	0.17	0.17	0.19	0.21	0.23	22.3	1975	0.63	0.16	0.17	0.18	0.19	0.21	0.23
	6	0.50	34.1	1929	0.63	0.16	0.17	0.17	0.18	0.21	0.23	31.9	1943	0.63	0.16	0.17	0.17	0.19	0.21	0.23
	8	0.50	45.8	1924	0.63	0.16	0.17	0.17	0.18	0.21	0.23	43.2	1941	0.63	0.16	0.17	0.17	0.19	0.21	0.23
	12	0.50	69.0	1923	0.63	0.16	0.17	0.17	0.18	0.21	0.23	65.1	1941	0.63	0.16	0.17	0.17	0.19	0.21	0.23
	20	0.50	99.4	1920	0.64	0.16	0.17	0.17	0.18	0.21	0.23	98.9	1947	0.64	0.16	0.17	0.17	0.19	0.21	0.23
0.10	**1**	0.125	5.7	739	1.06	0.13	0.14	0.15	0.18	0.22	0.27	5.3	760	1.06	0.13	0.14	0.16	0.18	0.23	0.27
	2	0.125	11.3	778	1.06	0.13	0.15	0.16	0.18	0.23	0.27	10.4	786	1.06	0.13	0.15	0.16	0.18	0.23	0.27
	3	0.125	18.1	772	1.06	0.13	0.14	0.16	0.18	0.23	0.27	16.9	781	1.06	0.13	0.15	0.16	0.18	0.23	0.27
	4	0.125	23.2	803	1.06	0.14	0.15	0.16	0.19	0.23	0.28	21.7	813	1.06	0.14	0.15	0.16	0.19	0.23	0.28
	6	0.125	33.9	784	1.06	0.13	0.15	0.16	0.18	0.23	0.27	31.8	793	1.06	0.13	0.15	0.16	0.18	0.23	0.28
	8	0.125	45.8	776	1.06	0.13	0.15	0.16	0.18	0.23	0.27	42.6	787	1.06	0.13	0.15	0.16	0.18	0.23	0.27
	12	0.125	67.9	772	1.06	0.13	0.14	0.16	0.18	0.23	0.27	63.7	784	1.06	0.13	0.15	0.16	0.18	0.23	0.27
	20	0.125	99.1	772	1.06	0.13	0.14	0.16	0.18	0.23	0.27	97.3	788	1.06	0.13	0.15	0.16	0.18	0.23	0.27
0.20	**1**	0.030	4.7	374	1.70	0.13	0.15	0.18	0.22	0.31	0.39	4.1	356	1.70	0.12	0.15	0.17	0.22	0.31	0.39
	2	0.030	8.4	356	1.70	0.12	0.15	0.17	0.22	0.31	0.39	7.4	331	1.70	0.11	0.14	0.17	0.21	0.30	0.38
	3	0.030	14.3	378	1.70	0.13	0.15	0.18	0.23	0.31	0.39	12.3	353	1.70	0.12	0.15	0.17	0.22	0.31	0.39
	4	0.030	18.0	414	1.70	0.14	0.16	0.19	0.23	0.32	0.40	15.2	380	1.70	0.13	0.15	0.18	0.23	0.31	0.39
	6	0.030	26.1	386	1.70	0.13	0.15	0.18	0.23	0.31	0.39	22.5	355	1.70	0.12	0.15	0.17	0.22	0.31	0.39
	8	0.030	36.1	394	1.70	0.13	0.16	0.18	0.23	0.32	0.39	30.7	362	1.70	0.12	0.15	0.17	0.22	0.31	0.39
	12	0.030	53.9	385	1.70	0.13	0.15	0.18	0.23	0.31	0.39	46.0	352	1.70	0.12	0.15	0.17	0.22	0.31	0.39
	20	0.030	80.8	394	1.71	0.13	0.16	0.18	0.23	0.32	0.39	70.9	355	1.71	0.12	0.15	0.17	0.22	0.31	0.39
0.50	**1**	0.015	2.4	93	2.94	0.08	0.15	0.21	0.32	0.51	0.68	2.2	104	2.94	0.09	0.16	0.22	0.33	0.52	0.68
	2	0.015	4.9	96	2.94	0.08	0.15	0.21	0.32	0.51	0.68	4.1	94	2.94	0.09	0.15	0.21	0.32	0.51	0.68
	3	0.015	7.3	104	2.94	0.09	0.16	0.22	0.33	0.51	0.68	6.2	102	2.94	0.09	0.16	0.22	0.33	0.51	0.68
	4	0.015	8.6	102	2.95	0.09	0.16	0.22	0.33	0.51	0.68	7.2	104	2.94	0.09	0.16	0.22	0.33	0.51	0.68
	6	0.015	13.7	97	2.95	0.09	0.15	0.21	0.32	0.51	0.68	11.5	94	2.95	0.09	0.15	0.21	0.32	0.51	0.68
	8	0.015	18.2	107	2.96	0.09	0.16	0.22	0.33	0.52	0.68	15.1	99	2.95	0.09	0.16	0.22	0.32	0.51	0.68
	12	0.015	27.6	98	2.97	0.09	0.15	0.21	0.32	0.51	0.68	23.9	100	2.96	0.09	0.16	0.22	0.33	0.51	0.68
	20	0.015	40.5	94	2.99	0.08	0.15	0.21	0.32	0.51	0.67	36.7	98	2.98	0.09	0.16	0.21	0.32	0.51	0.68

Table B.5: Detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area L for various RADTi in case of $\sigma^2_{\ln K} = 0.0$ assuming bimonthly (2M) and quarterly (3M) sampling frequencies

	$\sigma^2_{\ln K}$									0.00										
α_T(m)	now	nfds(max)	P_d (2M)	$<T_{(DET.)}>$ (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L	P_d (3M)	$<T_{(DET.)}>$ (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi)/L)	(36M. RADTi)/L
0.001	1	3.00	4.2	9528	0.03	0.02	0.02	0.03	0.03	0.03	0.02	4.2	9544	0.03	0.02	0.02	0.03	0.03	0.03	0.02
	2	3.00	8.2	9558	0.03	0.03	0.03	0.03	0.03	0.03	0.02	8.0	9572	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	3	3.00	13.1	9555	0.03	0.03	0.03	0.03	0.03	0.03	0.02	13.1	9573	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	4	3.00	16.5	9596	0.03	0.03	0.03	0.03	0.03	0.03	0.02	16.4	9610	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	6	3.00	24.6	9554	0.03	0.03	0.03	0.03	0.03	0.03	0.02	24.3	9571	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	8	3.00	32.3	9549	0.03	0.03	0.03	0.03	0.03	0.03	0.02	32.2	9563	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	12	3.00	48.4	9553	0.03	0.03	0.03	0.03	0.03	0.03	0.02	48.0	9568	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	20	3.00	81.0	9554	0.03	0.03	0.03	0.03	0.03	0.03	0.02	80.4	9568	0.03	0.03	0.03	0.03	0.03	0.03	0.02
0.01	1	2.25	5.6	7200	0.18	0.13	0.13	0.13	0.13	0.14	0.14	5.5	7204	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	2	2.25	11.3	7227	0.18	0.13	0.13	0.13	0.13	0.14	0.14	11.3	7243	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	3	2.25	17.8	7225	0.18	0.13	0.13	0.13	0.13	0.14	0.14	17.5	7240	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	4	2.25	23.0	7252	0.18	0.13	0.13	0.13	0.13	0.14	0.14	22.8	7268	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	6	2.25	33.6	7231	0.18	0.13	0.13	0.13	0.13	0.14	0.14	33.4	7246	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	8	2.25	44.8	7222	0.18	0.13	0.13	0.13	0.13	0.14	0.14	44.2	7237	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	12	2.25	67.4	7221	0.18	0.13	0.13	0.13	0.13	0.14	0.14	66.7	7234	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	20	2.25	99.4	7210	0.18	0.13	0.13	0.13	0.13	0.14	0.14	99.4	7225	0.18	0.13	0.13	0.13	0.13	0.14	0.14
0.02	1	1.50	5.5	4953	0.31	0.16	0.17	0.17	0.17	0.18	0.19	5.4	4975	0.31	0.16	0.17	0.17	0.17	0.18	0.19
	2	1.50	10.7	4974	0.31	0.16	0.17	0.17	0.17	0.18	0.19	10.4	4983	0.31	0.17	0.17	0.17	0.17	0.18	0.19
	3	1.50	17.0	4973	0.31	0.16	0.17	0.17	0.17	0.18	0.19	16.7	4989	0.31	0.16	0.17	0.17	0.17	0.18	0.19
	4	1.50	21.9	5000	0.31	0.17	0.17	0.17	0.17	0.18	0.19	21.5	5010	0.31	0.17	0.17	0.17	0.18	0.18	0.19
	6	1.50	31.8	4977	0.31	0.16	0.17	0.17	0.17	0.18	0.19	31.2	4987	0.31	0.17	0.17	0.17	0.17	0.18	0.19
	8	1.50	43.0	4974	0.31	0.16	0.17	0.17	0.17	0.18	0.19	42.1	4983	0.31	0.16	0.17	0.17	0.17	0.18	0.19
	12	1.50	64.5	4968	0.31	0.16	0.17	0.17	0.17	0.18	0.19	63.2	4979	0.31	0.16	0.17	0.17	0.17	0.18	0.19
	20	1.50	99.0	4970	0.31	0.16	0.17	0.17	0.17	0.18	0.19	98.7	4985	0.31	0.16	0.17	0.17	0.17	0.18	0.19
0.05	1	0.50	5.2	1919	0.63	0.16	0.17	0.17	0.18	0.21	0.23	5.3	1929	0.63	0.16	0.17	0.17	0.18	0.21	0.23
	2	0.50	10.4	1948	0.63	0.16	0.17	0.17	0.19	0.21	0.23	10.4	1959	0.63	0.16	0.17	0.17	0.19	0.21	0.23
	3	0.50	16.7	1957	0.63	0.16	0.17	0.17	0.19	0.21	0.23	16.3	1957	0.63	0.16	0.17	0.17	0.19	0.21	0.23
	4	0.50	21.3	1979	0.63	0.16	0.17	0.18	0.19	0.21	0.23	21.2	1999	0.63	0.17	0.17	0.18	0.19	0.21	0.24
	6	0.50	31.0	1954	0.63	0.16	0.17	0.17	0.19	0.21	0.23	30.6	1969	0.63	0.16	0.17	0.17	0.19	0.21	0.23
	8	0.50	42.2	1954	0.63	0.16	0.17	0.17	0.19	0.21	0.23	41.3	1965	0.63	0.16	0.17	0.17	0.19	0.21	0.23
	12	0.50	63.0	1949	0.63	0.16	0.17	0.17	0.19	0.21	0.23	61.9	1963	0.63	0.16	0.17	0.17	0.19	0.21	0.23
	20	0.50	98.1	1959	0.64	0.16	0.17	0.17	0.19	0.21	0.23	97.4	1971	0.64	0.16	0.17	0.17	0.19	0.21	0.23
0.10	1	0.125	5.1	771	1.06	0.13	0.14	0.16	0.18	0.23	0.27	4.9	768	1.06	0.13	0.14	0.16	0.18	0.23	0.27
	2	0.125	10.1	792	1.06	0.13	0.15	0.16	0.18	0.23	0.27	9.8	798	1.06	0.14	0.15	0.16	0.19	0.23	0.28
	3	0.125	16.4	791	1.06	0.13	0.15	0.16	0.18	0.23	0.27	15.9	792	1.06	0.13	0.15	0.16	0.18	0.23	0.28
	4	0.125	21.1	822	1.06	0.14	0.15	0.16	0.19	0.23	0.28	20.8	831	1.06	0.14	0.15	0.17	0.19	0.24	0.28
	6	0.125	30.9	801	1.06	0.14	0.15	0.16	0.19	0.23	0.28	30.0	810	1.06	0.14	0.15	0.16	0.19	0.23	0.28
	8	0.125	41.4	797	1.06	0.14	0.15	0.16	0.19	0.23	0.28	40.7	803	1.06	0.14	0.15	0.16	0.19	0.23	0.28
	12	0.125	62.0	793	1.06	0.13	0.15	0.16	0.18	0.23	0.28	60.5	802	1.06	0.14	0.15	0.16	0.19	0.23	0.28
	20	0.125	96.0	797	1.06	0.14	0.15	0.16	0.19	0.23	0.28	95.1	808	1.06	0.14	0.15	0.16	0.19	0.23	0.28
0.20	1	0.030	3.8	352	1.70	0.12	0.15	0.17	0.22	0.31	0.39	3.6	360	1.70	0.12	0.15	0.17	0.22	0.31	0.39
	2	0.030	7.0	328	1.70	0.11	0.14	0.16	0.21	0.30	0.38	6.7	328	1.70	0.11	0.14	0.17	0.21	0.30	0.38
	3	0.030	11.6	350	1.70	0.12	0.15	0.17	0.22	0.31	0.39	10.9	348	1.70	0.12	0.15	0.17	0.22	0.31	0.39
	4	0.030	14.4	375	1.70	0.13	0.15	0.18	0.22	0.31	0.39	13.7	373	1.70	0.13	0.15	0.18	0.22	0.31	0.39
	6	0.030	21.2	348	1.70	0.12	0.14	0.17	0.22	0.31	0.39	20.5	355	1.70	0.12	0.15	0.17	0.22	0.31	0.39
	8	0.030	29.1	360	1.70	0.12	0.15	0.17	0.22	0.31	0.39	27.9	359	1.70	0.12	0.15	0.17	0.22	0.31	0.39
	12	0.030	44.3	355	1.70	0.12	0.15	0.17	0.22	0.31	0.39	42.1	353	1.70	0.12	0.15	0.17	0.22	0.31	0.39
	20	0.030	68.2	354	1.71	0.12	0.15	0.17	0.22	0.31	0.39	65.9	357	1.70	0.12	0.15	0.17	0.22	0.31	0.39
0.50	1	0.015	1.9	107	2.94	0.10	0.16	0.22	0.33	0.52	0.68	1.9	124	2.94	0.11	0.17	0.23	0.34	0.52	0.69
	2	0.015	3.9	110	2.94	0.10	0.16	0.22	0.33	0.52	0.68	3.7	124	2.94	0.11	0.17	0.23	0.34	0.52	0.69
	3	0.015	5.8	111	2.94	0.10	0.16	0.22	0.33	0.52	0.68	5.6	124	2.94	0.11	0.17	0.23	0.34	0.52	0.69
	4	0.015	6.8	109	2.94	0.10	0.16	0.22	0.33	0.52	0.68	6.7	129	2.94	0.11	0.18	0.23	0.34	0.53	0.69
	6	0.015	11.1	110	2.95	0.10	0.16	0.22	0.33	0.52	0.68	10.7	124	2.95	0.11	0.17	0.23	0.34	0.52	0.69
	8	0.015	14.4	111	2.95	0.10	0.16	0.22	0.33	0.52	0.68	13.7	124	2.95	0.11	0.17	0.23	0.34	0.52	0.69
	12	0.015	22.5	109	2.96	0.10	0.16	0.22	0.33	0.52	0.68	22.2	127	2.96	0.11	0.18	0.23	0.34	0.53	0.69
	20	0.015	35.0	109	2.98	0.10	0.16	0.22	0.33	0.52	0.68	34.2	126	2.98	0.11	0.17	0.23	0.34	0.53	0.69

Table B.6: Detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area L for various RADTi in case of $\sigma^2_{\ln K} = 0.0$ assuming every 4 months (4M) and biannually (6M) sampling frequencies

	$\sigma^2_{\ln K}$	0.00																		
α_T(m)	now	nfds(max)	P_d (4M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L	P_d (6M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	1	3.00	4.1	9562	0.03	0.02	0.03	0.03	0.03	0.03	0.02	3.9	9573	0.03	0.02	0.03	0.03	0.03	0.02	0.02
	2	3.00	7.9	9578	0.03	0.03	0.03	0.03	0.03	0.03	0.02	7.6	9595	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	3	3.00	12.8	9588	0.03	0.03	0.03	0.03	0.03	0.03	0.02	12.4	9615	0.03	0.03	0.03	0.03	0.03	0.02	0.02
	4	3.00	16.1	9628	0.03	0.03	0.03	0.03	0.03	0.03	0.02	16.0	9654	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	6	3.00	24.0	9579	0.03	0.03	0.03	0.03	0.03	0.03	0.02	23.3	9604	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	8	3.00	31.8	9576	0.03	0.03	0.03	0.03	0.03	0.03	0.02	31.5	9602	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	12	3.00	47.4	9582	0.03	0.03	0.03	0.03	0.03	0.03	0.02	46.6	9610	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	20	3.00	79.6	9582	0.03	0.03	0.03	0.03	0.03	0.03	0.02	77.8	9609	0.03	0.03	0.03	0.03	0.03	0.03	0.02
0.01	1	2.25	5.4	7222	0.18	0.13	0.13	0.13	0.13	0.14	0.14	5.4	7240	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	2	2.25	10.8	7247	0.18	0.13	0.13	0.13	0.13	0.14	0.14	10.8	7277	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	3	2.25	17.1	7251	0.18	0.13	0.13	0.13	0.13	0.14	0.14	16.9	7277	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	4	2.25	22.5	7279	0.18	0.13	0.13	0.13	0.13	0.14	0.14	22.1	7306	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	6	2.25	32.7	7255	0.18	0.13	0.13	0.13	0.13	0.14	0.14	32.3	7284	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	8	2.25	43.3	7245	0.18	0.13	0.13	0.13	0.13	0.14	0.14	42.8	7274	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	12	2.25	65.8	7248	0.18	0.13	0.13	0.13	0.13	0.14	0.14	64.8	7274	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	20	2.25	99.3	7240	0.18	0.13	0.13	0.13	0.13	0.14	0.14	99.3	7271	0.18	0.13	0.13	0.13	0.13	0.14	0.14
0.02	1	1.50	5.3	4974	0.31	0.16	0.17	0.17	0.17	0.18	0.19	5.2	5008	0.31	0.17	0.17	0.17	0.18	0.18	0.19
	2	1.50	10.3	4996	0.31	0.17	0.17	0.17	0.17	0.18	0.19	10.0	5025	0.31	0.17	0.17	0.17	0.18	0.19	0.19
	3	1.50	16.3	4998	0.31	0.17	0.17	0.17	0.18	0.18	0.19	15.9	5026	0.31	0.17	0.17	0.17	0.18	0.19	0.19
	4	1.50	21.2	5024	0.31	0.17	0.17	0.17	0.18	0.18	0.19	20.8	5049	0.31	0.17	0.17	0.17	0.18	0.19	0.20
	6	1.50	31.0	5002	0.31	0.17	0.17	0.17	0.18	0.18	0.19	30.2	5029	0.31	0.17	0.17	0.17	0.18	0.19	0.19
	8	1.50	41.5	4998	0.31	0.17	0.17	0.17	0.17	0.18	0.19	40.2	5023	0.31	0.17	0.17	0.17	0.18	0.19	0.19
	12	1.50	62.4	4992	0.31	0.17	0.17	0.17	0.17	0.18	0.19	60.3	5016	0.31	0.17	0.17	0.17	0.18	0.18	0.19
	20	1.50	98.5	4999	0.31	0.17	0.17	0.17	0.17	0.18	0.19	97.1	5024	0.31	0.17	0.17	0.17	0.18	0.19	0.19
0.05	1	0.50	5.1	1937	0.63	0.16	0.17	0.17	0.18	0.21	0.23	4.9	1971	0.63	0.16	0.17	0.17	0.19	0.21	0.23
	2	0.50	10.2	1974	0.63	0.16	0.17	0.17	0.19	0.21	0.23	9.7	1991	0.63	0.16	0.17	0.18	0.19	0.21	0.23
	3	0.50	16.3	1978	0.63	0.16	0.17	0.18	0.19	0.21	0.23	15.6	1997	0.63	0.16	0.17	0.18	0.19	0.21	0.23
	4	0.50	20.8	2004	0.63	0.17	0.17	0.18	0.19	0.21	0.24	20.0	2033	0.63	0.17	0.17	0.18	0.19	0.21	0.24
	6	0.50	30.2	1981	0.63	0.16	0.17	0.18	0.19	0.21	0.23	29.0	2002	0.63	0.16	0.17	0.18	0.19	0.21	0.24
	8	0.50	40.5	1975	0.63	0.16	0.17	0.18	0.19	0.21	0.23	39.4	1998	0.63	0.16	0.17	0.18	0.19	0.21	0.23
	12	0.50	60.7	1971	0.63	0.16	0.17	0.17	0.19	0.21	0.23	59.0	1998	0.63	0.16	0.17	0.18	0.19	0.21	0.23
	20	0.50	96.5	1981	0.63	0.16	0.17	0.18	0.19	0.21	0.23	94.9	2004	0.63	0.17	0.17	0.18	0.19	0.21	0.24
0.10	1	0.125	5.0	790	1.06	0.13	0.15	0.16	0.18	0.23	0.27	4.7	799	1.06	0.14	0.15	0.16	0.19	0.23	0.28
	2	0.125	9.7	815	1.06	0.14	0.15	0.16	0.19	0.23	0.28	9.5	828	1.06	0.14	0.15	0.16	0.19	0.24	0.28
	3	0.125	16.0	813	1.06	0.14	0.15	0.16	0.19	0.23	0.28	15.3	830	1.06	0.14	0.15	0.17	0.19	0.24	0.28
	4	0.125	20.4	836	1.06	0.14	0.15	0.17	0.19	0.24	0.28	19.8	862	1.06	0.14	0.16	0.17	0.19	0.24	0.28
	6	0.125	29.5	818	1.06	0.14	0.15	0.16	0.19	0.23	0.28	28.6	840	1.06	0.14	0.15	0.17	0.19	0.24	0.28
	8	0.125	39.9	815	1.06	0.14	0.15	0.16	0.19	0.23	0.28	38.8	834	1.06	0.14	0.15	0.17	0.19	0.24	0.28
	12	0.125	59.8	808	1.06	0.14	0.15	0.16	0.19	0.23	0.28	57.5	832	1.06	0.14	0.15	0.17	0.19	0.24	0.28
	20	0.125	93.9	816	1.06	0.14	0.15	0.16	0.19	0.23	0.28	92.3	837	1.06	0.14	0.15	0.17	0.19	0.24	0.28
0.20	1	0.030	3.6	361	1.70	0.12	0.15	0.17	0.22	0.31	0.39	3.3	378	1.70	0.13	0.15	0.18	0.23	0.31	0.39
	2	0.030	6.5	334	1.70	0.12	0.14	0.17	0.21	0.30	0.38	6.3	368	1.70	0.13	0.15	0.18	0.22	0.31	0.39
	3	0.030	11.0	366	1.70	0.12	0.15	0.18	0.22	0.31	0.39	10.1	377	1.70	0.13	0.15	0.18	0.23	0.31	0.39
	4	0.030	13.6	383	1.70	0.13	0.16	0.18	0.23	0.31	0.39	12.5	390	1.70	0.13	0.16	0.18	0.23	0.32	0.39
	6	0.030	19.5	349	1.70	0.12	0.15	0.17	0.22	0.31	0.39	19.2	383	1.70	0.13	0.16	0.18	0.23	0.31	0.39
	8	0.030	27.5	371	1.70	0.13	0.15	0.18	0.22	0.31	0.39	26.1	385	1.70	0.13	0.16	0.18	0.23	0.31	0.39
	12	0.030	42.0	370	1.70	0.13	0.15	0.18	0.22	0.31	0.39	39.1	376	1.70	0.13	0.15	0.18	0.23	0.31	0.39
	20	0.030	64.8	366	1.70	0.12	0.15	0.17	0.22	0.31	0.39	62.1	383	1.70	0.13	0.16	0.18	0.23	0.31	0.39
0.50	1	0.015	1.9	141	2.94	0.12	0.19	0.24	0.35	0.53	0.69	1.7	180	2.94	0.15	0.21	0.27	0.37	0.55	0.71
	2	0.015	3.7	145	2.94	0.13	0.19	0.24	0.35	0.53	0.70	3.4	188	2.94	0.16	0.22	0.27	0.37	0.56	0.72
	3	0.015	5.5	143	2.94	0.13	0.19	0.24	0.35	0.53	0.70	5.0	182	2.94	0.15	0.21	0.27	0.37	0.55	0.71
	4	0.015	6.5	142	2.94	0.12	0.19	0.24	0.35	0.53	0.70	6.0	185	2.94	0.15	0.21	0.27	0.37	0.55	0.71
	6	0.015	10.5	146	2.95	0.13	0.19	0.24	0.35	0.54	0.70	9.8	186	2.95	0.16	0.21	0.27	0.37	0.55	0.72
	8	0.015	13.5	145	2.95	0.13	0.19	0.24	0.35	0.53	0.70	12.5	186	2.95	0.16	0.21	0.27	0.37	0.55	0.71
	12	0.015	21.3	142	2.96	0.12	0.19	0.24	0.35	0.53	0.70	19.8	185	2.96	0.16	0.21	0.27	0.37	0.55	0.71
	20	0.015	33.4	145	2.98	0.13	0.19	0.24	0.35	0.53	0.70	31.0	184	2.97	0.15	0.21	0.27	0.37	0.55	0.71

Table B.7: Detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area L for various RADTi in case of $\sigma^2_{\ln K} = 0.0$ assuming annually (12M) sampling frequency

	σ^2_{lnK}					0.00					
α_T(m)	now	nfds(max)	P_d (12M)	$<T_{(DET.)}>$ (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	**1**	3.00	3.0	9636	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	2	3.00	6.1	9640	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	3	3.00	10.1	9662	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	4	3.00	12.4	9708	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	6	3.00	18.3	9649	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	8	3.00	24.4	9643	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	12	3.00	36.3	9668	0.03	0.03	0.03	0.03	0.03	0.03	0.02
	20	3.00	61.0	9654	0.03	0.03	0.03	0.03	0.03	0.03	0.02
0.01	**1**	2.25	4.9	7344	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	2	2.25	10.2	7374	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	3	2.25	15.9	7367	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	4	2.25	20.4	7392	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	6	2.25	29.8	7367	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	8	2.25	39.9	7366	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	12	2.25	59.5	7354	0.18	0.13	0.13	0.13	0.13	0.14	0.14
	20	2.25	95.1	7360	0.18	0.13	0.13	0.13	0.13	0.14	0.14
0.02	**1**	1.50	4.5	5055	0.31	0.17	0.17	0.17	0.18	0.19	0.20
	2	1.50	8.8	5090	0.31	0.17	0.17	0.17	0.18	0.19	0.20
	3	1.50	14.0	5080	0.31	0.17	0.17	0.17	0.18	0.19	0.20
	4	1.50	19.2	5136	0.31	0.17	0.17	0.17	0.18	0.19	0.20
	6	1.50	27.4	5098	0.31	0.17	0.17	0.17	0.18	0.19	0.20
	8	1.50	36.5	5085	0.31	0.17	0.17	0.17	0.18	0.19	0.20
	12	1.50	55.0	5095	0.31	0.17	0.17	0.17	0.18	0.19	0.20
	20	1.50	89.4	5093	0.31	0.17	0.17	0.17	0.18	0.19	0.20
0.05	**1**	0.50	4.4	2028	0.63	0.17	0.17	0.18	0.19	0.21	0.24
	2	0.50	8.2	2035	0.63	0.17	0.17	0.18	0.19	0.21	0.24
	3	0.50	13.9	2047	0.63	0.17	0.17	0.18	0.19	0.22	0.24
	4	0.50	17.6	2079	0.63	0.17	0.18	0.18	0.19	0.22	0.24
	6	0.50	25.3	2047	0.63	0.17	0.17	0.18	0.19	0.22	0.24
	8	0.50	34.7	2048	0.63	0.17	0.17	0.18	0.19	0.22	0.24
	12	0.50	52.3	2042	0.63	0.17	0.17	0.18	0.19	0.21	0.24
	20	0.50	84.7	2050	0.63	0.17	0.17	0.18	0.19	0.22	0.24
0.10	**1**	0.125	4.4	863	1.06	0.14	0.16	0.17	0.19	0.24	0.28
	2	0.125	8.2	862	1.06	0.14	0.16	0.17	0.19	0.24	0.28
	3	0.125	13.9	886	1.06	0.15	0.16	0.17	0.20	0.24	0.29
	4	0.125	17.2	904	1.06	0.15	0.16	0.18	0.20	0.24	0.29
	6	0.125	25.1	878	1.06	0.15	0.16	0.17	0.20	0.24	0.28
	8	0.125	34.1	875	1.06	0.15	0.16	0.17	0.20	0.24	0.28
	12	0.125	51.1	881	1.06	0.15	0.16	0.17	0.20	0.24	0.29
	20	0.125	83.6	886	1.06	0.15	0.16	0.17	0.20	0.24	0.29
0.20	**1**	0.030	2.7	492	1.70	0.16	0.19	0.21	0.25	0.34	0.42
	2	0.030	4.8	456	1.70	0.15	0.18	0.20	0.25	0.33	0.41
	3	0.030	8.1	493	1.70	0.16	0.19	0.21	0.25	0.34	0.42
	4	0.030	9.4	478	1.70	0.16	0.18	0.21	0.25	0.33	0.41
	6	0.030	14.6	479	1.70	0.16	0.18	0.21	0.25	0.34	0.41
	8	0.030	20.0	475	1.70	0.16	0.18	0.20	0.25	0.33	0.41
	12	0.030	30.2	478	1.70	0.16	0.18	0.21	0.25	0.34	0.41
	20	0.030	47.7	485	1.70	0.16	0.18	0.21	0.25	0.34	0.41
0.50	**1**	0.015	0.1	365	2.94	0.27	0.32	0.37	0.46	0.64	0.79
	2	0.015	0.3	365	2.94	0.27	0.32	0.37	0.46	0.63	0.79
	3	0.015	0.4	365	2.94	0.27	0.32	0.37	0.47	0.64	0.79
	4	0.015	0.8	365	2.94	0.27	0.32	0.37	0.46	0.63	0.79
	6	0.015	0.8	365	2.94	0.27	0.32	0.37	0.46	0.63	0.79
	8	0.015	1.3	365	2.94	0.27	0.32	0.37	0.46	0.64	0.79
	12	0.015	2.4	365	2.94	0.27	0.32	0.37	0.46	0.63	0.79
	20	0.015	3.1	365	2.94	0.27	0.32	0.37	0.46	0.63	0.79

Table B.8: Detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area for various RARDTi in case of $\sigma^2_{\ln K} = 0.5$ assuming daily (ED) and monthly (1M) sampling frequencies

	$\sigma^2_{\ln K}$									0.50										
α_T(m)	now	nfds(max)	P_d (ED)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L	P_d (1M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	1	1.75	4.5	5722	0.06	0.03	0.03	0.03	0.03	0.03	0.03	4.5	5747	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	2	1.75	8.1	5678	0.06	0.03	0.03	0.03	0.03	0.03	0.03	8.1	5693	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	3	1.75	11.5	5674	0.06	0.03	0.03	0.03	0.03	0.03	0.03	11.4	5684	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	4	1.75	14.5	5650	0.06	0.03	0.03	0.03	0.03	0.03	0.03	14.2	5669	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	6	1.75	21.0	5617	0.06	0.03	0.03	0.03	0.03	0.03	0.03	20.7	5629	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	8	1.75	28.1	5649	0.06	0.03	0.03	0.03	0.03	0.03	0.03	27.7	5661	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	12	1.75	42.0	5668	0.06	0.03	0.03	0.03	0.03	0.03	0.03	41.5	5685	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	20	1.75	64.2	5652	0.06	0.03	0.03	0.03	0.03	0.03	0.03	63.7	5666	0.06	0.03	0.03	0.03	0.03	0.03	0.03
0.01	1	1.50	5.4	4830	0.34	0.13	0.13	0.14	0.14	0.15	0.16	5.2	4838	0.34	0.13	0.13	0.13	0.14	0.15	0.16
	2	1.50	10.9	4990	0.34	0.13	0.14	0.14	0.14	0.15	0.17	10.6	5019	0.34	0.13	0.14	0.14	0.14	0.15	0.17
	3	1.50	15.1	4788	0.34	0.13	0.13	0.14	0.14	0.15	0.16	14.5	4803	0.34	0.13	0.13	0.14	0.14	0.15	0.16
	4	1.50	20.7	4802	0.34	0.13	0.13	0.14	0.14	0.15	0.16	20.2	4822	0.34	0.13	0.13	0.14	0.14	0.15	0.16
	6	1.50	30.7	4937	0.34	0.13	0.14	0.14	0.14	0.15	0.17	29.5	4950	0.34	0.13	0.14	0.14	0.14	0.15	0.17
	8	1.50	41.5	4870	0.34	0.13	0.13	0.14	0.14	0.15	0.16	39.7	4879	0.34	0.13	0.13	0.14	0.14	0.15	0.16
	12	1.50	57.0	4843	0.34	0.13	0.13	0.14	0.14	0.15	0.16	55.5	4853	0.34	0.13	0.13	0.14	0.14	0.15	0.16
	20	1.50	77.2	4869	0.35	0.13	0.13	0.14	0.14	0.15	0.16	75.9	4885	0.35	0.13	0.13	0.14	0.14	0.15	0.16
0.02	1	0.50	5.9	1936	0.57	0.09	0.10	0.10	0.11	0.13	0.15	5.9	1956	0.57	0.09	0.10	0.10	0.11	0.13	0.15
	2	0.50	11.6	1956	0.57	0.09	0.09	0.10	0.11	0.13	0.14	11.2	1982	0.57	0.09	0.10	0.10	0.11	0.13	0.14
	3	0.50	16.9	2011	0.57	0.09	0.10	0.10	0.11	0.13	0.14	16.6	2021	0.57	0.09	0.10	0.10	0.11	0.13	0.14
	4	0.50	22.1	2022	0.57	0.09	0.10	0.10	0.11	0.13	0.14	21.2	2043	0.57	0.09	0.10	0.10	0.11	0.13	0.14
	6	0.50	33.2	1979	0.57	0.09	0.10	0.10	0.11	0.13	0.14	32.4	1993	0.57	0.09	0.10	0.10	0.11	0.13	0.14
	8	0.50	43.6	2021	0.57	0.09	0.10	0.10	0.11	0.13	0.14	42.0	2037	0.57	0.09	0.10	0.10	0.11	0.13	0.14
	12	0.50	61.9	2030	0.57	0.09	0.10	0.10	0.11	0.13	0.14	60.0	2050	0.57	0.09	0.10	0.10	0.11	0.13	0.14
	20	0.50	84.4	2017	0.58	0.09	0.09	0.10	0.11	0.13	0.14	83.0	2030	0.58	0.09	0.10	0.10	0.11	0.13	0.14
0.05	1	0.50	5.6	1890	1.08	0.19	0.20	0.21	0.23	0.26	0.30	5.0	1879	1.08	0.19	0.20	0.21	0.23	0.26	0.30
	2	0.50	10.8	1891	1.08	0.18	0.19	0.20	0.22	0.25	0.29	9.6	1910	1.08	0.18	0.19	0.20	0.22	0.25	0.29
	3	0.50	14.9	1934	1.09	0.18	0.19	0.20	0.22	0.25	0.29	13.6	1921	1.08	0.19	0.19	0.20	0.22	0.26	0.29
	4	0.50	19.8	1936	1.09	0.18	0.19	0.20	0.22	0.25	0.29	17.8	1948	1.09	0.18	0.19	0.20	0.22	0.25	0.29
	6	0.50	29.9	1904	1.08	0.18	0.19	0.20	0.22	0.25	0.29	27.0	1910	1.08	0.18	0.19	0.20	0.22	0.26	0.29
	8	0.50	39.1	1934	1.08	0.18	0.19	0.20	0.22	0.26	0.29	35.1	1935	1.08	0.18	0.19	0.20	0.22	0.26	0.29
	12	0.50	55.7	1953	1.09	0.19	0.19	0.20	0.22	0.26	0.29	50.2	1965	1.09	0.18	0.19	0.20	0.22	0.26	0.29
	20	0.50	78.2	1964	1.09	0.18	0.19	0.20	0.22	0.26	0.29	73.4	1971	1.09	0.18	0.19	0.20	0.22	0.26	0.29
0.10	1	0.125	6.4	870	1.68	0.14	0.16	0.17	0.20	0.26	0.32	5.9	881	1.68	0.14	0.16	0.17	0.21	0.27	0.32
	2	0.125	10.3	883	1.68	0.15	0.16	0.18	0.21	0.27	0.33	9.2	870	1.68	0.15	0.16	0.18	0.21	0.27	0.33
	3	0.125	16.2	829	1.68	0.14	0.16	0.17	0.20	0.26	0.32	14.9	844	1.68	0.14	0.16	0.17	0.20	0.26	0.32
	4	0.125	20.0	828	1.68	0.14	0.16	0.18	0.21	0.27	0.33	18.0	816	1.68	0.14	0.16	0.17	0.21	0.26	0.32
	6	0.125	30.3	828	1.68	0.14	0.16	0.17	0.20	0.26	0.32	28.0	831	1.68	0.14	0.16	0.17	0.21	0.27	0.32
	8	0.125	42.2	814	1.68	0.14	0.16	0.17	0.20	0.27	0.33	38.4	806	1.68	0.14	0.16	0.17	0.20	0.26	0.32
	12	0.125	62.2	819	1.67	0.14	0.16	0.17	0.21	0.27	0.33	56.4	813	1.68	0.14	0.16	0.17	0.20	0.26	0.32
	20	0.125	87.0	828	1.72	0.14	0.16	0.17	0.20	0.26	0.32	81.9	821	1.71	0.14	0.16	0.17	0.20	0.26	0.32
0.20	1	0.030	4.8	375	2.45	0.12	0.15	0.18	0.23	0.33	0.43	4.2	373	2.45	0.12	0.15	0.17	0.23	0.33	0.42
	2	0.030	7.9	375	2.45	0.12	0.15	0.18	0.24	0.35	0.45	6.8	338	2.45	0.12	0.15	0.18	0.23	0.34	0.44
	3	0.030	12.9	356	2.46	0.12	0.15	0.18	0.23	0.33	0.43	11.2	339	2.46	0.11	0.14	0.17	0.22	0.33	0.42
	4	0.030	15.3	372	2.45	0.13	0.16	0.19	0.24	0.35	0.45	13.5	355	2.45	0.12	0.15	0.18	0.24	0.34	0.44
	6	0.030	24.1	375	2.45	0.12	0.16	0.18	0.24	0.35	0.45	20.2	329	2.45	0.11	0.15	0.17	0.23	0.34	0.44
	8	0.030	32.5	369	2.46	0.12	0.15	0.18	0.24	0.34	0.44	28.5	358	2.46	0.12	0.15	0.18	0.23	0.34	0.44
	12	0.030	48.3	369	2.46	0.12	0.15	0.18	0.24	0.34	0.44	42.3	349	2.46	0.12	0.15	0.18	0.23	0.34	0.44
	20	0.030	69.6	378	2.47	0.12	0.15	0.18	0.24	0.35	0.45	61.7	349	2.47	0.12	0.15	0.18	0.23	0.34	0.44
0.50	1	0.015	3.0	113	3.63	0.10	0.17	0.24	0.36	0.57	0.76	2.6	111	3.63	0.10	0.17	0.24	0.36	0.57	0.76
	2	0.015	4.5	119	3.63	0.09	0.17	0.23	0.35	0.56	0.76	3.7	113	3.63	0.09	0.16	0.22	0.34	0.56	0.75
	3	0.015	7.8	101	3.64	0.08	0.16	0.22	0.34	0.56	0.75	6.9	107	3.63	0.09	0.16	0.23	0.35	0.55	0.74
	4	0.015	7.8	120	3.63	0.10	0.17	0.24	0.36	0.57	0.76	6.6	120	3.63	0.10	0.17	0.24	0.35	0.56	0.76
	6	0.015	13.5	110	3.64	0.09	0.17	0.23	0.35	0.57	0.77	10.9	104	3.64	0.09	0.16	0.23	0.35	0.56	0.76
	8	0.015	18.0	110	3.64	0.09	0.17	0.23	0.36	0.57	0.77	15.1	106	3.64	0.09	0.17	0.23	0.35	0.57	0.76
	12	0.015	27.5	121	3.65	0.10	0.17	0.23	0.35	0.57	0.76	22.6	111	3.65	0.09	0.17	0.23	0.35	0.56	0.76
	20	0.015	38.2	104	3.67	0.09	0.16	0.23	0.35	0.57	0.77	34.0	105	3.66	0.09	0.16	0.23	0.35	0.57	0.77

Table B.9: Detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area for various RADTi in case of $\sigma^2_{\ln K} = 0.5$ assuming bimonthly (2M) and quarterly (3M) sampling frequencies

$\sigma^2_{\ln K}$		0.50																		
α_T(m)	now	nfds(max)	P_d (2M)	$<T_{(DET.)}>$ (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L	P_d (3M)	$<T_{(DET.)}>$ (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	**1**	1.75	4.4	5749	0.06	0.03	0.03	0.03	0.03	0.03	0.03	4.5	5776	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	2	1.75	8.0	5692	0.06	0.03	0.03	0.03	0.03	0.03	0.03	7.8	5751	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	3	1.75	11.3	5703	0.06	0.03	0.03	0.03	0.03	0.03	0.03	11.3	5720	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	4	1.75	14.1	5680	0.06	0.03	0.03	0.03	0.03	0.03	0.03	14.0	5711	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	6	1.75	20.6	5639	0.06	0.03	0.03	0.03	0.03	0.03	0.03	20.3	5678	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	8	1.75	27.5	5678	0.06	0.03	0.03	0.03	0.03	0.03	0.03	27.2	5705	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	12	1.75	41.1	5699	0.06	0.03	0.03	0.03	0.03	0.03	0.03	40.8	5723	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	20	1.75	63.2	5677	0.06	0.03	0.03	0.03	0.03	0.03	0.03	62.7	5700	0.06	0.03	0.03	0.03	0.03	0.03	0.03
0.01	**1**	1.50	5.2	4863	0.34	0.13	0.13	0.14	0.14	0.15	0.16	5.2	4868	0.34	0.13	0.13	0.14	0.14	0.15	0.16
	2	1.50	10.5	5029	0.34	0.13	0.14	0.14	0.14	0.16	0.17	10.3	5041	0.34	0.13	0.14	0.14	0.14	0.16	0.17
	3	1.50	14.3	4815	0.34	0.13	0.13	0.14	0.14	0.15	0.16	14.1	4821	0.34	0.13	0.13	0.14	0.14	0.15	0.16
	4	1.50	19.9	4812	0.34	0.13	0.13	0.14	0.14	0.15	0.16	19.6	4814	0.34	0.13	0.13	0.14	0.14	0.15	0.16
	6	1.50	29.0	4966	0.34	0.13	0.14	0.14	0.14	0.16	0.17	28.6	4967	0.34	0.13	0.14	0.14	0.14	0.15	0.17
	8	1.50	38.9	4878	0.34	0.13	0.13	0.14	0.14	0.15	0.16	38.3	4897	0.34	0.13	0.13	0.14	0.14	0.15	0.16
	12	1.50	54.5	4863	0.34	0.13	0.13	0.14	0.14	0.15	0.16	53.5	4857	0.34	0.13	0.13	0.14	0.14	0.15	0.16
	20	1.50	75.0	4890	0.35	0.13	0.13	0.14	0.14	0.15	0.16	74.2	4907	0.35	0.13	0.13	0.14	0.14	0.15	0.16
0.02	**1**	0.50	5.9	1967	0.57	0.09	0.10	0.10	0.11	0.13	0.15	5.7	1977	0.57	0.09	0.10	0.10	0.11	0.13	0.15
	2	0.50	11.1	1988	0.57	0.09	0.10	0.10	0.11	0.13	0.14	11.0	2001	0.57	0.09	0.10	0.10	0.11	0.13	0.15
	3	0.50	16.4	2036	0.57	0.09	0.10	0.10	0.11	0.13	0.15	15.9	2044	0.57	0.09	0.10	0.10	0.11	0.13	0.15
	4	0.50	20.9	2051	0.57	0.09	0.10	0.10	0.11	0.13	0.15	20.7	2078	0.57	0.09	0.10	0.10	0.11	0.13	0.15
	6	0.50	32.0	2002	0.57	0.09	0.10	0.10	0.11	0.13	0.15	31.7	2019	0.57	0.09	0.10	0.10	0.11	0.13	0.15
	8	0.50	41.5	2051	0.57	0.09	0.10	0.10	0.11	0.13	0.15	40.9	2063	0.57	0.09	0.10	0.10	0.11	0.13	0.15
	12	0.50	59.2	2065	0.57	0.09	0.10	0.10	0.11	0.13	0.15	58.7	2078	0.57	0.09	0.10	0.10	0.11	0.13	0.15
	20	0.50	82.2	2041	0.58	0.09	0.10	0.10	0.11	0.13	0.14	81.9	2050	0.58	0.09	0.10	0.10	0.11	0.13	0.14
0.05	**1**	0.50	4.7	1879	1.08	0.19	0.20	0.21	0.23	0.26	0.30	4.5	1871	1.08	0.19	0.20	0.21	0.22	0.26	0.29
	2	0.50	9.2	1919	1.08	0.18	0.19	0.20	0.22	0.25	0.29	8.8	1935	1.08	0.18	0.19	0.20	0.22	0.26	0.29
	3	0.50	12.9	1936	1.08	0.19	0.19	0.20	0.22	0.25	0.29	12.6	1935	1.08	0.19	0.19	0.20	0.22	0.26	0.29
	4	0.50	17.1	1955	1.09	0.18	0.19	0.20	0.22	0.25	0.29	16.4	1976	1.09	0.18	0.19	0.20	0.22	0.25	0.29
	6	0.50	25.5	1919	1.08	0.18	0.19	0.20	0.22	0.25	0.29	24.7	1930	1.08	0.18	0.19	0.20	0.22	0.26	0.29
	8	0.50	33.7	1939	1.08	0.18	0.19	0.20	0.22	0.26	0.29	33.0	1946	1.08	0.19	0.19	0.20	0.22	0.26	0.29
	12	0.50	48.0	1970	1.09	0.18	0.19	0.20	0.22	0.25	0.29	46.2	1982	1.09	0.19	0.19	0.20	0.22	0.25	0.29
	20	0.50	70.9	1978	1.09	0.19	0.19	0.20	0.22	0.26	0.29	69.2	1988	1.09	0.19	0.19	0.20	0.22	0.26	0.29
0.10	**1**	0.125	5.6	877	1.68	0.14	0.16	0.18	0.21	0.27	0.32	5.3	893	1.68	0.15	0.16	0.18	0.21	0.27	0.32
	2	0.125	9.0	888	1.68	0.15	0.16	0.18	0.21	0.27	0.33	8.5	877	1.68	0.15	0.16	0.18	0.21	0.27	0.33
	3	0.125	14.4	845	1.68	0.14	0.16	0.17	0.20	0.26	0.32	13.9	849	1.68	0.14	0.16	0.17	0.20	0.26	0.32
	4	0.125	17.2	818	1.68	0.14	0.16	0.17	0.21	0.26	0.32	16.5	818	1.68	0.14	0.16	0.17	0.20	0.26	0.32
	6	0.125	27.1	832	1.68	0.14	0.16	0.18	0.21	0.27	0.33	26.0	827	1.68	0.14	0.16	0.17	0.21	0.27	0.32
	8	0.125	37.1	813	1.68	0.14	0.16	0.17	0.20	0.26	0.32	35.9	817	1.69	0.14	0.16	0.17	0.20	0.26	0.32
	12	0.125	54.6	818	1.68	0.14	0.16	0.17	0.20	0.26	0.32	52.3	813	1.68	0.14	0.16	0.17	0.20	0.26	0.32
	20	0.125	79.9	829	1.71	0.14	0.16	0.17	0.20	0.26	0.32	77.9	824	1.71	0.14	0.16	0.17	0.20	0.26	0.32
0.20	**1**	0.030	4.1	382	2.45	0.12	0.15	0.18	0.23	0.33	0.43	4.0	394	2.45	0.13	0.15	0.18	0.23	0.34	0.43
	2	0.030	6.4	339	2.45	0.12	0.15	0.17	0.23	0.34	0.44	6.1	346	2.45	0.12	0.15	0.18	0.24	0.34	0.45
	3	0.030	10.9	344	2.46	0.11	0.14	0.17	0.23	0.33	0.42	10.6	355	2.46	0.12	0.15	0.17	0.23	0.33	0.43
	4	0.030	12.9	366	2.45	0.13	0.16	0.18	0.24	0.34	0.45	12.3	380	2.45	0.13	0.16	0.19	0.24	0.34	0.44
	6	0.030	19.2	335	2.45	0.12	0.15	0.18	0.23	0.34	0.44	18.6	340	2.45	0.12	0.15	0.18	0.23	0.34	0.44
	8	0.030	27.1	360	2.46	0.12	0.15	0.18	0.23	0.34	0.44	25.9	369	2.46	0.12	0.15	0.18	0.24	0.34	0.44
	12	0.030	40.5	355	2.46	0.12	0.15	0.18	0.23	0.34	0.44	39.2	368	2.46	0.12	0.15	0.18	0.24	0.34	0.44
	20	0.030	59.7	354	2.47	0.12	0.15	0.18	0.23	0.34	0.44	58.0	358	2.47	0.12	0.15	0.18	0.23	0.34	0.44
0.50	**1**	0.015	2.4	125	3.63	0.11	0.18	0.24	0.36	0.57	0.76	2.2	132	3.63	0.12	0.19	0.25	0.36	0.57	0.76
	2	0.015	3.4	131	3.63	0.10	0.17	0.23	0.35	0.56	0.75	3.3	136	3.63	0.11	0.18	0.24	0.35	0.56	0.76
	3	0.015	6.6	120	3.63	0.10	0.17	0.24	0.35	0.56	0.75	6.2	135	3.63	0.12	0.18	0.25	0.36	0.56	0.75
	4	0.015	6.1	126	3.63	0.11	0.18	0.24	0.36	0.56	0.76	6.0	148	3.63	0.13	0.19	0.25	0.37	0.57	0.76
	6	0.015	10.5	121	3.64	0.10	0.17	0.24	0.36	0.57	0.76	10.0	135	3.64	0.11	0.18	0.24	0.36	0.57	0.76
	8	0.015	14.4	122	3.64	0.11	0.18	0.24	0.36	0.58	0.77	13.7	138	3.64	0.12	0.19	0.25	0.37	0.58	0.77
	12	0.015	21.3	122	3.65	0.11	0.17	0.24	0.36	0.57	0.76	20.5	140	3.65	0.12	0.19	0.25	0.37	0.58	0.77
	20	0.015	32.8	118	3.66	0.10	0.18	0.24	0.36	0.58	0.77	31.7	137	3.66	0.12	0.19	0.25	0.37	0.58	0.78

Table B.10: Detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area L for various RADTi in case of $\sigma^2_{\ln K} = 0.5$ assuming every 4 months (4M) and biannually (6M) sampling frequencies

	$\sigma^2_{\ln K}$									0.50										
α_T(m)	now	nfds(max)	P_d (4M)	$\langle T_{(DET,)}\rangle$ (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L	P_d (6M)	$\langle T_{(DET,)}\rangle$ (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	**1**	1.75	4.3	5774	0.06	0.03	0.03	0.03	0.03	0.03	0.03	4.2	5784	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	2	1.75	7.8	5736	0.06	0.03	0.03	0.03	0.03	0.03	0.03	7.4	5833	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	3	1.75	11.0	5750	0.06	0.03	0.03	0.03	0.03	0.03	0.03	10.6	5771	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	4	1.75	13.8	5713	0.06	0.03	0.03	0.03	0.03	0.03	0.03	13.2	5786	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	6	1.75	20.2	5685	0.06	0.03	0.03	0.03	0.03	0.03	0.03	19.3	5759	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	8	1.75	26.6	5725	0.06	0.03	0.03	0.03	0.03	0.03	0.03	25.7	5798	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	12	1.75	40.3	5740	0.06	0.03	0.03	0.03	0.03	0.03	0.03	38.3	5819	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	20	1.75	62.0	5717	0.06	0.03	0.03	0.03	0.03	0.03	0.03	59.8	5776	0.06	0.03	0.03	0.03	0.03	0.03	0.03
0.01	**1**	1.50	5.1	4887	0.34	0.13	0.13	0.14	0.14	0.15	0.16	5.0	4882	0.34	0.13	0.13	0.14	0.14	0.15	0.16
	2	1.50	10.2	5057	0.34	0.13	0.14	0.14	0.15	0.16	0.17	10.0	5095	0.34	0.14	0.14	0.14	0.15	0.16	0.17
	3	1.50	13.9	4859	0.34	0.13	0.13	0.14	0.14	0.15	0.16	13.6	4858	0.34	0.13	0.13	0.14	0.14	0.15	0.16
	4	1.50	19.3	4835	0.34	0.13	0.13	0.14	0.14	0.15	0.16	18.9	4840	0.34	0.13	0.13	0.14	0.14	0.15	0.16
	6	1.50	28.2	4992	0.34	0.13	0.14	0.14	0.14	0.15	0.17	27.5	5001	0.34	0.13	0.14	0.14	0.14	0.16	0.17
	8	1.50	37.9	4921	0.34	0.13	0.14	0.14	0.14	0.15	0.16	37.1	4949	0.34	0.13	0.14	0.14	0.14	0.15	0.17
	12	1.50	53.1	4884	0.34	0.13	0.13	0.14	0.14	0.15	0.16	51.8	4903	0.34	0.13	0.13	0.14	0.14	0.15	0.16
	20	1.50	73.5	4924	0.35	0.13	0.13	0.14	0.14	0.15	0.17	72.7	4948	0.35	0.13	0.14	0.14	0.14	0.15	0.17
0.02	**1**	0.50	5.7	2009	0.57	0.10	0.10	0.10	0.11	0.13	0.15	5.6	2016	0.57	0.10	0.10	0.10	0.11	0.13	0.15
	2	0.50	10.9	2009	0.57	0.09	0.10	0.10	0.11	0.13	0.15	10.8	2033	0.57	0.09	0.10	0.10	0.11	0.13	0.15
	3	0.50	16.0	2072	0.57	0.09	0.10	0.10	0.11	0.13	0.15	15.5	2087	0.57	0.10	0.10	0.10	0.11	0.13	0.15
	4	0.50	20.4	2090	0.57	0.09	0.10	0.10	0.11	0.13	0.15	20.1	2114	0.57	0.10	0.10	0.10	0.11	0.13	0.15
	6	0.50	31.2	2034	0.57	0.09	0.10	0.10	0.11	0.13	0.15	30.8	2062	0.57	0.09	0.10	0.10	0.11	0.13	0.15
	8	0.50	40.7	2070	0.57	0.09	0.10	0.10	0.11	0.13	0.15	39.5	2104	0.57	0.09	0.10	0.10	0.11	0.13	0.15
	12	0.50	58.0	2093	0.57	0.09	0.10	0.10	0.11	0.13	0.15	57.0	2123	0.57	0.10	0.10	0.10	0.11	0.13	0.15
	20	0.50	81.6	2069	0.58	0.09	0.10	0.10	0.11	0.13	0.15	80.8	2092	0.58	0.09	0.10	0.10	0.11	0.13	0.15
0.05	**1**	0.50	4.2	1885	1.08	0.19	0.20	0.21	0.22	0.26	0.29	4.0	1892	1.08	0.19	0.20	0.21	0.22	0.26	0.29
	2	0.50	8.6	1917	1.08	0.18	0.19	0.20	0.22	0.26	0.29	8.2	1969	1.08	0.19	0.20	0.20	0.22	0.26	0.29
	3	0.50	12.0	1959	1.09	0.19	0.19	0.20	0.22	0.25	0.29	11.5	1963	1.09	0.19	0.20	0.20	0.22	0.26	0.29
	4	0.50	15.8	1970	1.09	0.18	0.19	0.20	0.22	0.25	0.29	14.7	2009	1.09	0.18	0.19	0.20	0.22	0.25	0.29
	6	0.50	24.0	1934	1.08	0.18	0.19	0.20	0.22	0.25	0.29	22.8	1973	1.08	0.19	0.19	0.20	0.22	0.26	0.29
	8	0.50	31.5	1940	1.08	0.19	0.19	0.20	0.22	0.26	0.29	29.7	1985	1.08	0.19	0.20	0.20	0.22	0.26	0.29
	12	0.50	44.4	1981	1.09	0.19	0.19	0.20	0.22	0.26	0.29	41.8	2017	1.09	0.19	0.19	0.20	0.22	0.25	0.29
	20	0.50	67.4	1986	1.09	0.19	0.19	0.20	0.22	0.26	0.29	64.5	2021	1.10	0.19	0.20	0.20	0.22	0.26	0.29
0.10	**1**	0.125	5.2	901	1.68	0.15	0.16	0.18	0.21	0.26	0.32	4.8	903	1.68	0.15	0.16	0.18	0.21	0.27	0.32
	2	0.125	8.7	912	1.68	0.15	0.17	0.18	0.21	0.27	0.33	8.1	910	1.68	0.15	0.17	0.18	0.21	0.27	0.33
	3	0.125	13.5	866	1.68	0.14	0.16	0.17	0.20	0.26	0.32	12.9	873	1.69	0.14	0.16	0.18	0.21	0.26	0.32
	4	0.125	16.4	837	1.68	0.15	0.16	0.18	0.21	0.27	0.32	15.3	835	1.68	0.14	0.16	0.18	0.21	0.26	0.32
	6	0.125	25.7	851	1.68	0.15	0.16	0.18	0.21	0.27	0.33	24.3	858	1.69	0.15	0.16	0.18	0.21	0.27	0.33
	8	0.125	36.0	837	1.69	0.14	0.16	0.18	0.21	0.27	0.33	33.8	848	1.69	0.15	0.16	0.18	0.21	0.27	0.33
	12	0.125	51.8	834	1.68	0.14	0.16	0.17	0.21	0.27	0.32	48.7	842	1.68	0.14	0.16	0.18	0.21	0.27	0.32
	20	0.125	76.5	838	1.71	0.14	0.16	0.17	0.21	0.27	0.32	73.2	847	1.71	0.14	0.16	0.18	0.21	0.27	0.32
0.20	**1**	0.030	3.9	403	2.45	0.13	0.15	0.18	0.23	0.33	0.43	3.7	445	2.45	0.14	0.16	0.19	0.24	0.34	0.43
	2	0.030	5.9	355	2.45	0.12	0.15	0.18	0.23	0.34	0.44	5.4	376	2.45	0.13	0.15	0.18	0.24	0.34	0.44
	3	0.030	10.4	366	2.46	0.12	0.15	0.18	0.23	0.33	0.43	9.8	403	2.46	0.13	0.16	0.18	0.23	0.33	0.43
	4	0.030	12.0	381	2.45	0.13	0.16	0.19	0.24	0.34	0.44	11.5	419	2.45	0.14	0.17	0.19	0.25	0.35	0.45
	6	0.030	17.9	351	2.46	0.12	0.15	0.18	0.23	0.34	0.44	16.7	379	2.46	0.13	0.16	0.18	0.24	0.34	0.44
	8	0.030	25.4	376	2.46	0.12	0.15	0.18	0.24	0.34	0.44	23.2	407	2.46	0.13	0.16	0.19	0.24	0.34	0.44
	12	0.030	37.9	371	2.46	0.12	0.15	0.18	0.24	0.34	0.44	35.9	406	2.47	0.13	0.16	0.19	0.24	0.34	0.44
	20	0.030	56.6	362	2.47	0.12	0.15	0.18	0.24	0.34	0.44	53.3	394	2.48	0.13	0.16	0.19	0.24	0.34	0.44
0.50	**1**	0.015	2.1	156	3.63	0.13	0.19	0.25	0.37	0.56	0.75	1.8	196	3.63	0.15	0.21	0.27	0.37	0.57	0.75
	2	0.015	3.2	161	3.63	0.13	0.19	0.25	0.37	0.58	0.77	2.5	201	3.63	0.15	0.20	0.26	0.36	0.57	0.75
	3	0.015	5.9	156	3.63	0.13	0.20	0.25	0.37	0.57	0.75	4.9	203	3.63	0.16	0.21	0.27	0.38	0.57	0.76
	4	0.015	5.7	159	3.63	0.14	0.20	0.26	0.38	0.58	0.77	4.9	196	3.63	0.16	0.22	0.28	0.39	0.59	0.78
	6	0.015	9.3	157	3.64	0.13	0.19	0.25	0.37	0.57	0.76	7.8	204	3.64	0.15	0.21	0.26	0.37	0.57	0.75
	8	0.015	13.0	158	3.64	0.14	0.20	0.26	0.38	0.59	0.78	10.6	203	3.64	0.16	0.22	0.27	0.38	0.58	0.77
	12	0.015	19.5	158	3.65	0.13	0.20	0.26	0.38	0.58	0.78	16.1	200	3.65	0.16	0.22	0.27	0.38	0.58	0.77
	20	0.015	30.0	155	3.66	0.13	0.20	0.26	0.38	0.58	0.78	25.4	202	3.66	0.16	0.22	0.27	0.38	0.58	0.77

Table B.11: Detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area L for various RADTi in case of $\sigma^2_{\ln K} = 0.5$ assuming annually sampling frequency

$\sigma^2_{\ln K}$				0.50							
σ_T(m)	now	nfds(max)	P_d (12M)	$<T_{(DET.)}>$ (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	1	1.75	3.1	6150	0.06	0.03	0.03	0.03	0.03	0.03	0.04
	2	1.75	5.6	6046	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	3	1.75	7.8	6125	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	4	1.75	9.2	6107	0.06	0.03	0.03	0.03	0.03	0.03	0.04
	6	1.75	14.1	5975	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	8	1.75	18.2	6130	0.06	0.03	0.03	0.03	0.03	0.03	0.03
	12	1.75	28.1	6133	0.06	0.03	0.03	0.03	0.03	0.03	0.04
	20	1.75	44.4	6089	0.06	0.03	0.03	0.03	0.03	0.03	0.03
0.01	1	1.50	4.5	4988	0.34	0.13	0.13	0.14	0.14	0.15	0.16
	2	1.50	8.9	5266	0.34	0.14	0.14	0.14	0.15	0.16	0.17
	3	1.50	11.8	5027	0.34	0.13	0.14	0.14	0.14	0.15	0.17
	4	1.50	16.6	5000	0.34	0.13	0.14	0.14	0.14	0.16	0.17
	6	1.50	24.1	5217	0.34	0.14	0.14	0.14	0.15	0.16	0.17
	8	1.50	32.7	5111	0.35	0.14	0.14	0.14	0.15	0.16	0.17
	12	1.50	46.7	5051	0.35	0.13	0.14	0.14	0.15	0.16	0.17
	20	1.50	66.8	5082	0.35	0.13	0.14	0.14	0.15	0.16	0.17
0.02	1	0.50	4.5	2171	0.57	0.10	0.11	0.11	0.12	0.14	0.15
	2	0.50	8.8	2202	0.57	0.10	0.10	0.11	0.12	0.13	0.15
	3	0.50	12.8	2214	0.57	0.10	0.10	0.11	0.11	0.13	0.15
	4	0.50	17.0	2273	0.57	0.10	0.10	0.11	0.12	0.13	0.15
	6	0.50	25.8	2216	0.57	0.10	0.10	0.11	0.12	0.13	0.15
	8	0.50	33.8	2240	0.57	0.10	0.10	0.11	0.12	0.13	0.15
	12	0.50	48.6	2271	0.58	0.10	0.10	0.11	0.12	0.13	0.15
	20	0.50	71.8	2246	0.60	0.10	0.10	0.11	0.11	0.13	0.15
0.05	1	0.50	3.0	2046	1.09	0.19	0.20	0.21	0.23	0.26	0.29
	2	0.50	5.9	2085	1.09	0.19	0.20	0.21	0.22	0.26	0.29
	3	0.50	8.9	2078	1.09	0.19	0.20	0.21	0.22	0.26	0.29
	4	0.50	11.5	2118	1.09	0.19	0.20	0.20	0.22	0.25	0.29
	6	0.50	17.0	2082	1.09	0.19	0.20	0.20	0.22	0.26	0.29
	8	0.50	23.4	2112	1.09	0.19	0.20	0.21	0.22	0.26	0.29
	12	0.50	33.2	2137	1.10	0.19	0.20	0.21	0.22	0.26	0.29
	20	0.50	51.7	2124	1.11	0.19	0.20	0.21	0.22	0.26	0.29
0.10	1	0.125	4.0	917	1.68	0.15	0.16	0.18	0.21	0.26	0.32
	2	0.125	6.7	943	1.68	0.15	0.17	0.18	0.21	0.27	0.33
	3	0.125	10.3	917	1.69	0.15	0.16	0.18	0.21	0.26	0.32
	4	0.125	12.7	910	1.68	0.15	0.16	0.18	0.21	0.27	0.32
	6	0.125	19.9	913	1.69	0.15	0.17	0.18	0.21	0.27	0.33
	8	0.125	27.6	913	1.69	0.15	0.16	0.18	0.21	0.27	0.32
	12	0.125	39.8	913	1.69	0.15	0.16	0.18	0.21	0.27	0.32
	20	0.125	60.7	916	1.73	0.15	0.16	0.18	0.21	0.27	0.32
0.20	1	0.030	2.7	547	2.45	0.15	0.17	0.20	0.24	0.34	0.43
	2	0.030	3.9	488	2.45	0.15	0.17	0.20	0.25	0.35	0.45
	3	0.030	7.2	507	2.46	0.15	0.17	0.20	0.24	0.34	0.43
	4	0.030	8.0	502	2.46	0.16	0.18	0.21	0.26	0.35	0.45
	6	0.030	11.7	496	2.46	0.15	0.17	0.20	0.25	0.34	0.44
	8	0.030	16.2	511	2.47	0.15	0.18	0.20	0.25	0.35	0.44
	12	0.030	25.3	501	2.47	0.15	0.18	0.20	0.25	0.35	0.44
	20	0.030	37.4	501	2.49	0.15	0.18	0.20	0.25	0.35	0.44
0.50	1	0.015	0.9	365	3.63	0.21	0.26	0.31	0.40	0.58	0.76
	2	0.015	1.0	389	3.63	0.20	0.24	0.28	0.37	0.54	0.71
	3	0.015	1.8	378	3.63	0.21	0.25	0.30	0.38	0.56	0.73
	4	0.015	1.5	365	3.63	0.20	0.24	0.28	0.36	0.52	0.68
	6	0.015	2.8	378	3.63	0.20	0.24	0.28	0.37	0.54	0.71
	8	0.015	3.4	372	3.63	0.20	0.24	0.29	0.37	0.54	0.71
	12	0.015	5.6	371	3.64	0.20	0.24	0.28	0.36	0.53	0.69
	20	0.015	8.7	371	3.64	0.20	0.24	0.29	0.37	0.54	0.71

Table B.12: Detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area for various RADTi in case of $\sigma^2_{\ln K} = 1.0$ assuming daily (ED) and monthly (1M) sampling frequencies

$\sigma^2_{\ln K}$											1.00									
α_T(m)	now	nfds(max)	P_d (ED)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L	P_d (1M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	1	1.75	3.8	5629	0.12	0.04	0.04	0.04	0.04	0.05	0.05	3.8	5605	0.12	0.04	0.04	0.04	0.04	0.05	0.05
	2	1.75	7.1	5373	0.12	0.04	0.04	0.04	0.04	0.05	0.05	7.0	5388	0.12	0.04	0.04	0.04	0.05	0.05	0.05
	3	1.75	9.8	5606	0.12	0.04	0.04	0.04	0.04	0.05	0.05	9.7	5597	0.12	0.04	0.04	0.04	0.04	0.05	0.05
	4	1.75	14.0	5509	0.12	0.04	0.04	0.04	0.04	0.04	0.05	13.8	5510	0.12	0.04	0.04	0.04	0.04	0.04	0.05
	6	1.75	20.6	5397	0.12	0.04	0.04	0.04	0.04	0.04	0.05	20.3	5415	0.12	0.04	0.04	0.04	0.04	0.05	0.05
	8	1.75	26.5	5439	0.12	0.04	0.04	0.04	0.04	0.04	0.05	26.1	5446	0.12	0.04	0.04	0.04	0.04	0.04	0.05
	12	1.75	39.9	5455	0.12	0.04	0.04	0.04	0.04	0.04	0.05	39.3	5471	0.12	0.04	0.04	0.04	0.04	0.04	0.05
	20	1.75	57.2	5407	0.11	0.04	0.04	0.04	0.04	0.04	0.05	56.4	5423	0.11	0.04	0.04	0.04	0.04	0.04	0.05
0.01	1	1.25	5.7	3950	0.55	0.14	0.14	0.15	0.15	0.17	0.19	5.3	3916	0.55	0.14	0.14	0.14	0.15	0.17	0.19
	2	1.25	9.5	3961	0.55	0.14	0.14	0.15	0.15	0.17	0.19	9.1	3962	0.55	0.14	0.14	0.15	0.15	0.17	0.19
	3	1.25	14.7	4008	0.55	0.14	0.14	0.15	0.16	0.17	0.19	14.0	4005	0.56	0.14	0.14	0.15	0.16	0.17	0.19
	4	1.25	18.1	4005	0.55	0.14	0.14	0.15	0.15	0.17	0.19	17.5	4014	0.55	0.14	0.14	0.14	0.15	0.17	0.18
	6	1.25	27.4	4020	0.55	0.14	0.14	0.15	0.15	0.17	0.19	26.3	4015	0.55	0.14	0.14	0.15	0.15	0.17	0.19
	8	1.25	35.7	3983	0.55	0.14	0.14	0.14	0.15	0.17	0.19	34.4	3995	0.55	0.14	0.14	0.14	0.15	0.17	0.19
	12	1.25	50.4	3980	0.54	0.14	0.14	0.14	0.15	0.17	0.19	48.4	4000	0.55	0.14	0.14	0.14	0.15	0.17	0.19
	20	1.25	68.8	4028	0.55	0.14	0.14	0.14	0.15	0.17	0.19	66.7	4022	0.55	0.14	0.14	0.14	0.15	0.17	0.19
0.02	1	0.50	6.3	1940	0.88	0.10	0.11	0.12	0.13	0.15	0.18	5.9	1957	0.88	0.10	0.11	0.12	0.13	0.15	0.18
	2	0.50	10.1	2100	0.88	0.10	0.11	0.11	0.13	0.15	0.17	9.7	2110	0.88	0.10	0.11	0.12	0.13	0.15	0.17
	3	0.50	17.0	1938	0.88	0.10	0.11	0.11	0.13	0.15	0.17	16.2	1949	0.88	0.10	0.11	0.11	0.13	0.15	0.17
	4	0.50	20.5	2046	0.88	0.11	0.11	0.12	0.13	0.15	0.18	19.7	2066	0.88	0.11	0.11	0.12	0.13	0.15	0.18
	6	0.50	28.5	2055	0.88	0.10	0.11	0.12	0.13	0.15	0.18	27.5	2071	0.88	0.10	0.11	0.12	0.13	0.15	0.18
	8	0.50	42.1	2082	0.87	0.11	0.11	0.12	0.13	0.15	0.18	40.8	2088	0.87	0.11	0.11	0.12	0.13	0.15	0.18
	12	0.50	57.5	2073	0.87	0.10	0.11	0.12	0.13	0.15	0.18	55.6	2086	0.88	0.10	0.11	0.12	0.13	0.15	0.18
	20	0.50	77.0	2046	0.86	0.10	0.11	0.11	0.13	0.15	0.18	75.5	2056	0.86	0.10	0.11	0.11	0.13	0.15	0.18
0.05	1	0.13	5.7	874	1.54	0.10	0.11	0.12	0.15	0.19	0.24	5.6	887	1.54	0.10	0.11	0.12	0.15	0.20	0.25
	2	0.13	11.6	1033	1.55	0.09	0.10	0.11	0.13	0.18	0.22	11.2	1037	1.55	0.09	0.10	0.11	0.14	0.18	0.22
	3	0.13	17.0	906	1.54	0.09	0.10	0.11	0.14	0.18	0.23	16.5	925	1.55	0.09	0.11	0.12	0.14	0.19	0.23
	4	0.13	22.0	968	1.55	0.09	0.10	0.11	0.13	0.18	0.22	21.3	985	1.55	0.09	0.10	0.11	0.13	0.18	0.22
	6	0.13	33.3	985	1.56	0.09	0.10	0.11	0.14	0.18	0.22	31.9	999	1.56	0.09	0.10	0.12	0.14	0.18	0.22
	8	0.13	43.5	963	1.55	0.09	0.10	0.11	0.14	0.18	0.22	42.1	985	1.56	0.09	0.10	0.12	0.14	0.18	0.23
	12	0.13	61.8	965	1.56	0.09	0.10	0.11	0.13	0.18	0.22	59.7	983	1.57	0.09	0.10	0.11	0.14	0.18	0.22
	20	0.13	86.3	931	1.54	0.09	0.10	0.11	0.13	0.18	0.22	84.7	942	1.54	0.09	0.10	0.11	0.13	0.18	0.22
0.10	1	0.063	5.4	668	2.23	0.12	0.14	0.16	0.20	0.28	0.36	5.1	697	2.24	0.12	0.14	0.16	0.20	0.28	0.36
	2	0.063	11.1	804	2.24	0.12	0.14	0.16	0.19	0.26	0.34	10.2	779	2.24	0.12	0.14	0.16	0.19	0.26	0.34
	3	0.063	17.1	654	2.24	0.12	0.13	0.15	0.19	0.27	0.34	15.9	663	2.24	0.11	0.13	0.15	0.19	0.26	0.34
	4	0.063	21.6	686	2.25	0.11	0.13	0.15	0.19	0.26	0.33	20.4	681	2.24	0.12	0.13	0.15	0.19	0.26	0.33
	6	0.063	31.6	740	2.25	0.12	0.14	0.16	0.19	0.27	0.34	29.4	733	2.24	0.12	0.14	0.16	0.19	0.27	0.34
	8	0.063	43.2	705	2.25	0.12	0.14	0.16	0.19	0.26	0.34	40.0	703	2.24	0.12	0.14	0.15	0.19	0.26	0.34
	12	0.063	60.8	689	2.25	0.12	0.14	0.15	0.19	0.26	0.34	56.5	686	2.24	0.12	0.14	0.15	0.19	0.26	0.34
	20	0.063	86.2	691	2.24	0.11	0.13	0.15	0.19	0.26	0.34	82.7	695	2.24	0.12	0.13	0.15	0.19	0.27	0.34
0.20	1	0.030	4.0	435	3.03	0.13	0.17	0.20	0.26	0.39	0.51	3.4	403	3.03	0.13	0.16	0.19	0.26	0.38	0.51
	2	0.030	7.7	407	3.03	0.13	0.16	0.20	0.26	0.38	0.50	6.5	398	3.03	0.12	0.15	0.19	0.25	0.37	0.48
	3	0.030	12.8	373	3.03	0.12	0.16	0.19	0.25	0.38	0.50	11.2	355	3.03	0.12	0.15	0.18	0.25	0.37	0.49
	4	0.030	16.6	401	3.03	0.12	0.16	0.19	0.25	0.37	0.49	14.5	383	3.03	0.12	0.15	0.18	0.25	0.36	0.48
	6	0.030	22.0	395	3.03	0.12	0.16	0.19	0.25	0.38	0.50	19.2	390	3.03	0.12	0.15	0.18	0.25	0.37	0.49
	8	0.030	31.1	382	3.03	0.12	0.16	0.19	0.26	0.38	0.50	26.6	359	3.03	0.12	0.15	0.18	0.25	0.37	0.49
	12	0.030	44.7	398	3.03	0.12	0.16	0.19	0.25	0.38	0.50	38.6	380	3.04	0.12	0.15	0.18	0.24	0.36	0.48
	20	0.030	64.6	390	3.02	0.12	0.16	0.19	0.25	0.38	0.50	57.8	362	3.02	0.12	0.15	0.18	0.25	0.37	0.49
0.50	1	0.015	2.2	124	4.02	0.10	0.18	0.25	0.38	0.63	0.86	2.0	131	4.02	0.11	0.19	0.26	0.40	0.65	0.88
	2	0.015	4.2	112	4.03	0.09	0.17	0.24	0.38	0.62	0.84	3.6	112	4.03	0.09	0.17	0.25	0.38	0.62	0.85
	3	0.015	7.7	117	4.03	0.10	0.18	0.26	0.39	0.64	0.87	6.7	118	4.03	0.10	0.19	0.26	0.40	0.64	0.87
	4	0.015	9.0	127	4.02	0.10	0.18	0.25	0.38	0.63	0.86	7.5	127	4.02	0.10	0.18	0.24	0.38	0.62	0.85
	6	0.015	12.7	131	4.03	0.09	0.17	0.25	0.38	0.62	0.84	10.9	124	4.03	0.09	0.17	0.25	0.38	0.62	0.84
	8	0.015	18.1	125	4.03	0.10	0.18	0.25	0.38	0.63	0.85	15.6	121	4.03	0.10	0.18	0.25	0.39	0.63	0.86
	12	0.015	25.3	119	4.03	0.09	0.17	0.25	0.38	0.62	0.85	21.6	117	4.03	0.09	0.17	0.24	0.38	0.62	0.84
	20	0.015	36.9	114	4.04	0.09	0.17	0.24	0.38	0.62	0.85	32.9	119	4.04	0.09	0.17	0.25	0.38	0.62	0.84

Table B.13: Detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area for various RADTi in case of $\sigma^2_{\ln K} = 1.0$ assuming bimonthly (2M) and quarterly (3M) sampling frequencies

$\sigma^2_{\ln K}$										1.00										
α_T(m)	now	nfds(max)	P_d (2M)	$\langle T_{(DET.)} \rangle$ (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L	P_d (3M)	$\langle T_{(DET.)} \rangle$ (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	1	1.75	3.8	5620	0.12	0.04	0.04	0.04	0.04	0.05	0.05	3.7	5645	0.12	0.04	0.04	0.04	0.04	0.05	0.05
	2	1.75	6.9	5395	0.12	0.04	0.04	0.04	0.05	0.05	0.05	6.8	5446	0.12	0.04	0.04	0.04	0.05	0.05	0.05
	3	1.75	9.6	5617	0.12	0.04	0.04	0.04	0.04	0.05	0.05	9.5	5643	0.12	0.04	0.04	0.04	0.04	0.05	0.05
	4	1.75	13.5	5513	0.12	0.04	0.04	0.04	0.04	0.04	0.05	13.4	5518	0.12	0.04	0.04	0.04	0.04	0.04	0.05
	6	1.75	20.1	5435	0.12	0.04	0.04	0.04	0.04	0.05	0.05	19.8	5456	0.12	0.04	0.04	0.04	0.04	0.05	0.05
	8	1.75	25.9	5458	0.12	0.04	0.04	0.04	0.04	0.05	0.05	25.5	5456	0.12	0.04	0.04	0.04	0.04	0.05	0.05
	12	1.75	38.8	5486	0.12	0.04	0.04	0.04	0.04	0.04	0.05	38.5	5500	0.12	0.04	0.04	0.04	0.04	0.04	0.05
	20	1.75	55.9	5434	0.11	0.04	0.04	0.04	0.04	0.04	0.05	55.2	5451	0.12	0.04	0.04	0.04	0.04	0.04	0.05
0.01	1	1.25	5.2	3872	0.55	0.14	0.14	0.14	0.15	0.17	0.19	5.2	3893	0.55	0.14	0.14	0.15	0.15	0.17	0.19
	2	1.25	8.8	4008	0.55	0.14	0.14	0.15	0.16	0.17	0.19	8.7	3992	0.55	0.14	0.14	0.15	0.16	0.17	0.19
	3	1.25	13.6	3982	0.56	0.14	0.14	0.15	0.16	0.17	0.19	13.4	4003	0.56	0.14	0.14	0.15	0.16	0.17	0.19
	4	1.25	17.1	4025	0.55	0.14	0.14	0.14	0.15	0.17	0.18	16.7	4022	0.55	0.14	0.14	0.14	0.15	0.17	0.18
	6	1.25	25.6	4041	0.55	0.14	0.14	0.15	0.15	0.17	0.19	25.0	4042	0.55	0.14	0.14	0.15	0.15	0.17	0.19
	8	1.25	33.6	4004	0.55	0.14	0.14	0.14	0.15	0.17	0.19	32.9	4022	0.55	0.14	0.14	0.14	0.15	0.17	0.19
	12	1.25	47.8	4019	0.55	0.14	0.14	0.14	0.15	0.17	0.19	46.7	4028	0.55	0.14	0.14	0.14	0.15	0.17	0.19
	20	1.25	65.7	4030	0.55	0.14	0.14	0.14	0.15	0.17	0.19	64.7	4047	0.55	0.14	0.14	0.14	0.15	0.17	0.19
0.02	1	0.50	5.7	1926	0.88	0.10	0.11	0.12	0.13	0.15	0.18	5.7	1971	0.88	0.10	0.11	0.12	0.13	0.16	0.18
	2	0.50	9.6	2141	0.88	0.10	0.11	0.12	0.13	0.15	0.17	9.5	2167	0.88	0.11	0.11	0.12	0.13	0.15	0.18
	3	0.50	15.9	1943	0.88	0.10	0.11	0.11	0.13	0.15	0.17	15.7	1974	0.88	0.10	0.11	0.12	0.13	0.15	0.18
	4	0.50	19.3	2078	0.88	0.11	0.11	0.12	0.13	0.16	0.18	19.2	2098	0.88	0.11	0.11	0.12	0.13	0.16	0.18
	6	0.50	26.9	2076	0.88	0.11	0.11	0.12	0.13	0.15	0.18	26.6	2098	0.88	0.11	0.11	0.12	0.13	0.15	0.18
	8	0.50	39.9	2101	0.88	0.11	0.11	0.12	0.13	0.15	0.18	39.3	2120	0.88	0.11	0.11	0.12	0.13	0.16	0.18
	12	0.50	54.7	2097	0.88	0.11	0.11	0.12	0.13	0.15	0.18	53.9	2115	0.88	0.11	0.11	0.12	0.13	0.15	0.18
	20	0.50	74.6	2064	0.87	0.10	0.11	0.11	0.13	0.15	0.18	74.2	2077	0.87	0.10	0.11	0.12	0.13	0.15	0.18
0.05	1	0.13	5.5	894	1.54	0.10	0.11	0.12	0.15	0.20	0.25	5.4	904	1.54	0.10	0.11	0.13	0.15	0.20	0.25
	2	0.13	11.1	1049	1.55	0.10	0.11	0.12	0.14	0.18	0.22	10.9	1052	1.55	0.10	0.11	0.12	0.14	0.18	0.22
	3	0.13	16.2	926	1.54	0.09	0.11	0.12	0.14	0.19	0.23	16.0	959	1.55	0.10	0.11	0.12	0.14	0.19	0.23
	4	0.13	21.0	999	1.55	0.09	0.10	0.11	0.13	0.18	0.22	20.7	1017	1.56	0.09	0.10	0.11	0.14	0.18	0.22
	6	0.13	31.2	1013	1.56	0.09	0.11	0.12	0.14	0.18	0.22	30.8	1022	1.56	0.10	0.11	0.12	0.14	0.18	0.23
	8	0.13	41.5	999	1.56	0.10	0.11	0.12	0.14	0.18	0.23	40.9	1015	1.56	0.10	0.11	0.12	0.14	0.18	0.23
	12	0.13	59.1	998	1.57	0.09	0.10	0.11	0.14	0.18	0.23	58.3	1014	1.57	0.10	0.11	0.12	0.14	0.18	0.23
	20	0.13	84.2	957	1.55	0.09	0.10	0.11	0.14	0.18	0.23	83.1	972	1.57	0.09	0.10	0.11	0.14	0.18	0.23
0.10	1	0.063	5.1	715	2.24	0.13	0.14	0.16	0.20	0.28	0.36	4.8	717	2.24	0.13	0.14	0.16	0.20	0.28	0.36
	2	0.063	9.9	787	2.24	0.12	0.14	0.16	0.19	0.26	0.34	9.7	785	2.24	0.12	0.14	0.16	0.19	0.27	0.34
	3	0.063	15.8	678	2.24	0.12	0.14	0.15	0.19	0.27	0.34	15.2	683	2.24	0.12	0.14	0.15	0.19	0.26	0.34
	4	0.063	19.9	687	2.24	0.12	0.14	0.15	0.19	0.26	0.34	19.6	710	2.24	0.12	0.14	0.15	0.19	0.26	0.33
	6	0.063	28.5	731	2.24	0.12	0.14	0.16	0.19	0.27	0.34	27.6	745	2.25	0.12	0.14	0.16	0.19	0.27	0.34
	8	0.063	38.6	709	2.25	0.12	0.14	0.16	0.19	0.26	0.34	37.8	725	2.25	0.12	0.14	0.16	0.19	0.27	0.34
	12	0.063	54.8	696	2.24	0.12	0.14	0.16	0.19	0.26	0.34	53.7	714	2.25	0.12	0.14	0.16	0.19	0.27	0.34
	20	0.063	81.0	703	2.25	0.12	0.14	0.15	0.19	0.27	0.34	79.5	712	2.25	0.12	0.14	0.16	0.19	0.27	0.34
0.20	1	0.030	3.2	399	3.03	0.13	0.16	0.19	0.26	0.38	0.51	3.0	392	3.03	0.13	0.16	0.19	0.26	0.38	0.50
	2	0.030	6.2	405	3.03	0.12	0.16	0.19	0.25	0.37	0.48	6.1	409	3.03	0.13	0.16	0.19	0.25	0.37	0.48
	3	0.030	10.6	359	3.03	0.12	0.15	0.19	0.25	0.37	0.49	10.3	361	3.03	0.12	0.16	0.19	0.25	0.38	0.50
	4	0.030	13.9	392	3.03	0.12	0.15	0.18	0.25	0.36	0.48	13.2	401	3.03	0.12	0.16	0.19	0.25	0.36	0.48
	6	0.030	18.0	385	3.03	0.12	0.15	0.18	0.25	0.37	0.49	17.8	394	3.03	0.12	0.16	0.19	0.25	0.37	0.49
	8	0.030	25.3	362	3.03	0.12	0.15	0.18	0.25	0.37	0.49	24.5	373	3.03	0.12	0.16	0.19	0.25	0.37	0.49
	12	0.030	37.0	388	3.04	0.12	0.15	0.18	0.25	0.37	0.48	35.8	397	3.04	0.12	0.15	0.19	0.25	0.37	0.49
	20	0.030	55.6	367	3.03	0.12	0.15	0.18	0.25	0.37	0.49	53.6	372	3.03	0.12	0.15	0.19	0.25	0.37	0.49
0.50	1	0.015	1.9	152	4.02	0.13	0.20	0.27	0.41	0.65	0.88	1.6	170	4.02	0.14	0.21	0.28	0.41	0.65	0.88
	2	0.015	3.4	127	4.03	0.11	0.18	0.25	0.39	0.62	0.85	3.2	134	4.03	0.12	0.19	0.26	0.39	0.63	0.86
	3	0.015	6.4	131	4.03	0.12	0.20	0.27	0.41	0.65	0.88	5.8	153	4.03	0.13	0.21	0.28	0.41	0.65	0.87
	4	0.015	7.0	136	4.02	0.11	0.18	0.25	0.38	0.62	0.85	6.5	162	4.03	0.12	0.19	0.25	0.38	0.62	0.84
	6	0.015	10.4	133	4.03	0.11	0.18	0.25	0.38	0.62	0.84	9.7	152	4.03	0.12	0.19	0.26	0.39	0.62	0.83
	8	0.015	14.4	132	4.03	0.11	0.19	0.26	0.39	0.63	0.86	13.4	150	4.03	0.12	0.20	0.26	0.39	0.63	0.85
	12	0.015	20.5	126	4.03	0.11	0.18	0.25	0.38	0.62	0.85	19.0	143	4.03	0.12	0.19	0.26	0.39	0.62	0.85
	20	0.015	31.5	132	4.04	0.11	0.19	0.26	0.39	0.63	0.85	29.8	151	4.04	0.12	0.20	0.26	0.39	0.63	0.85

Table B.14: Detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area L for various RADTi in case of $\sigma^2_{\ln K} = 1.0$ assuming every 4 months (4M) and biannually (6M) sampling frequencies

	$\sigma^2_{\ln K}$										1.00									
α_T(m)	now	nfds(max)	P_d (4M)	$<T_{(DET.)}>$ (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L	P_d (6M)	$<T_{(DET.)}>$ (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	1	1.75	3.7	5682	0.12	0.04	0.04	0.04	0.04	0.05	0.05	3.6	5643	0.12	0.04	0.04	0.04	0.04	0.05	0.05
	2	1.75	6.8	5413	0.12	0.04	0.04	0.04	0.05	0.05	0.05	6.5	5535	0.12	0.04	0.04	0.04	0.05	0.05	0.05
	3	1.75	9.4	5660	0.12	0.04	0.04	0.04	0.04	0.05	0.05	9.1	5709	0.12	0.04	0.04	0.04	0.04	0.05	0.05
	4	1.75	13.0	5554	0.12	0.04	0.04	0.04	0.04	0.04	0.05	12.4	5646	0.12	0.04	0.04	0.04	0.04	0.04	0.05
	6	1.75	19.6	5480	0.12	0.04	0.04	0.04	0.04	0.05	0.05	18.5	5579	0.12	0.04	0.04	0.04	0.04	0.05	0.05
	8	1.75	25.4	5484	0.12	0.04	0.04	0.04	0.04	0.05	0.05	24.1	5581	0.12	0.04	0.04	0.04	0.04	0.05	0.05
	12	1.75	37.6	5539	0.12	0.04	0.04	0.04	0.04	0.04	0.05	36.2	5607	0.12	0.04	0.04	0.04	0.04	0.04	0.05
	20	1.75	54.8	5471	0.11	0.04	0.04	0.04	0.04	0.04	0.05	52.5	5542	0.12	0.04	0.04	0.04	0.04	0.05	0.05
0.01	1	1.25	5.1	3878	0.55	0.14	0.14	0.14	0.15	0.17	0.19	5.0	3926	0.55	0.14	0.14	0.15	0.15	0.17	0.19
	2	1.25	8.5	4046	0.55	0.14	0.14	0.15	0.16	0.17	0.19	8.2	4058	0.55	0.14	0.14	0.15	0.16	0.17	0.19
	3	1.25	13.2	4005	0.56	0.14	0.14	0.15	0.16	0.17	0.19	12.8	4038	0.56	0.14	0.14	0.15	0.16	0.17	0.19
	4	1.25	16.5	4043	0.55	0.14	0.14	0.14	0.15	0.17	0.18	16.0	4054	0.55	0.14	0.14	0.15	0.15	0.17	0.19
	6	1.25	24.5	4085	0.55	0.14	0.14	0.15	0.15	0.17	0.19	23.8	4100	0.55	0.14	0.14	0.15	0.15	0.17	0.19
	8	1.25	32.6	4029	0.55	0.14	0.14	0.14	0.15	0.17	0.19	31.3	4074	0.55	0.14	0.14	0.15	0.15	0.17	0.19
	12	1.25	46.2	4041	0.55	0.14	0.14	0.14	0.15	0.17	0.19	45.2	4075	0.55	0.14	0.14	0.14	0.15	0.17	0.19
	20	1.25	64.3	4064	0.55	0.14	0.14	0.14	0.15	0.17	0.19	62.4	4085	0.55	0.14	0.14	0.15	0.15	0.17	0.19
0.02	1	0.50	5.6	1955	0.88	0.10	0.11	0.12	0.13	0.15	0.18	5.3	2002	0.88	0.11	0.11	0.12	0.13	0.16	0.18
	2	0.50	9.3	2200	0.88	0.11	0.11	0.12	0.13	0.15	0.18	8.9	2242	0.88	0.11	0.11	0.12	0.13	0.15	0.18
	3	0.50	15.5	1968	0.88	0.10	0.11	0.12	0.13	0.15	0.18	14.8	2024	0.88	0.11	0.11	0.12	0.13	0.15	0.18
	4	0.50	18.9	2115	0.88	0.11	0.11	0.12	0.13	0.16	0.18	18.6	2153	0.88	0.11	0.12	0.12	0.13	0.16	0.18
	6	0.50	26.0	2123	0.88	0.11	0.11	0.12	0.13	0.15	0.18	25.0	2167	0.88	0.11	0.11	0.12	0.13	0.16	0.18
	8	0.50	38.6	2141	0.88	0.11	0.11	0.12	0.13	0.16	0.18	37.0	2188	0.88	0.11	0.11	0.12	0.13	0.16	0.18
	12	0.50	53.5	2134	0.88	0.11	0.11	0.12	0.13	0.16	0.18	52.2	2172	0.88	0.11	0.11	0.12	0.13	0.16	0.18
	20	0.50	73.5	2092	0.87	0.10	0.11	0.12	0.13	0.15	0.18	72.0	2135	0.89	0.11	0.11	0.12	0.13	0.15	0.18
0.05	1	0.13	5.1	927	1.54	0.10	0.11	0.13	0.15	0.20	0.25	5.0	950	1.54	0.11	0.12	0.13	0.15	0.20	0.25
	2	0.13	10.7	1083	1.55	0.10	0.11	0.12	0.14	0.18	0.23	10.4	1112	1.55	0.10	0.11	0.12	0.14	0.19	0.23
	3	0.13	15.4	964	1.55	0.10	0.11	0.12	0.14	0.19	0.23	14.8	1005	1.55	0.10	0.11	0.12	0.15	0.19	0.24
	4	0.13	20.4	1028	1.56	0.10	0.11	0.12	0.14	0.18	0.23	19.6	1076	1.56	0.10	0.11	0.12	0.14	0.18	0.23
	6	0.13	30.2	1044	1.56	0.10	0.11	0.12	0.14	0.18	0.23	29.2	1083	1.56	0.10	0.11	0.12	0.14	0.19	0.23
	8	0.13	40.3	1027	1.56	0.10	0.11	0.12	0.14	0.18	0.23	39.0	1070	1.57	0.10	0.11	0.12	0.14	0.19	0.23
	12	0.13	57.5	1031	1.57	0.10	0.11	0.12	0.14	0.18	0.23	55.8	1071	1.58	0.10	0.11	0.12	0.14	0.19	0.23
	20	0.13	82.9	985	1.56	0.09	0.10	0.12	0.14	0.18	0.23	80.6	1026	1.61	0.10	0.11	0.12	0.14	0.19	0.23
0.10	1	0.063	4.8	725	2.24	0.13	0.14	0.16	0.20	0.28	0.36	4.6	765	2.24	0.13	0.15	0.17	0.21	0.28	0.36
	2	0.063	9.5	804	2.24	0.13	0.15	0.16	0.20	0.27	0.34	9.0	822	2.24	0.13	0.15	0.16	0.20	0.27	0.34
	3	0.063	14.9	687	2.24	0.12	0.14	0.16	0.19	0.27	0.34	14.1	729	2.25	0.12	0.14	0.16	0.19	0.27	0.34
	4	0.063	19.0	702	2.24	0.12	0.14	0.15	0.19	0.26	0.34	18.1	741	2.24	0.12	0.14	0.16	0.19	0.26	0.34
	6	0.063	27.1	755	2.24	0.13	0.14	0.16	0.20	0.27	0.34	25.5	776	2.25	0.13	0.15	0.16	0.20	0.27	0.34
	8	0.063	36.8	735	2.25	0.12	0.14	0.16	0.19	0.27	0.34	34.8	767	2.26	0.13	0.14	0.16	0.20	0.27	0.34
	12	0.063	52.5	717	2.25	0.12	0.14	0.16	0.19	0.27	0.34	49.5	756	2.26	0.13	0.14	0.16	0.20	0.27	0.34
	20	0.063	78.5	722	2.26	0.12	0.14	0.16	0.20	0.27	0.34	74.9	754	2.29	0.13	0.14	0.16	0.20	0.27	0.34
0.20	1	0.030	3.0	396	3.03	0.13	0.17	0.20	0.26	0.39	0.51	2.7	418	3.03	0.14	0.17	0.20	0.26	0.38	0.50
	2	0.030	5.6	393	3.03	0.12	0.16	0.19	0.25	0.36	0.48	5.2	456	3.03	0.13	0.16	0.19	0.25	0.36	0.47
	3	0.030	10.0	368	3.03	0.13	0.16	0.19	0.26	0.38	0.50	9.2	401	3.03	0.13	0.17	0.20	0.26	0.38	0.49
	4	0.030	13.1	421	3.03	0.13	0.16	0.19	0.25	0.37	0.49	11.8	435	3.03	0.13	0.16	0.19	0.25	0.37	0.48
	6	0.030	16.7	400	3.03	0.12	0.16	0.19	0.25	0.37	0.49	15.6	428	3.03	0.13	0.16	0.19	0.25	0.37	0.48
	8	0.030	23.2	387	3.04	0.12	0.16	0.19	0.25	0.37	0.49	21.3	419	3.04	0.13	0.16	0.19	0.25	0.37	0.49
	12	0.030	34.3	406	3.05	0.13	0.16	0.19	0.25	0.37	0.48	31.7	433	3.05	0.13	0.16	0.19	0.25	0.37	0.48
	20	0.030	52.7	391	3.04	0.13	0.16	0.19	0.25	0.37	0.49	48.0	413	3.05	0.13	0.16	0.19	0.25	0.37	0.49
0.50	1	0.015	1.5	189	4.03	0.14	0.21	0.27	0.40	0.63	0.84	1.2	260	4.03	0.18	0.24	0.30	0.41	0.63	0.84
	2	0.015	3.0	170	4.03	0.14	0.21	0.27	0.40	0.63	0.84	2.4	215	4.03	0.16	0.23	0.29	0.41	0.63	0.85
	3	0.015	5.4	171	4.03	0.15	0.22	0.28	0.41	0.64	0.86	4.1	226	4.03	0.17	0.23	0.28	0.40	0.62	0.83
	4	0.015	6.1	176	4.03	0.14	0.20	0.27	0.39	0.62	0.84	4.8	231	4.03	0.15	0.20	0.26	0.37	0.59	0.80
	6	0.015	9.3	166	4.03	0.14	0.21	0.27	0.39	0.62	0.83	7.2	230	4.03	0.16	0.22	0.28	0.39	0.60	0.81
	8	0.015	12.2	171	4.03	0.14	0.21	0.27	0.40	0.63	0.85	9.5	219	4.03	0.16	0.21	0.27	0.38	0.60	0.81
	12	0.015	17.8	167	4.04	0.14	0.20	0.27	0.39	0.62	0.84	14.0	214	4.04	0.15	0.21	0.27	0.38	0.59	0.80
	20	0.015	28.0	171	4.04	0.14	0.21	0.27	0.39	0.62	0.84	22.3	229	4.05	0.16	0.22	0.27	0.39	0.60	0.81

Table B.15: Detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area L for various RADTi in case of $\sigma^2_{\ln K} = 1.0$ assuming annually sampling frequency

$\sigma^2_{\ln K}$					1.00						
α_T(m)	now	nfds(max)	P_d (12M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	1	1.75	2.7	6049	0.12	0.04	0.04	0.04	0.04	0.05	0.05
	2	1.75	5.0	5808	0.12	0.04	0.04	0.05	0.05	0.05	0.05
	3	1.75	6.9	6106	0.12	0.04	0.04	0.04	0.05	0.05	0.05
	4	1.75	9.5	5992	0.12	0.04	0.04	0.04	0.04	0.05	0.05
	6	1.75	14.2	5914	0.12	0.04	0.04	0.04	0.05	0.05	0.05
	8	1.75	17.6	5935	0.12	0.04	0.04	0.04	0.05	0.05	0.05
	12	1.75	27.8	5964	0.12	0.04	0.04	0.04	0.04	0.05	0.05
	20	1.75	41.5	5907	0.12	0.04	0.04	0.04	0.04	0.05	0.05
0.01	1	1.25	4.0	4257	0.56	0.14	0.14	0.14	0.15	0.17	0.18
	2	1.25	6.9	4378	0.55	0.15	0.15	0.15	0.16	0.18	0.20
	3	1.25	10.4	4303	0.56	0.14	0.14	0.15	0.16	0.17	0.19
	4	1.25	13.1	4334	0.56	0.14	0.14	0.14	0.15	0.17	0.18
	6	1.25	19.9	4377	0.56	0.14	0.15	0.15	0.16	0.17	0.19
	8	1.25	25.6	4350	0.56	0.14	0.14	0.15	0.16	0.17	0.19
	12	1.25	37.5	4343	0.57	0.14	0.14	0.15	0.15	0.17	0.19
	20	1.25	53.6	4313	0.57	0.14	0.14	0.15	0.16	0.17	0.19
0.02	1	0.50	4.5	2138	0.88	0.11	0.11	0.12	0.13	0.15	0.18
	2	0.50	7.3	2498	0.89	0.11	0.12	0.12	0.13	0.15	0.18
	3	0.50	12.0	2182	0.88	0.11	0.11	0.12	0.13	0.15	0.18
	4	0.50	15.4	2335	0.89	0.11	0.12	0.13	0.14	0.16	0.19
	6	0.50	20.7	2399	0.89	0.11	0.12	0.12	0.13	0.16	0.18
	8	0.50	29.9	2379	0.90	0.11	0.12	0.12	0.13	0.16	0.18
	12	0.50	44.1	2363	0.90	0.11	0.12	0.12	0.14	0.16	0.19
	20	0.50	61.9	2308	0.93	0.11	0.12	0.12	0.13	0.16	0.18
0.05	1	0.13	3.7	1023	1.54	0.11	0.12	0.13	0.15	0.20	0.25
	2	0.13	8.4	1246	1.55	0.11	0.12	0.13	0.15	0.19	0.23
	3	0.13	11.9	1110	1.55	0.10	0.11	0.12	0.15	0.19	0.23
	4	0.13	16.9	1186	1.56	0.10	0.11	0.12	0.14	0.19	0.23
	6	0.13	23.7	1214	1.57	0.11	0.12	0.13	0.15	0.19	0.23
	8	0.13	32.7	1195	1.58	0.11	0.12	0.13	0.15	0.19	0.23
	12	0.13	47.1	1205	1.61	0.11	0.12	0.13	0.15	0.19	0.23
	20	0.13	68.7	1159	1.65	0.10	0.11	0.12	0.15	0.19	0.23
0.10	1	0.063	3.7	889	2.24	0.14	0.16	0.17	0.21	0.28	0.36
	2	0.063	7.3	977	2.25	0.14	0.16	0.17	0.20	0.27	0.34
	3	0.063	10.9	858	2.25	0.13	0.15	0.16	0.20	0.27	0.33
	4	0.063	14.3	883	2.25	0.13	0.15	0.17	0.20	0.27	0.33
	6	0.063	19.7	932	2.26	0.14	0.15	0.17	0.20	0.27	0.34
	8	0.063	27.6	904	2.27	0.14	0.15	0.17	0.20	0.27	0.34
	12	0.063	38.8	897	2.29	0.14	0.15	0.17	0.20	0.27	0.34
	20	0.063	59.3	895	2.35	0.14	0.15	0.17	0.20	0.27	0.34
0.20	1	0.030	1.7	558	3.03	0.16	0.18	0.20	0.26	0.36	0.46
	2	0.030	3.5	543	3.03	0.15	0.18	0.21	0.26	0.37	0.47
	3	0.030	5.9	519	3.04	0.15	0.18	0.20	0.25	0.36	0.46
	4	0.030	8.2	592	3.04	0.15	0.18	0.20	0.25	0.36	0.47
	6	0.030	10.0	592	3.04	0.15	0.18	0.20	0.25	0.36	0.46
	8	0.030	14.7	556	3.05	0.15	0.18	0.20	0.26	0.36	0.47
	12	0.030	21.0	583	3.06	0.15	0.18	0.20	0.25	0.36	0.46
	20	0.030	32.8	578	3.09	0.15	0.18	0.20	0.26	0.36	0.47
0.50	1	0.015	0.4	365	4.03	0.19	0.22	0.26	0.35	0.51	0.68
	2	0.015	0.7	417	4.03	0.20	0.24	0.27	0.35	0.52	0.69
	3	0.015	1.6	387	4.03	0.20	0.25	0.29	0.38	0.57	0.75
	4	0.015	2.1	410	4.03	0.18	0.22	0.26	0.34	0.51	0.69
	6	0.015	2.7	409	4.03	0.19	0.23	0.27	0.35	0.52	0.69
	8	0.015	4.0	428	4.03	0.20	0.24	0.28	0.36	0.54	0.71
	12	0.015	5.7	401	4.04	0.19	0.23	0.27	0.36	0.54	0.72
	20	0.015	9.2	402	4.04	0.19	0.24	0.28	0.37	0.54	0.72

Table B.16: Detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area for various RADTi in case of $\sigma^2_{\ln K} = 1.5$ assuming daily (ED) and monthly (1M) sampling frequencies

	$\sigma^2_{\ln K}$									1.50										
α_T(m)	now	nfds(max)	P_d (ED)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L	P_d (1M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	1	1.25	3.9	3790	0.21	0.03	0.03	0.03	0.04	0.04	0.05	3.8	3826	0.21	0.03	0.03	0.03	0.04	0.04	0.05
	2	1.25	7.2	4296	0.20	0.04	0.04	0.04	0.04	0.04	0.05	7.2	4319	0.20	0.04	0.04	0.04	0.04	0.04	0.05
	3	1.25	9.4	3999	0.21	0.03	0.03	0.04	0.04	0.04	0.05	9.3	4028	0.21	0.03	0.03	0.04	0.04	0.04	0.05
	4	1.25	13.3	3962	0.21	0.03	0.04	0.04	0.04	0.04	0.05	13.2	3986	0.21	0.03	0.04	0.04	0.04	0.04	0.05
	6	1.25	20.9	4164	0.20	0.03	0.03	0.04	0.04	0.04	0.05	20.7	4180	0.20	0.03	0.04	0.04	0.04	0.04	0.05
	8	1.25	25.7	4176	0.21	0.03	0.03	0.04	0.04	0.04	0.05	25.3	4189	0.21	0.03	0.03	0.04	0.04	0.04	0.05
	12	1.25	35.6	4093	0.20	0.03	0.03	0.04	0.04	0.04	0.05	35.2	4109	0.20	0.03	0.03	0.04	0.04	0.04	0.05
	20	1.25	54.9	4095	0.22	0.03	0.03	0.03	0.04	0.04	0.05	54.4	4116	0.22	0.03	0.03	0.03	0.04	0.04	0.05
0.01	1	1.00	5.0	3389	0.80	0.13	0.13	0.14	0.15	0.17	0.19	4.7	3373	0.80	0.13	0.13	0.14	0.15	0.17	0.19
	2	1.00	9.0	3282	0.79	0.13	0.13	0.14	0.15	0.17	0.20	8.6	3293	0.79	0.13	0.13	0.14	0.15	0.17	0.19
	3	1.00	13.5	3355	0.80	0.13	0.13	0.14	0.15	0.17	0.19	12.9	3356	0.80	0.13	0.13	0.14	0.15	0.17	0.19
	4	1.00	16.9	3359	0.80	0.13	0.13	0.14	0.15	0.17	0.19	16.3	3349	0.80	0.13	0.13	0.14	0.15	0.17	0.19
	6	1.00	24.2	3261	0.78	0.13	0.13	0.14	0.15	0.17	0.20	23.0	3241	0.78	0.13	0.13	0.14	0.15	0.17	0.19
	8	1.00	33.2	3288	0.79	0.13	0.13	0.14	0.15	0.17	0.19	31.8	3269	0.79	0.12	0.13	0.13	0.14	0.17	0.19
	12	1.00	45.8	3325	0.79	0.12	0.13	0.13	0.15	0.17	0.19	44.4	3337	0.79	0.12	0.13	0.13	0.15	0.17	0.19
	20	1.00	61.6	3308	0.79	0.12	0.13	0.13	0.15	0.17	0.19	59.9	3301	0.79	0.12	0.13	0.13	0.14	0.17	0.19
0.02	1	0.50	5.7	1974	1.20	0.11	0.12	0.13	0.14	0.18	0.21	5.4	1997	1.20	0.11	0.12	0.13	0.14	0.18	0.21
	2	0.50	9.7	2045	1.20	0.11	0.12	0.13	0.14	0.17	0.21	9.3	2062	1.20	0.11	0.12	0.13	0.14	0.17	0.20
	3	0.50	14.8	2089	1.20	0.12	0.12	0.13	0.15	0.18	0.21	14.0	2095	1.20	0.12	0.12	0.13	0.15	0.18	0.21
	4	0.50	18.9	1982	1.20	0.11	0.12	0.13	0.14	0.17	0.21	18.2	1991	1.19	0.11	0.12	0.13	0.14	0.17	0.21
	6	0.50	28.1	2046	1.18	0.11	0.12	0.13	0.14	0.18	0.21	26.9	2057	1.19	0.11	0.12	0.13	0.14	0.17	0.21
	8	0.50	36.7	2003	1.20	0.11	0.12	0.13	0.14	0.17	0.21	35.3	2014	1.20	0.11	0.12	0.13	0.14	0.17	0.21
	12	0.50	50.0	2040	1.20	0.11	0.12	0.13	0.14	0.17	0.20	48.4	2055	1.20	0.11	0.12	0.13	0.14	0.17	0.20
	20	0.50	69.1	2055	1.17	0.11	0.12	0.12	0.14	0.17	0.21	67.1	2056	1.17	0.11	0.12	0.13	0.14	0.17	0.21
0.05	1	0.13	5.5	927	1.96	0.09	0.11	0.12	0.15	0.20	0.26	5.2	938	1.96	0.09	0.11	0.12	0.14	0.20	0.25
	2	0.13	11.3	1023	1.96	0.10	0.11	0.12	0.15	0.20	0.26	10.7	1046	1.96	0.10	0.11	0.13	0.15	0.21	0.26
	3	0.13	14.9	1029	1.96	0.10	0.11	0.12	0.15	0.20	0.25	14.5	1052	1.96	0.10	0.11	0.12	0.15	0.20	0.25
	4	0.13	19.3	1057	1.97	0.10	0.11	0.12	0.15	0.20	0.26	18.4	1051	1.97	0.10	0.11	0.12	0.15	0.20	0.26
	6	0.13	31.8	1093	1.97	0.10	0.11	0.12	0.15	0.20	0.26	30.4	1115	1.96	0.10	0.11	0.13	0.15	0.20	0.26
	8	0.13	40.1	1018	1.97	0.10	0.11	0.12	0.15	0.20	0.25	38.6	1039	1.97	0.10	0.11	0.12	0.15	0.20	0.25
	12	0.13	57.6	1030	1.95	0.10	0.11	0.12	0.15	0.20	0.26	55.4	1034	1.95	0.10	0.11	0.12	0.15	0.20	0.26
	20	0.13	81.6	1054	1.98	0.09	0.11	0.12	0.14	0.20	0.25	79.6	1054	1.98	0.09	0.11	0.12	0.15	0.20	0.26
0.10	1	0.063	6.1	763	2.68	0.12	0.15	0.17	0.21	0.30	0.39	5.6	760	2.68	0.12	0.14	0.17	0.21	0.30	0.39
	2	0.063	10.3	726	2.68	0.12	0.14	0.16	0.20	0.28	0.36	9.5	735	2.68	0.12	0.14	0.16	0.20	0.28	0.36
	3	0.063	15.8	735	2.68	0.12	0.14	0.16	0.20	0.28	0.37	14.3	724	2.68	0.12	0.14	0.16	0.20	0.28	0.37
	4	0.063	19.9	766	2.69	0.12	0.14	0.16	0.20	0.29	0.37	18.6	795	2.69	0.12	0.14	0.16	0.20	0.29	0.37
	6	0.063	29.7	737	2.67	0.12	0.14	0.16	0.20	0.29	0.37	27.1	748	2.68	0.12	0.14	0.16	0.20	0.29	0.37
	8	0.063	40.0	754	2.70	0.12	0.14	0.16	0.20	0.29	0.37	36.5	758	2.70	0.12	0.14	0.16	0.20	0.28	0.37
	12	0.063	57.6	742	2.70	0.12	0.14	0.16	0.20	0.29	0.37	54.2	759	2.71	0.12	0.14	0.16	0.20	0.29	0.37
	20	0.063	80.8	736	2.65	0.12	0.14	0.16	0.20	0.29	0.37	76.9	738	2.67	0.12	0.14	0.16	0.20	0.29	0.37
0.20	1	0.015	4.1	435	3.41	0.14	0.18	0.22	0.29	0.43	0.57	3.4	411	3.41	0.13	0.17	0.21	0.28	0.42	0.55
	2	0.015	8.4	399	3.41	0.12	0.16	0.20	0.27	0.40	0.53	7.3	398	3.41	0.12	0.15	0.19	0.26	0.39	0.53
	3	0.015	12.1	401	3.41	0.12	0.16	0.20	0.27	0.40	0.54	10.6	388	3.41	0.12	0.15	0.19	0.26	0.39	0.53
	4	0.015	15.2	433	3.42	0.12	0.16	0.19	0.26	0.40	0.53	13.3	410	3.42	0.11	0.15	0.18	0.25	0.39	0.53
	6	0.015	23.3	411	3.41	0.12	0.16	0.19	0.26	0.40	0.54	20.1	408	3.42	0.11	0.15	0.19	0.26	0.39	0.53
	8	0.015	31.3	400	3.42	0.12	0.16	0.19	0.26	0.40	0.53	27.7	387	3.42	0.12	0.15	0.19	0.26	0.39	0.52
	12	0.015	46.2	413	3.43	0.12	0.16	0.19	0.26	0.40	0.53	40.4	399	3.44	0.11	0.15	0.18	0.25	0.39	0.52
	20	0.015	65.3	410	3.43	0.12	0.15	0.19	0.26	0.40	0.53	58.8	393	3.43	0.11	0.15	0.18	0.25	0.39	0.52
0.50	1	0.015	1.9	195	4.25	0.13	0.21	0.29	0.42	0.67	0.90	1.4	158	4.25	0.11	0.19	0.26	0.39	0.63	0.86
	2	0.015	4.4	137	4.25	0.10	0.19	0.26	0.40	0.65	0.90	3.7	132	4.25	0.10	0.19	0.26	0.40	0.65	0.90
	3	0.015	6.4	135	4.25	0.10	0.18	0.25	0.39	0.63	0.86	5.4	125	4.25	0.09	0.17	0.24	0.38	0.62	0.85
	4	0.015	8.2	145	4.25	0.08	0.17	0.25	0.39	0.64	0.88	7.1	150	4.26	0.09	0.17	0.24	0.38	0.63	0.87
	6	0.015	12.5	135	4.25	0.10	0.18	0.26	0.40	0.65	0.89	10.6	145	4.26	0.10	0.18	0.26	0.40	0.64	0.88
	8	0.015	16.5	139	4.26	0.10	0.18	0.25	0.39	0.63	0.87	14.3	148	4.26	0.10	0.18	0.25	0.39	0.62	0.85
	12	0.015	24.9	151	4.27	0.10	0.18	0.26	0.40	0.65	0.88	21.0	148	4.26	0.10	0.18	0.25	0.39	0.64	0.87
	20	0.015	34.6	135	4.27	0.09	0.18	0.25	0.39	0.64	0.88	30.8	145	4.27	0.10	0.18	0.25	0.39	0.64	0.88

Table B.17: Detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area for various RADTi in case of $\sigma^2_{\ln K} = 1.5$ assuming bimonthly (2M) and quarterly (3M) sampling frequencies

$\sigma^2_{\ln K}$											1.50									
α_T(m)	now	nfds(max)	P_d (2M)	<$T_{(DET,i)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi)/L	(36M. RADTi)/L	P_d (3M)	<$T_{(DET,i)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi)/L	(36M. RADTi)/L
0.001	**1**	1.25	3.8	3851	0.21	0.03	0.03	0.03	0.04	0.04	0.05	3.8	3864	0.21	0.03	0.03	0.03	0.04	0.04	0.05
	2	1.25	7.1	4356	0.21	0.04	0.04	0.04	0.04	0.04	0.05	7.0	4416	0.21	0.04	0.04	0.04	0.04	0.05	0.05
	3	1.25	9.2	4048	0.21	0.03	0.03	0.04	0.04	0.04	0.05	9.1	4044	0.21	0.03	0.03	0.04	0.04	0.04	0.05
	4	1.25	13.1	4009	0.21	0.03	0.04	0.04	0.04	0.04	0.05	12.7	4082	0.21	0.03	0.04	0.04	0.04	0.04	0.05
	6	1.25	20.4	4218	0.21	0.03	0.04	0.04	0.04	0.04	0.05	19.9	4270	0.21	0.03	0.04	0.04	0.04	0.04	0.05
	8	1.25	24.8	4222	0.21	0.03	0.03	0.04	0.04	0.04	0.05	24.4	4256	0.21	0.03	0.03	0.04	0.04	0.04	0.05
	12	1.25	34.9	4136	0.21	0.03	0.03	0.04	0.04	0.04	0.05	34.3	4165	0.21	0.03	0.04	0.04	0.04	0.04	0.05
	20	1.25	54.0	4137	0.22	0.03	0.03	0.04	0.04	0.04	0.05	52.8	4179	0.23	0.03	0.03	0.04	0.04	0.04	0.05
0.01	**1**	1.00	4.7	3384	0.80	0.13	0.13	0.14	0.15	0.17	0.19	4.6	3420	0.80	0.13	0.13	0.14	0.15	0.17	0.19
	2	1.00	8.3	3326	0.79	0.13	0.13	0.14	0.15	0.17	0.19	8.2	3369	0.79	0.13	0.13	0.14	0.15	0.17	0.20
	3	1.00	12.7	3355	0.80	0.13	0.13	0.14	0.15	0.17	0.19	12.4	3409	0.80	0.13	0.13	0.14	0.15	0.17	0.19
	4	1.00	15.8	3366	0.80	0.13	0.13	0.14	0.14	0.17	0.19	15.7	3376	0.79	0.13	0.13	0.14	0.15	0.17	0.19
	6	1.00	22.4	3265	0.79	0.13	0.13	0.14	0.15	0.17	0.19	21.9	3285	0.79	0.13	0.13	0.14	0.15	0.17	0.19
	8	1.00	30.9	3290	0.79	0.12	0.13	0.13	0.14	0.17	0.19	30.7	3306	0.79	0.13	0.13	0.14	0.15	0.17	0.19
	12	1.00	43.4	3353	0.79	0.12	0.13	0.13	0.15	0.17	0.19	43.0	3366	0.79	0.13	0.13	0.14	0.15	0.17	0.19
	20	1.00	59.0	3315	0.79	0.12	0.13	0.13	0.14	0.17	0.19	58.8	3326	0.79	0.12	0.13	0.13	0.15	0.17	0.19
0.02	**1**	0.50	5.4	2016	1.20	0.12	0.12	0.13	0.15	0.18	0.21	5.3	2003	1.20	0.12	0.12	0.13	0.15	0.18	0.21
	2	0.50	9.2	2072	1.20	0.11	0.12	0.13	0.14	0.17	0.21	9.0	2098	1.20	0.11	0.12	0.13	0.14	0.17	0.21
	3	0.50	13.6	2097	1.20	0.12	0.13	0.13	0.15	0.18	0.21	13.5	2110	1.20	0.12	0.13	0.13	0.15	0.18	0.21
	4	0.50	17.8	2023	1.20	0.11	0.12	0.13	0.14	0.17	0.21	17.4	2038	1.20	0.11	0.12	0.13	0.14	0.17	0.21
	6	0.50	26.6	2071	1.19	0.11	0.12	0.13	0.14	0.18	0.21	26.3	2098	1.19	0.11	0.12	0.13	0.15	0.18	0.21
	8	0.50	34.3	2031	1.20	0.11	0.12	0.13	0.14	0.17	0.21	33.8	2045	1.20	0.11	0.12	0.13	0.14	0.17	0.21
	12	0.50	47.5	2067	1.20	0.11	0.12	0.13	0.14	0.17	0.21	46.8	2086	1.20	0.11	0.12	0.13	0.14	0.17	0.21
	20	0.50	66.2	2073	1.17	0.11	0.12	0.13	0.14	0.17	0.21	65.5	2084	1.18	0.11	0.12	0.13	0.14	0.17	0.21
0.05	**1**	0.13	5.1	946	1.96	0.09	0.11	0.12	0.15	0.20	0.26	4.9	982	1.96	0.10	0.11	0.12	0.15	0.20	0.25
	2	0.13	10.4	1059	1.96	0.10	0.12	0.13	0.16	0.21	0.27	10.4	1059	1.96	0.10	0.12	0.13	0.16	0.21	0.27
	3	0.13	14.2	1060	1.96	0.10	0.11	0.12	0.15	0.20	0.25	13.9	1092	1.97	0.10	0.11	0.12	0.15	0.20	0.25
	4	0.13	17.9	1054	1.97	0.10	0.11	0.12	0.15	0.20	0.26	17.6	1080	1.97	0.10	0.11	0.13	0.15	0.21	0.26
	6	0.13	29.5	1135	1.96	0.10	0.11	0.13	0.15	0.20	0.26	29.6	1145	1.96	0.10	0.12	0.13	0.16	0.21	0.26
	8	0.13	37.8	1047	1.97	0.10	0.11	0.12	0.15	0.20	0.26	37.4	1071	1.97	0.10	0.11	0.13	0.15	0.20	0.26
	12	0.13	54.4	1040	1.96	0.10	0.11	0.12	0.15	0.20	0.26	53.7	1064	1.96	0.10	0.11	0.13	0.15	0.20	0.26
	20	0.13	78.3	1067	1.99	0.10	0.11	0.12	0.15	0.20	0.26	78.0	1078	1.98	0.10	0.11	0.12	0.15	0.20	0.26
0.10	**1**	0.063	5.4	779	2.68	0.13	0.15	0.17	0.21	0.30	0.39	5.3	774	2.68	0.13	0.15	0.17	0.21	0.30	0.39
	2	0.063	9.1	735	2.68	0.12	0.14	0.16	0.20	0.28	0.36	8.8	773	2.68	0.12	0.14	0.16	0.20	0.27	0.36
	3	0.063	13.9	734	2.68	0.12	0.14	0.16	0.20	0.28	0.37	13.6	739	2.68	0.12	0.14	0.16	0.20	0.29	0.37
	4	0.063	18.1	797	2.69	0.12	0.14	0.17	0.21	0.29	0.37	17.5	809	2.69	0.12	0.14	0.16	0.20	0.29	0.37
	6	0.063	26.3	761	2.68	0.12	0.14	0.16	0.20	0.29	0.37	25.2	777	2.68	0.12	0.14	0.16	0.20	0.28	0.37
	8	0.063	35.3	760	2.70	0.12	0.14	0.16	0.20	0.29	0.37	34.0	761	2.70	0.12	0.14	0.16	0.20	0.28	0.37
	12	0.063	52.4	770	2.71	0.12	0.14	0.16	0.20	0.29	0.37	51.0	782	2.72	0.12	0.14	0.16	0.20	0.29	0.37
	20	0.063	75.5	743	2.68	0.12	0.14	0.16	0.20	0.29	0.38	73.8	756	2.70	0.12	0.14	0.16	0.20	0.29	0.37
0.20	**1**	0.015	3.1	403	3.41	0.13	0.17	0.20	0.27	0.41	0.55	2.9	414	3.41	0.13	0.17	0.21	0.28	0.41	0.55
	2	0.015	7.0	413	3.41	0.12	0.16	0.19	0.26	0.39	0.52	6.8	405	3.41	0.12	0.16	0.19	0.26	0.39	0.53
	3	0.015	9.8	392	3.41	0.12	0.15	0.19	0.26	0.39	0.52	9.4	412	3.41	0.12	0.16	0.19	0.26	0.39	0.52
	4	0.015	12.7	407	3.42	0.12	0.15	0.19	0.25	0.39	0.53	12.1	424	3.42	0.12	0.15	0.19	0.26	0.39	0.52
	6	0.015	19.2	424	3.42	0.12	0.15	0.19	0.26	0.39	0.52	18.1	422	3.42	0.12	0.15	0.19	0.26	0.39	0.52
	8	0.015	25.9	392	3.42	0.12	0.15	0.19	0.25	0.38	0.52	25.4	411	3.42	0.12	0.16	0.19	0.26	0.39	0.52
	12	0.015	38.4	400	3.44	0.12	0.15	0.18	0.25	0.38	0.52	37.3	415	3.44	0.12	0.16	0.19	0.26	0.39	0.52
	20	0.015	56.8	397	3.44	0.11	0.15	0.18	0.25	0.39	0.52	54.8	414	3.45	0.12	0.15	0.19	0.25	0.39	0.52
0.50	**1**	0.015	1.4	180	4.25	0.13	0.20	0.27	0.40	0.63	0.86	1.3	203	4.25	0.14	0.22	0.28	0.41	0.65	0.88
	2	0.015	3.4	137	4.25	0.12	0.20	0.27	0.41	0.66	0.90	3.2	153	4.25	0.13	0.20	0.27	0.41	0.65	0.89
	3	0.015	5.1	142	4.25	0.11	0.18	0.25	0.38	0.61	0.84	4.7	160	4.25	0.12	0.19	0.25	0.38	0.60	0.83
	4	0.015	6.8	173	4.26	0.11	0.18	0.25	0.39	0.63	0.86	6.3	194	4.26	0.12	0.19	0.26	0.38	0.62	0.85
	6	0.015	9.9	160	4.26	0.12	0.19	0.26	0.40	0.64	0.88	9.1	161	4.26	0.13	0.20	0.27	0.40	0.64	0.87
	8	0.015	13.2	161	4.26	0.12	0.19	0.26	0.39	0.62	0.85	12.2	175	4.26	0.12	0.20	0.26	0.39	0.62	0.84
	12	0.015	19.9	166	4.27	0.11	0.19	0.26	0.39	0.64	0.87	18.0	189	4.27	0.13	0.20	0.26	0.39	0.63	0.86
	20	0.015	29.6	160	4.27	0.11	0.19	0.26	0.40	0.64	0.88	27.4	174	4.28	0.12	0.20	0.26	0.39	0.63	0.87

Table B.18: Detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area L for various RADTi in case of $\sigma^2_{\ln K} = 1.5$ assuming every 4 months (4M) and biannually (6M) sampling frequencies

$\sigma^2_{\ln K}$									1.50											
α_T(m)	now	nfds(max)	P_d (4M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L	P_d (6M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	1	1.25	3.7	3926	0.21	0.03	0.03	0.04	0.04	0.04	0.05	3.3	4062	0.21	0.03	0.04	0.04	0.04	0.04	0.05
	2	1.25	6.7	4484	0.21	0.04	0.04	0.04	0.04	0.05	0.05	6.4	4522	0.21	0.04	0.04	0.04	0.04	0.05	0.05
	3	1.25	8.8	4101	0.21	0.03	0.03	0.04	0.04	0.04	0.05	8.0	4226	0.21	0.03	0.04	0.04	0.04	0.04	0.05
	4	1.25	12.7	4094	0.21	0.04	0.04	0.04	0.04	0.04	0.05	11.5	4274	0.21	0.04	0.04	0.04	0.04	0.05	0.05
	6	1.25	19.5	4326	0.21	0.04	0.04	0.04	0.04	0.04	0.05	18.1	4419	0.21	0.04	0.04	0.04	0.04	0.04	0.05
	8	1.25	23.5	4326	0.22	0.03	0.04	0.04	0.04	0.04	0.05	21.9	4416	0.21	0.03	0.04	0.04	0.04	0.04	0.05
	12	1.25	33.8	4214	0.21	0.03	0.04	0.04	0.04	0.04	0.05	31.0	4370	0.22	0.04	0.04	0.04	0.04	0.04	0.05
	20	1.25	52.3	4217	0.23	0.03	0.03	0.04	0.04	0.04	0.05	48.1	4351	0.23	0.03	0.04	0.04	0.04	0.04	0.05
0.01	1	1.00	4.6	3411	0.80	0.13	0.13	0.14	0.15	0.17	0.19	4.3	3558	0.80	0.13	0.13	0.14	0.15	0.17	0.19
	2	1.00	7.9	3397	0.79	0.13	0.13	0.14	0.15	0.17	0.19	7.8	3433	0.79	0.13	0.14	0.14	0.15	0.17	0.20
	3	1.00	12.2	3425	0.80	0.13	0.13	0.14	0.15	0.17	0.19	11.4	3497	0.80	0.13	0.13	0.14	0.15	0.17	0.19
	4	1.00	15.4	3409	0.80	0.13	0.13	0.14	0.15	0.17	0.19	14.6	3459	0.80	0.13	0.13	0.14	0.15	0.17	0.19
	6	1.00	21.4	3319	0.79	0.13	0.13	0.14	0.15	0.17	0.19	20.7	3345	0.79	0.13	0.13	0.14	0.15	0.17	0.19
	8	1.00	30.0	3348	0.80	0.13	0.13	0.14	0.15	0.17	0.19	28.7	3374	0.80	0.13	0.13	0.14	0.15	0.17	0.19
	12	1.00	42.3	3392	0.79	0.13	0.13	0.14	0.15	0.17	0.19	40.1	3437	0.80	0.13	0.13	0.14	0.15	0.17	0.19
	20	1.00	57.7	3345	0.79	0.12	0.13	0.13	0.15	0.17	0.19	56.2	3402	0.80	0.13	0.13	0.14	0.15	0.17	0.19
0.02	1	0.50	5.2	2023	1.20	0.12	0.12	0.13	0.15	0.18	0.22	4.6	2160	1.20	0.12	0.12	0.13	0.15	0.18	0.21
	2	0.50	8.9	2133	1.20	0.11	0.12	0.13	0.15	0.18	0.21	8.3	2202	1.20	0.12	0.12	0.13	0.15	0.18	0.21
	3	0.50	13.0	2123	1.20	0.12	0.13	0.13	0.15	0.18	0.21	12.2	2197	1.20	0.12	0.13	0.13	0.15	0.18	0.21
	4	0.50	17.2	2082	1.20	0.12	0.12	0.13	0.14	0.18	0.21	16.2	2138	1.20	0.12	0.12	0.13	0.15	0.18	0.21
	6	0.50	25.8	2109	1.19	0.12	0.12	0.13	0.15	0.18	0.21	24.5	2195	1.20	0.12	0.13	0.13	0.15	0.18	0.21
	8	0.50	33.2	2066	1.21	0.11	0.12	0.13	0.14	0.17	0.21	31.6	2120	1.21	0.12	0.12	0.13	0.15	0.18	0.21
	12	0.50	46.2	2109	1.21	0.11	0.12	0.13	0.14	0.17	0.21	43.6	2177	1.22	0.12	0.12	0.13	0.15	0.18	0.21
	20	0.50	64.8	2100	1.18	0.11	0.12	0.13	0.14	0.18	0.21	62.7	2157	1.21	0.11	0.12	0.13	0.15	0.18	0.21
0.05	1	0.13	4.8	990	1.96	0.10	0.11	0.12	0.15	0.20	0.25	4.6	1056	1.96	0.10	0.11	0.12	0.15	0.20	0.25
	2	0.13	10.0	1104	1.96	0.11	0.12	0.13	0.16	0.21	0.27	9.7	1128	1.96	0.11	0.12	0.13	0.16	0.21	0.27
	3	0.13	13.8	1097	1.97	0.10	0.11	0.12	0.15	0.20	0.25	13.2	1143	1.97	0.10	0.11	0.13	0.15	0.20	0.25
	4	0.13	17.4	1097	1.97	0.10	0.12	0.13	0.15	0.20	0.26	16.5	1134	1.97	0.10	0.12	0.13	0.15	0.21	0.26
	6	0.13	28.3	1178	1.97	0.11	0.12	0.13	0.16	0.21	0.26	27.4	1223	1.97	0.11	0.12	0.13	0.16	0.21	0.26
	8	0.13	36.9	1084	1.97	0.10	0.11	0.13	0.15	0.20	0.26	35.1	1118	1.98	0.10	0.12	0.13	0.15	0.21	0.26
	12	0.13	52.7	1085	1.97	0.10	0.11	0.13	0.15	0.20	0.26	50.5	1124	1.98	0.11	0.12	0.13	0.15	0.21	0.26
	20	0.13	76.8	1103	2.02	0.10	0.11	0.12	0.15	0.20	0.26	74.0	1135	2.03	0.10	0.11	0.13	0.15	0.20	0.26
0.10	1	0.063	5.1	809	2.68	0.13	0.15	0.17	0.21	0.30	0.39	4.8	853	2.68	0.13	0.15	0.17	0.21	0.30	0.39
	2	0.063	8.5	777	2.68	0.12	0.14	0.16	0.20	0.28	0.36	8.1	830	2.68	0.13	0.15	0.16	0.20	0.28	0.36
	3	0.063	13.2	761	2.68	0.12	0.14	0.16	0.20	0.28	0.37	12.4	811	2.68	0.13	0.15	0.16	0.20	0.29	0.37
	4	0.063	17.1	838	2.69	0.13	0.15	0.17	0.21	0.29	0.37	16.0	870	2.70	0.13	0.15	0.17	0.21	0.28	0.37
	6	0.063	24.6	797	2.68	0.13	0.14	0.16	0.20	0.29	0.37	23.0	842	2.69	0.13	0.15	0.16	0.20	0.28	0.37
	8	0.063	33.4	784	2.70	0.13	0.14	0.16	0.20	0.29	0.37	31.5	813	2.71	0.13	0.15	0.17	0.20	0.28	0.37
	12	0.063	49.8	804	2.72	0.13	0.15	0.17	0.21	0.29	0.37	46.2	839	2.74	0.13	0.15	0.17	0.20	0.28	0.37
	20	0.063	72.4	773	2.71	0.12	0.14	0.16	0.21	0.29	0.38	68.7	808	2.77	0.13	0.15	0.17	0.21	0.29	0.37
0.20	1	0.015	2.8	422	3.41	0.14	0.17	0.21	0.27	0.41	0.55	2.5	423	3.41	0.14	0.17	0.21	0.27	0.41	0.55
	2	0.015	6.4	419	3.41	0.13	0.16	0.19	0.26	0.39	0.52	5.8	468	3.42	0.13	0.16	0.19	0.26	0.38	0.51
	3	0.015	8.8	433	3.42	0.12	0.16	0.19	0.25	0.38	0.51	8.2	465	3.42	0.13	0.17	0.20	0.26	0.39	0.52
	4	0.015	11.5	442	3.43	0.12	0.16	0.19	0.25	0.39	0.52	10.4	480	3.43	0.13	0.17	0.20	0.26	0.39	0.52
	6	0.015	17.1	451	3.42	0.12	0.16	0.19	0.25	0.38	0.52	15.6	493	3.43	0.13	0.16	0.19	0.26	0.38	0.51
	8	0.015	23.7	430	3.43	0.13	0.16	0.19	0.26	0.38	0.51	21.6	465	3.43	0.13	0.17	0.20	0.26	0.38	0.51
	12	0.015	35.0	436	3.45	0.12	0.16	0.19	0.25	0.38	0.51	31.7	473	3.45	0.13	0.17	0.20	0.26	0.38	0.51
	20	0.015	52.1	430	3.46	0.12	0.16	0.19	0.26	0.39	0.52	47.6	475	3.47	0.13	0.16	0.19	0.26	0.38	0.51
0.50	1	0.015	1.2	216	4.25	0.15	0.21	0.28	0.40	0.62	0.85	0.9	282	4.25	0.17	0.23	0.28	0.39	0.62	0.84
	2	0.015	2.9	182	4.25	0.14	0.21	0.28	0.40	0.64	0.88	2.1	217	4.25	0.15	0.21	0.26	0.37	0.58	0.80
	3	0.015	4.4	185	4.25	0.13	0.20	0.26	0.38	0.60	0.82	3.3	243	4.25	0.15	0.20	0.25	0.36	0.56	0.76
	4	0.015	5.6	229	4.26	0.13	0.19	0.25	0.37	0.60	0.82	4.6	290	4.26	0.15	0.20	0.26	0.36	0.57	0.78
	6	0.015	8.4	209	4.26	0.14	0.21	0.27	0.39	0.62	0.84	6.2	241	4.26	0.15	0.20	0.26	0.36	0.57	0.77
	8	0.015	11.0	193	4.26	0.14	0.20	0.26	0.39	0.61	0.82	8.6	259	4.26	0.15	0.21	0.26	0.37	0.58	0.78
	12	0.015	16.3	207	4.27	0.14	0.20	0.26	0.39	0.62	0.84	13.0	270	4.27	0.15	0.21	0.26	0.37	0.59	0.80
	20	0.015	24.9	205	4.28	0.14	0.20	0.27	0.39	0.63	0.85	20.4	255	4.28	0.15	0.21	0.27	0.38	0.60	0.81

Table B.19: Detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area L for various RADTi in case of $\sigma^2_{\ln K} = 1.5$ assuming annually sampling frequency

	$\sigma^2_{\ln K}$					1.50					
α_T(m)	now	nfds(max)	P_d (12M)	$\langle T_{(DET.)}\rangle$ (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	1	1.25	2.5	4365	0.21	0.04	0.04	0.04	0.04	0.05	0.05
	2	1.25	4.8	5115	0.21	0.04	0.04	0.04	0.05	0.05	0.05
	3	1.25	6.1	4566	0.21	0.04	0.04	0.04	0.04	0.05	0.05
	4	1.25	8.2	4677	0.21	0.04	0.04	0.04	0.05	0.05	0.05
	6	1.25	13.7	4879	0.21	0.04	0.04	0.04	0.04	0.05	0.05
	8	1.25	16.2	4945	0.21	0.04	0.04	0.04	0.04	0.05	0.05
	12	1.25	23.0	4770	0.22	0.04	0.04	0.04	0.04	0.05	0.05
	20	1.25	36.0	4742	0.22	0.04	0.04	0.04	0.04	0.05	0.05
0.01	1	1.00	3.4	3896	0.80	0.13	0.14	0.14	0.15	0.18	0.20
	2	1.00	6.1	3702	0.79	0.14	0.14	0.14	0.16	0.18	0.20
	3	1.00	9.1	3902	0.80	0.14	0.14	0.14	0.15	0.17	0.20
	4	1.00	11.6	3817	0.80	0.13	0.14	0.14	0.15	0.17	0.19
	6	1.00	16.1	3662	0.80	0.13	0.14	0.14	0.15	0.18	0.20
	8	1.00	22.4	3776	0.81	0.13	0.14	0.14	0.15	0.17	0.19
	12	1.00	32.5	3769	0.82	0.13	0.13	0.14	0.15	0.17	0.19
	20	1.00	46.7	3693	0.84	0.13	0.14	0.14	0.15	0.17	0.19
0.02	1	0.50	3.9	2397	1.20	0.12	0.13	0.13	0.15	0.18	0.21
	2	0.50	6.8	2403	1.21	0.12	0.13	0.13	0.15	0.18	0.21
	3	0.50	10.0	2411	1.20	0.12	0.13	0.14	0.15	0.18	0.21
	4	0.50	12.7	2383	1.21	0.12	0.13	0.14	0.15	0.18	0.21
	6	0.50	20.0	2385	1.21	0.12	0.13	0.14	0.15	0.18	0.21
	8	0.50	25.2	2352	1.23	0.12	0.13	0.14	0.15	0.18	0.21
	12	0.50	35.5	2414	1.24	0.12	0.13	0.14	0.15	0.18	0.21
	20	0.50	52.8	2357	1.25	0.12	0.13	0.13	0.15	0.18	0.21
0.05	1	0.13	3.8	1197	1.96	0.10	0.11	0.12	0.15	0.20	0.25
	2	0.13	8.1	1284	1.97	0.12	0.13	0.14	0.16	0.21	0.27
	3	0.13	11.2	1285	1.97	0.11	0.12	0.13	0.15	0.20	0.25
	4	0.13	13.6	1327	1.98	0.11	0.12	0.14	0.16	0.21	0.26
	6	0.13	22.8	1386	1.99	0.12	0.13	0.14	0.16	0.21	0.26
	8	0.13	29.2	1286	2.00	0.11	0.12	0.13	0.16	0.21	0.26
	12	0.13	41.7	1297	2.02	0.11	0.12	0.13	0.16	0.21	0.26
	20	0.13	63.3	1317	2.12	0.11	0.12	0.13	0.16	0.21	0.26
0.10	1	0.063	3.8	1020	2.68	0.15	0.16	0.18	0.22	0.30	0.38
	2	0.063	6.3	973	2.69	0.14	0.15	0.17	0.21	0.28	0.35
	3	0.063	9.9	970	2.68	0.14	0.16	0.17	0.21	0.29	0.37
	4	0.063	11.9	1040	2.70	0.14	0.15	0.17	0.21	0.28	0.35
	6	0.063	18.1	1003	2.70	0.14	0.15	0.17	0.21	0.28	0.36
	8	0.063	25.0	972	2.72	0.14	0.16	0.17	0.21	0.28	0.36
	12	0.063	35.5	996	2.76	0.14	0.16	0.17	0.21	0.28	0.36
	20	0.063	53.2	959	2.81	0.14	0.15	0.17	0.21	0.28	0.36
0.20	1	0.015	1.5	650	3.42	0.16	0.19	0.21	0.26	0.37	0.47
	2	0.015	4.0	619	3.42	0.15	0.17	0.20	0.25	0.36	0.48
	3	0.015	5.3	647	3.43	0.15	0.17	0.20	0.25	0.35	0.46
	4	0.015	7.2	648	3.43	0.15	0.17	0.20	0.25	0.36	0.48
	6	0.015	10.5	670	3.43	0.15	0.17	0.20	0.25	0.36	0.47
	8	0.015	14.4	616	3.44	0.15	0.18	0.20	0.25	0.36	0.48
	12	0.015	21.5	657	3.47	0.15	0.18	0.20	0.26	0.36	0.48
	20	0.015	32.9	641	3.50	0.15	0.18	0.20	0.26	0.37	0.49
0.50	1	0.015	0.4	486	4.25	0.17	0.21	0.25	0.33	0.49	0.67
	2	0.015	1.2	375	4.25	0.19	0.23	0.28	0.37	0.56	0.75
	3	0.015	1.7	416	4.25	0.17	0.21	0.25	0.33	0.49	0.67
	4	0.015	2.4	496	4.26	0.18	0.22	0.26	0.34	0.51	0.69
	6	0.015	3.3	409	4.26	0.18	0.22	0.26	0.35	0.52	0.69
	8	0.015	4.2	414	4.26	0.18	0.22	0.26	0.34	0.51	0.69
	12	0.015	6.4	468	4.27	0.19	0.23	0.27	0.35	0.52	0.69
	20	0.015	9.9	432	4.28	0.18	0.22	0.26	0.35	0.52	0.70

TableB.20: Detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area for various RADTi in case of $\sigma^2_{\ln K} = 2.0$ assuming daily (ED) and monthly (1M) sampling frequencies

	σ^2_{lnK}									2.00										
α_T(m)	now	nfds(max)	P_d (ED)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L	P_d (1M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	1	0.75	3.4	3075	0.37	0.02	0.03	0.03	0.03	0.04	0.04	3.4	3089	0.37	0.03	0.03	0.03	0.03	0.04	0.04
	2	0.75	6.8	2996	0.36	0.02	0.02	0.02	0.03	0.03	0.04	6.7	2999	0.36	0.02	0.02	0.03	0.03	0.03	0.04
	3	0.75	9.2	3015	0.36	0.02	0.02	0.03	0.03	0.03	0.04	9.1	3040	0.36	0.02	0.02	0.03	0.03	0.03	0.04
	4	0.75	11.9	3002	0.37	0.03	0.03	0.03	0.03	0.04	0.04	11.8	3016	0.37	0.03	0.03	0.03	0.03	0.04	0.04
	6	0.75	19.3	3114	0.37	0.02	0.03	0.03	0.03	0.03	0.04	18.9	3144	0.37	0.03	0.03	0.03	0.03	0.03	0.04
	8	0.75	24.3	3020	0.38	0.02	0.03	0.03	0.03	0.03	0.04	23.9	3052	0.38	0.02	0.03	0.03	0.03	0.03	0.04
	12	0.75	34.2	3028	0.35	0.02	0.03	0.03	0.03	0.03	0.04	33.6	3059	0.36	0.02	0.03	0.03	0.03	0.04	0.04
	20	0.75	53.1	3008	0.35	0.02	0.03	0.03	0.03	0.03	0.04	52.3	3019	0.35	0.02	0.03	0.03	0.03	0.03	0.04
0.01	1	0.50	5.3	2322	1.07	0.08	0.09	0.09	0.10	0.13	0.15	5.1	2327	1.07	0.08	0.09	0.09	0.10	0.13	0.15
	2	0.50	8.0	2188	1.07	0.08	0.08	0.09	0.10	0.12	0.15	7.9	2211	1.07	0.08	0.08	0.09	0.10	0.12	0.15
	3	0.50	14.2	2294	1.07	0.08	0.08	0.09	0.10	0.12	0.15	13.9	2309	1.07	0.08	0.08	0.09	0.10	0.12	0.15
	4	0.50	16.8	2382	1.07	0.08	0.08	0.09	0.10	0.12	0.15	16.5	2396	1.07	0.08	0.08	0.09	0.10	0.12	0.15
	6	0.50	23.8	2317	1.07	0.08	0.08	0.09	0.10	0.12	0.15	23.2	2331	1.07	0.08	0.08	0.09	0.10	0.12	0.15
	8	0.50	32.3	2265	1.07	0.08	0.08	0.09	0.10	0.12	0.15	31.6	2296	1.08	0.08	0.08	0.09	0.10	0.12	0.15
	12	0.50	46.8	2308	1.05	0.08	0.08	0.09	0.10	0.12	0.15	45.8	2331	1.05	0.08	0.08	0.09	0.10	0.12	0.15
	20	0.50	64.7	2297	1.04	0.07	0.08	0.09	0.10	0.12	0.14	63.4	2303	1.03	0.07	0.08	0.09	0.10	0.12	0.14
0.02	1	0.25	5.0	1642	1.52	0.08	0.08	0.09	0.11	0.14	0.17	4.9	1666	1.52	0.08	0.08	0.09	0.11	0.14	0.17
	2	0.25	10.4	1514	1.51	0.08	0.09	0.10	0.11	0.15	0.19	10.0	1544	1.52	0.08	0.09	0.10	0.11	0.15	0.19
	3	0.25	13.5	1609	1.52	0.08	0.08	0.09	0.11	0.14	0.17	13.0	1621	1.52	0.08	0.08	0.09	0.11	0.14	0.17
	4	0.25	17.7	1585	1.53	0.08	0.09	0.09	0.11	0.14	0.18	17.2	1619	1.53	0.08	0.09	0.10	0.11	0.15	0.18
	6	0.25	28.0	1585	1.53	0.08	0.09	0.10	0.11	0.15	0.18	27.1	1607	1.53	0.08	0.09	0.10	0.11	0.15	0.18
	8	0.25	36.7	1593	1.53	0.08	0.09	0.09	0.11	0.14	0.18	35.3	1607	1.53	0.08	0.09	0.09	0.11	0.14	0.18
	12	0.25	50.6	1566	1.51	0.08	0.08	0.09	0.11	0.14	0.18	49.1	1585	1.52	0.08	0.09	0.09	0.11	0.15	0.18
	20	0.25	71.7	1550	1.49	0.07	0.08	0.09	0.11	0.14	0.18	70.2	1562	1.49	0.07	0.08	0.09	0.11	0.14	0.18
0.05	1	0.13	5.1	1084	2.32	0.11	0.12	0.14	0.17	0.23	0.29	4.9	1076	2.32	0.11	0.13	0.14	0.17	0.23	0.29
	2	0.13	10.6	1139	2.31	0.11	0.12	0.14	0.17	0.23	0.30	9.9	1155	2.31	0.11	0.12	0.13	0.16	0.23	0.29
	3	0.13	14.0	1034	2.32	0.10	0.12	0.13	0.16	0.22	0.28	13.4	1045	2.32	0.10	0.12	0.13	0.16	0.22	0.29
	4	0.13	19.9	1133	2.32	0.10	0.12	0.13	0.16	0.22	0.28	19.2	1138	2.32	0.10	0.12	0.13	0.16	0.22	0.28
	6	0.13	29.8	1168	2.32	0.11	0.12	0.14	0.17	0.23	0.29	28.3	1171	2.32	0.11	0.12	0.13	0.16	0.22	0.29
	8	0.13	40.4	1065	2.30	0.10	0.12	0.13	0.16	0.22	0.29	38.3	1087	2.31	0.10	0.12	0.13	0.16	0.22	0.29
	12	0.13	56.4	1066	2.29	0.10	0.11	0.13	0.16	0.22	0.28	54.2	1076	2.30	0.10	0.12	0.13	0.16	0.22	0.28
	20	0.13	76.9	1079	2.22	0.10	0.11	0.13	0.16	0.22	0.28	74.8	1096	2.25	0.10	0.11	0.13	0.16	0.22	0.28
0.10	1	0.063	4.9	818	3.02	0.12	0.14	0.16	0.21	0.30	0.39	4.6	861	3.02	0.12	0.14	0.16	0.20	0.29	0.39
	2	0.063	10.3	801	3.02	0.13	0.16	0.18	0.23	0.32	0.42	9.6	762	3.02	0.13	0.15	0.17	0.22	0.32	0.42
	3	0.063	14.7	799	3.02	0.12	0.15	0.17	0.22	0.31	0.41	13.7	793	3.02	0.12	0.14	0.17	0.21	0.31	0.41
	4	0.063	19.2	751	3.01	0.12	0.15	0.17	0.22	0.32	0.42	17.9	773	3.01	0.12	0.15	0.17	0.22	0.31	0.42
	6	0.063	28.9	781	3.03	0.13	0.15	0.17	0.22	0.32	0.42	26.6	758	3.02	0.12	0.15	0.17	0.22	0.31	0.41
	8	0.063	37.5	791	3.02	0.12	0.15	0.17	0.22	0.31	0.42	34.7	802	3.02	0.13	0.15	0.17	0.22	0.31	0.42
	12	0.063	54.5	763	3.00	0.12	0.14	0.17	0.21	0.31	0.41	50.4	767	3.01	0.12	0.14	0.17	0.21	0.31	0.41
	20	0.063	74.7	737	2.96	0.12	0.14	0.16	0.21	0.31	0.41	71.1	743	2.98	0.12	0.14	0.16	0.21	0.31	0.41
0.20	1	0.015	3.8	505	3.69	0.12	0.16	0.19	0.26	0.40	0.54	3.5	499	3.69	0.12	0.15	0.19	0.26	0.39	0.53
	2	0.015	7.8	438	3.69	0.12	0.16	0.20	0.27	0.41	0.55	6.8	420	3.69	0.12	0.16	0.19	0.26	0.40	0.53
	3	0.015	12.2	457	3.68	0.12	0.16	0.20	0.28	0.43	0.59	10.4	459	3.68	0.12	0.16	0.20	0.27	0.42	0.57
	4	0.015	15.5	414	3.67	0.12	0.16	0.20	0.28	0.44	0.60	13.2	399	3.68	0.11	0.15	0.19	0.27	0.42	0.58
	6	0.015	22.0	419	3.68	0.12	0.16	0.20	0.28	0.42	0.58	19.0	408	3.69	0.12	0.16	0.20	0.27	0.42	0.56
	8	0.015	29.2	432	3.68	0.12	0.16	0.20	0.28	0.43	0.58	24.8	418	3.68	0.11	0.15	0.19	0.26	0.41	0.56
	12	0.015	44.0	391	3.65	0.12	0.16	0.19	0.27	0.42	0.57	38.2	385	3.67	0.11	0.15	0.19	0.26	0.41	0.56
	20	0.015	62.3	402	3.63	0.11	0.16	0.19	0.27	0.42	0.58	55.6	388	3.66	0.11	0.15	0.19	0.26	0.41	0.56
0.50	1	0.015	2.1	140	4.37	0.10	0.19	0.27	0.42	0.68	0.95	1.8	135	4.37	0.10	0.18	0.26	0.40	0.66	0.92
	2	0.015	4.6	188	4.38	0.12	0.20	0.26	0.40	0.63	0.86	3.8	182	4.38	0.11	0.19	0.26	0.39	0.64	0.86
	3	0.015	6.8	158	4.37	0.11	0.20	0.28	0.43	0.70	0.96	5.4	163	4.38	0.11	0.19	0.27	0.41	0.67	0.92
	4	0.015	8.9	134	4.38	0.10	0.19	0.28	0.43	0.71	0.98	7.8	152	4.38	0.11	0.20	0.28	0.43	0.70	0.97
	6	0.015	12.0	160	4.38	0.10	0.19	0.27	0.41	0.67	0.91	10.0	167	4.38	0.11	0.19	0.26	0.40	0.66	0.90
	8	0.015	16.6	143	4.38	0.10	0.19	0.27	0.41	0.68	0.94	13.9	137	4.38	0.10	0.18	0.26	0.40	0.67	0.92
	12	0.015	25.4	147	4.38	0.09	0.18	0.26	0.41	0.68	0.93	22.1	157	4.38	0.10	0.19	0.26	0.41	0.67	0.92
	20	0.015	34.7	129	4.38	0.09	0.18	0.26	0.41	0.68	0.94	30.6	136	4.39	0.10	0.18	0.26	0.40	0.67	0.92

Table B.21: Detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area for various RADTi in case of $\sigma^2_{\ln K} = 2.0$ assuming bimonthly (2M) and quarterly (3M) sampling frequencies

$\sigma^2_{\ln K}$		2.00																		
α_T(m)	now	nfds(max)	P_d (2M)	<$T_{(DET,)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L	P_d (3M)	<$T_{(DET,)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	1	0.75	3.3	3114	0.37	0.03	0.03	0.03	0.03	0.04	0.04	3.3	3103	0.37	0.03	0.03	0.03	0.03	0.04	0.04
	2	0.75	6.7	3035	0.36	0.02	0.02	0.03	0.03	0.03	0.04	6.4	3130	0.36	0.02	0.02	0.03	0.03	0.03	0.04
	3	0.75	8.8	3081	0.36	0.02	0.02	0.03	0.03	0.03	0.04	8.5	3162	0.36	0.02	0.02	0.03	0.03	0.03	0.04
	4	0.75	11.5	3068	0.37	0.03	0.03	0.03	0.03	0.04	0.04	11.0	3119	0.37	0.03	0.03	0.03	0.03	0.04	0.04
	6	0.75	18.6	3192	0.37	0.03	0.03	0.03	0.03	0.03	0.04	18.1	3244	0.37	0.03	0.03	0.03	0.03	0.03	0.04
	8	0.75	23.4	3090	0.38	0.02	0.03	0.03	0.03	0.03	0.04	22.6	3151	0.38	0.02	0.03	0.03	0.03	0.03	0.04
	12	0.75	32.8	3107	0.36	0.02	0.03	0.03	0.03	0.04	0.04	31.8	3152	0.36	0.02	0.03	0.03	0.03	0.04	0.04
	20	0.75	51.6	3053	0.35	0.02	0.03	0.03	0.03	0.03	0.04	49.9	3110	0.36	0.02	0.03	0.03	0.03	0.03	0.04
0.01	1	0.50	5.1	2340	1.07	0.08	0.09	0.09	0.10	0.13	0.15	5.1	2368	1.07	0.08	0.09	0.09	0.10	0.13	0.15
	2	0.50	7.8	2245	1.08	0.08	0.08	0.09	0.10	0.12	0.15	7.7	2280	1.08	0.08	0.08	0.09	0.10	0.12	0.15
	3	0.50	13.8	2323	1.07	0.08	0.08	0.09	0.10	0.12	0.15	13.6	2345	1.07	0.08	0.09	0.09	0.10	0.13	0.15
	4	0.50	16.2	2422	1.07	0.08	0.08	0.09	0.10	0.12	0.15	16.0	2453	1.07	0.08	0.08	0.09	0.10	0.12	0.15
	6	0.50	22.7	2359	1.08	0.08	0.08	0.09	0.10	0.12	0.15	22.5	2387	1.08	0.08	0.09	0.09	0.10	0.12	0.15
	8	0.50	31.1	2311	1.08	0.08	0.08	0.09	0.10	0.12	0.15	30.7	2337	1.08	0.08	0.08	0.09	0.10	0.12	0.15
	12	0.50	45.2	2346	1.06	0.08	0.08	0.09	0.10	0.12	0.15	44.4	2367	1.07	0.08	0.08	0.09	0.10	0.12	0.15
	20	0.50	62.7	2314	1.04	0.08	0.08	0.09	0.10	0.12	0.14	62.1	2327	1.04	0.08	0.08	0.09	0.10	0.12	0.15
0.02	1	0.25	4.8	1694	1.52	0.08	0.09	0.09	0.11	0.14	0.17	4.7	1732	1.52	0.08	0.09	0.09	0.11	0.14	0.17
	2	0.25	9.7	1573	1.52	0.08	0.09	0.10	0.11	0.15	0.19	9.5	1579	1.52	0.08	0.09	0.10	0.11	0.15	0.19
	3	0.25	12.9	1645	1.52	0.08	0.09	0.09	0.11	0.14	0.17	12.7	1669	1.52	0.08	0.09	0.09	0.11	0.14	0.17
	4	0.25	16.7	1604	1.53	0.08	0.09	0.10	0.11	0.14	0.18	16.7	1665	1.53	0.08	0.09	0.10	0.11	0.15	0.18
	6	0.25	26.7	1630	1.54	0.08	0.09	0.10	0.11	0.15	0.18	26.0	1642	1.54	0.08	0.09	0.10	0.11	0.15	0.18
	8	0.25	34.5	1634	1.54	0.08	0.09	0.09	0.11	0.14	0.18	34.3	1642	1.54	0.08	0.09	0.10	0.11	0.15	0.18
	12	0.25	48.1	1592	1.53	0.08	0.09	0.09	0.11	0.15	0.18	47.6	1629	1.54	0.08	0.09	0.10	0.11	0.15	0.18
	20	0.25	69.0	1580	1.50	0.08	0.08	0.09	0.11	0.14	0.18	68.6	1600	1.51	0.08	0.08	0.09	0.11	0.14	0.18
0.05	1	0.13	4.7	1108	2.32	0.11	0.13	0.14	0.17	0.23	0.29	4.6	1114	2.32	0.11	0.13	0.14	0.17	0.23	0.29
	2	0.13	9.6	1163	2.31	0.11	0.12	0.14	0.17	0.23	0.29	9.4	1165	2.31	0.11	0.12	0.14	0.17	0.23	0.29
	3	0.13	13.0	1069	2.32	0.11	0.12	0.13	0.16	0.22	0.29	12.6	1081	2.32	0.11	0.12	0.14	0.17	0.23	0.29
	4	0.13	18.9	1148	2.32	0.11	0.12	0.13	0.16	0.22	0.28	18.7	1171	2.32	0.11	0.12	0.13	0.16	0.22	0.28
	6	0.13	27.8	1187	2.33	0.11	0.12	0.14	0.16	0.22	0.29	27.0	1200	2.33	0.11	0.12	0.14	0.16	0.22	0.29
	8	0.13	37.5	1103	2.32	0.11	0.12	0.13	0.16	0.22	0.29	37.1	1115	2.32	0.11	0.12	0.13	0.16	0.22	0.29
	12	0.13	53.1	1093	2.31	0.10	0.12	0.13	0.16	0.22	0.28	52.2	1105	2.31	0.10	0.12	0.13	0.16	0.22	0.28
	20	0.13	73.9	1113	2.28	0.10	0.11	0.13	0.16	0.22	0.29	73.1	1123	2.29	0.10	0.12	0.13	0.16	0.22	0.29
0.10	1	0.063	4.4	875	3.02	0.12	0.14	0.16	0.20	0.29	0.38	4.1	924	3.02	0.12	0.14	0.16	0.20	0.28	0.37
	2	0.063	9.3	773	3.02	0.13	0.15	0.17	0.22	0.32	0.41	9.0	790	3.02	0.13	0.15	0.17	0.22	0.31	0.41
	3	0.063	13.0	803	3.02	0.12	0.14	0.17	0.21	0.31	0.41	12.4	822	3.02	0.12	0.15	0.17	0.21	0.30	0.40
	4	0.063	17.3	788	3.01	0.13	0.15	0.17	0.22	0.32	0.42	16.6	795	3.01	0.13	0.15	0.17	0.22	0.32	0.42
	6	0.063	25.7	767	3.03	0.12	0.15	0.17	0.22	0.32	0.41	25.0	785	3.03	0.13	0.15	0.17	0.22	0.31	0.41
	8	0.063	33.2	811	3.03	0.13	0.15	0.17	0.22	0.31	0.41	32.4	817	3.03	0.13	0.15	0.17	0.22	0.31	0.41
	12	0.063	48.9	779	3.01	0.12	0.15	0.17	0.21	0.31	0.41	47.1	791	3.02	0.12	0.15	0.17	0.21	0.31	0.41
	20	0.063	69.4	751	3.00	0.12	0.14	0.16	0.21	0.31	0.41	67.8	763	3.01	0.12	0.14	0.17	0.21	0.31	0.41
0.20	1	0.015	3.4	525	3.69	0.12	0.16	0.19	0.26	0.39	0.53	3.2	542	3.69	0.13	0.16	0.20	0.26	0.40	0.54
	2	0.015	6.3	417	3.69	0.12	0.15	0.19	0.26	0.39	0.52	6.0	439	3.69	0.12	0.16	0.19	0.25	0.38	0.51
	3	0.015	10.0	480	3.68	0.12	0.16	0.20	0.27	0.42	0.57	9.4	496	3.68	0.13	0.16	0.20	0.27	0.42	0.57
	4	0.015	12.4	405	3.68	0.12	0.16	0.19	0.27	0.42	0.58	11.8	418	3.68	0.12	0.16	0.19	0.27	0.42	0.57
	6	0.015	17.8	411	3.69	0.12	0.16	0.20	0.27	0.41	0.56	16.6	427	3.69	0.13	0.16	0.20	0.27	0.41	0.55
	8	0.015	23.4	423	3.69	0.12	0.15	0.19	0.26	0.41	0.56	22.2	439	3.69	0.12	0.15	0.19	0.26	0.41	0.55
	12	0.015	36.2	400	3.67	0.11	0.15	0.19	0.26	0.41	0.56	34.8	407	3.68	0.12	0.15	0.19	0.26	0.41	0.55
	20	0.015	53.0	393	3.68	0.11	0.15	0.19	0.26	0.41	0.56	50.9	407	3.69	0.12	0.15	0.19	0.26	0.41	0.56
0.50	1	0.015	1.7	153	4.37	0.12	0.20	0.28	0.42	0.68	0.93	1.5	183	4.37	0.13	0.20	0.27	0.40	0.66	0.91
	2	0.015	3.2	189	4.38	0.12	0.19	0.25	0.38	0.60	0.82	2.9	219	4.38	0.13	0.19	0.25	0.36	0.58	0.79
	3	0.015	4.9	171	4.37	0.12	0.20	0.27	0.41	0.67	0.92	4.4	199	4.38	0.13	0.20	0.27	0.39	0.64	0.88
	4	0.015	7.3	176	4.38	0.13	0.21	0.28	0.43	0.70	0.96	6.5	180	4.38	0.14	0.21	0.29	0.43	0.69	0.95
	6	0.015	8.9	177	4.38	0.11	0.19	0.26	0.40	0.65	0.89	8.0	207	4.38	0.12	0.19	0.26	0.39	0.63	0.86
	8	0.015	12.5	150	4.38	0.11	0.19	0.26	0.40	0.66	0.91	11.8	171	4.38	0.12	0.20	0.27	0.40	0.66	0.90
	12	0.015	20.5	171	4.38	0.11	0.20	0.27	0.41	0.67	0.92	19.2	191	4.38	0.13	0.20	0.27	0.41	0.66	0.91
	20	0.015	28.9	151	4.39	0.11	0.19	0.27	0.41	0.67	0.92	26.8	168	4.39	0.13	0.20	0.27	0.41	0.66	0.91

Table B.22: Detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area L for various RADTi in case of $\sigma^2_{\ln K} = 2.0$ assuming every 4 months (4M) and biannually (6M) sampling frequencies

	$\sigma^2_{\ln K}$									2.00										
α_T(m)	now	nfds(max)	P_d (4M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L	P_d (6M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	1	0.75	3.1	3254	0.37	0.03	0.03	0.03	0.03	0.04	0.04	2.8	3381	0.37	0.03	0.03	0.03	0.03	0.04	0.04
	2	0.75	6.0	3240	0.37	0.02	0.03	0.03	0.03	0.03	0.04	5.6	3326	0.37	0.02	0.03	0.03	0.03	0.03	0.04
	3	0.75	8.2	3247	0.36	0.02	0.03	0.03	0.03	0.03	0.04	7.2	3420	0.36	0.03	0.03	0.03	0.03	0.03	0.04
	4	0.75	10.6	3211	0.37	0.03	0.03	0.03	0.03	0.04	0.04	9.7	3343	0.37	0.03	0.03	0.03	0.03	0.04	0.04
	6	0.75	17.3	3357	0.37	0.03	0.03	0.03	0.03	0.04	0.04	15.6	3503	0.38	0.03	0.03	0.03	0.03	0.04	0.04
	8	0.75	21.6	3252	0.39	0.03	0.03	0.03	0.03	0.04	0.04	19.6	3380	0.39	0.03	0.03	0.03	0.03	0.04	0.04
	12	0.75	30.4	3244	0.37	0.03	0.03	0.03	0.03	0.04	0.04	27.6	3404	0.37	0.03	0.03	0.03	0.03	0.04	0.04
	20	0.75	47.6	3201	0.37	0.03	0.03	0.03	0.03	0.04	0.04	43.4	3348	0.39	0.03	0.03	0.03	0.03	0.04	0.04
0.01	1	0.50	4.8	2414	1.07	0.08	0.09	0.09	0.11	0.13	0.15	4.7	2473	1.07	0.08	0.09	0.09	0.10	0.13	0.15
	2	0.50	7.6	2304	1.08	0.08	0.08	0.09	0.10	0.12	0.15	7.1	2362	1.08	0.08	0.08	0.09	0.10	0.12	0.15
	3	0.50	13.1	2398	1.07	0.08	0.09	0.09	0.10	0.13	0.15	12.4	2477	1.07	0.08	0.09	0.09	0.10	0.13	0.15
	4	0.50	15.8	2496	1.08	0.08	0.09	0.09	0.10	0.12	0.15	14.9	2585	1.08	0.08	0.09	0.09	0.10	0.12	0.15
	6	0.50	22.1	2418	1.08	0.08	0.09	0.09	0.10	0.12	0.15	20.9	2496	1.09	0.08	0.09	0.09	0.10	0.12	0.15
	8	0.50	30.0	2365	1.08	0.08	0.08	0.09	0.10	0.12	0.15	28.4	2451	1.09	0.08	0.09	0.09	0.10	0.12	0.15
	12	0.50	43.6	2413	1.07	0.08	0.08	0.09	0.10	0.12	0.15	40.9	2496	1.09	0.08	0.08	0.09	0.10	0.12	0.15
	20	0.50	61.1	2365	1.07	0.08	0.08	0.09	0.10	0.12	0.15	58.2	2437	1.09	0.08	0.08	0.09	0.10	0.12	0.15
0.02	1	0.25	4.7	1743	1.52	0.08	0.09	0.10	0.11	0.14	0.17	4.6	1784	1.52	0.08	0.09	0.10	0.11	0.14	0.17
	2	0.25	9.4	1638	1.52	0.08	0.09	0.10	0.12	0.15	0.19	8.9	1671	1.52	0.09	0.09	0.10	0.12	0.15	0.19
	3	0.25	12.4	1704	1.52	0.08	0.09	0.10	0.11	0.14	0.17	12.0	1758	1.52	0.08	0.09	0.10	0.11	0.14	0.17
	4	0.25	16.2	1662	1.53	0.08	0.09	0.10	0.11	0.15	0.18	15.4	1740	1.53	0.09	0.09	0.10	0.12	0.15	0.18
	6	0.25	25.7	1688	1.55	0.08	0.09	0.10	0.11	0.15	0.18	24.4	1732	1.55	0.09	0.09	0.10	0.12	0.15	0.18
	8	0.25	33.3	1685	1.54	0.08	0.09	0.10	0.11	0.15	0.18	31.6	1746	1.55	0.08	0.09	0.10	0.11	0.15	0.18
	12	0.25	46.2	1649	1.54	0.08	0.09	0.10	0.11	0.15	0.18	44.0	1726	1.56	0.08	0.09	0.10	0.12	0.15	0.19
	20	0.25	67.0	1632	1.55	0.08	0.09	0.09	0.11	0.14	0.18	64.6	1696	1.57	0.08	0.09	0.10	0.11	0.15	0.18
0.05	1	0.13	4.4	1114	2.32	0.12	0.13	0.14	0.17	0.23	0.29	4.1	1183	2.32	0.12	0.13	0.14	0.17	0.23	0.29
	2	0.13	9.1	1203	2.32	0.11	0.12	0.14	0.16	0.22	0.28	8.4	1272	2.32	0.11	0.12	0.14	0.17	0.22	0.28
	3	0.13	12.4	1096	2.32	0.11	0.12	0.14	0.17	0.23	0.29	11.5	1165	2.33	0.11	0.12	0.14	0.17	0.22	0.29
	4	0.13	18.1	1189	2.32	0.11	0.12	0.13	0.16	0.22	0.28	17.6	1245	2.33	0.11	0.12	0.14	0.16	0.22	0.29
	6	0.13	26.5	1237	2.34	0.11	0.12	0.14	0.16	0.22	0.29	24.7	1301	2.34	0.11	0.13	0.14	0.17	0.22	0.29
	8	0.13	36.1	1138	2.33	0.11	0.12	0.13	0.16	0.22	0.29	34.3	1195	2.33	0.11	0.12	0.14	0.16	0.22	0.29
	12	0.13	51.2	1128	2.32	0.11	0.12	0.13	0.16	0.22	0.29	48.2	1178	2.35	0.11	0.12	0.13	0.16	0.22	0.28
	20	0.13	71.7	1144	2.32	0.10	0.12	0.13	0.16	0.22	0.29	68.9	1197	2.37	0.11	0.12	0.13	0.16	0.22	0.29
0.10	1	0.063	4.1	934	3.02	0.12	0.14	0.16	0.20	0.29	0.38	3.9	981	3.02	0.13	0.14	0.16	0.20	0.29	0.37
	2	0.063	8.6	819	3.03	0.13	0.15	0.17	0.22	0.31	0.40	8.1	837	3.03	0.13	0.15	0.17	0.22	0.31	0.40
	3	0.063	12.2	840	3.02	0.13	0.15	0.17	0.21	0.31	0.40	11.5	882	3.02	0.13	0.15	0.17	0.21	0.30	0.40
	4	0.063	15.8	827	3.02	0.13	0.15	0.17	0.22	0.32	0.42	14.6	883	3.02	0.13	0.16	0.18	0.22	0.32	0.42
	6	0.063	24.0	811	3.04	0.13	0.15	0.17	0.22	0.31	0.41	22.7	831	3.04	0.13	0.15	0.17	0.22	0.31	0.41
	8	0.063	31.2	832	3.03	0.13	0.15	0.17	0.22	0.31	0.41	29.2	872	3.05	0.13	0.15	0.17	0.22	0.31	0.41
	12	0.063	45.6	817	3.03	0.13	0.15	0.17	0.21	0.31	0.41	42.7	860	3.05	0.13	0.15	0.17	0.22	0.31	0.41
	20	0.063	65.9	774	3.03	0.12	0.14	0.17	0.21	0.31	0.41	61.9	820	3.08	0.13	0.15	0.17	0.21	0.31	0.40
0.20	1	0.015	3.0	572	3.69	0.13	0.17	0.20	0.26	0.39	0.52	2.7	632	3.69	0.13	0.16	0.19	0.25	0.37	0.50
	2	0.015	5.6	460	3.69	0.13	0.16	0.19	0.25	0.38	0.50	5.2	506	3.69	0.13	0.16	0.19	0.25	0.37	0.50
	3	0.015	8.9	519	3.69	0.13	0.16	0.20	0.27	0.41	0.55	7.9	586	3.69	0.13	0.17	0.20	0.26	0.39	0.52
	4	0.015	11.0	423	3.68	0.12	0.16	0.20	0.27	0.42	0.57	9.6	491	3.69	0.13	0.16	0.20	0.26	0.41	0.56
	6	0.015	15.8	450	3.70	0.13	0.16	0.20	0.27	0.40	0.54	14.3	492	3.70	0.14	0.17	0.20	0.27	0.40	0.54
	8	0.015	21.2	459	3.70	0.12	0.16	0.19	0.26	0.40	0.55	18.6	513	3.70	0.13	0.16	0.19	0.26	0.39	0.53
	12	0.015	33.0	424	3.68	0.12	0.16	0.19	0.26	0.41	0.55	29.4	479	3.70	0.13	0.16	0.19	0.26	0.40	0.54
	20	0.015	48.6	425	3.70	0.12	0.16	0.19	0.26	0.41	0.55	43.4	485	3.73	0.13	0.16	0.19	0.26	0.40	0.54
0.50	1	0.015	1.4	196	4.37	0.14	0.20	0.27	0.39	0.65	0.89	1.0	261	4.38	0.14	0.19	0.24	0.34	0.56	0.77
	2	0.015	2.7	219	4.38	0.13	0.19	0.25	0.36	0.57	0.78	2.2	271	4.38	0.15	0.20	0.25	0.35	0.55	0.75
	3	0.015	4.0	208	4.38	0.13	0.20	0.26	0.39	0.63	0.87	3.1	286	4.38	0.15	0.20	0.25	0.35	0.56	0.77
	4	0.015	6.0	208	4.38	0.15	0.22	0.29	0.43	0.69	0.95	4.3	275	4.38	0.17	0.23	0.28	0.40	0.64	0.88
	6	0.015	7.3	224	4.38	0.13	0.20	0.26	0.38	0.61	0.84	5.6	290	4.39	0.15	0.21	0.26	0.37	0.58	0.80
	8	0.015	10.6	188	4.38	0.13	0.20	0.27	0.40	0.65	0.88	8.4	240	4.39	0.15	0.21	0.26	0.38	0.60	0.83
	12	0.015	17.5	215	4.39	0.14	0.21	0.28	0.41	0.65	0.89	13.5	277	4.40	0.16	0.22	0.27	0.39	0.61	0.84
	20	0.015	24.6	193	4.40	0.14	0.21	0.27	0.40	0.65	0.88	19.3	250	4.41	0.15	0.21	0.27	0.38	0.61	0.83

Table B.23: Detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area L for various RADTi in case of $\sigma^2_{\ln K} = 2.0$ assuming annually sampling frequency

$\sigma^2_{\ln K}$						2.00					
α_T(m)	**now**	**nfds(max)**	**P_d (12M)**	**$\langle T_{(DET.)}\rangle$ (DAYS)**	**AREA ON FAILURE**	**(AREA ON DET.)/L**	**(3M. RADTi)/L**	**(6M. RADTi)/L**	**(12M. RADTi)/L**	**(24M. RADTi/L)**	**(36M. RADTi)/L**
0.001	**1**	0.75	1.7	4085	0.37	0.03	0.03	0.03	0.04	0.04	0.05
	2	0.75	3.9	3826	0.37	0.03	0.03	0.03	0.03	0.04	0.04
	3	0.75	5.1	3930	0.37	0.03	0.03	0.03	0.03	0.04	0.04
	4	0.75	6.7	3849	0.37	0.03	0.03	0.03	0.04	0.04	0.05
	6	0.75	11.1	4009	0.37	0.03	0.03	0.03	0.03	0.04	0.04
	8	0.75	14.3	3842	0.39	0.03	0.03	0.03	0.03	0.04	0.05
	12	0.75	19.5	3851	0.37	0.03	0.03	0.03	0.03	0.04	0.05
	20	0.75	30.6	3811	0.40	0.03	0.03	0.03	0.03	0.04	0.04
0.01	**1**	0.50	3.3	2872	1.07	0.09	0.09	0.10	0.11	0.13	0.15
	2	0.50	5.8	2649	1.08	0.08	0.09	0.09	0.10	0.13	0.15
	3	0.50	9.7	2792	1.08	0.09	0.09	0.10	0.11	0.13	0.16
	4	0.50	12.0	2952	1.09	0.09	0.09	0.10	0.11	0.13	0.15
	6	0.50	16.9	2811	1.10	0.09	0.09	0.10	0.11	0.13	0.15
	8	0.50	22.8	2763	1.10	0.08	0.09	0.09	0.11	0.13	0.15
	12	0.50	33.6	2833	1.12	0.09	0.09	0.10	0.11	0.13	0.15
	20	0.50	47.5	2750	1.16	0.08	0.09	0.09	0.11	0.13	0.15
0.02	**1**	0.25	3.8	1994	1.52	0.09	0.09	0.10	0.11	0.14	0.17
	2	0.25	7.1	1913	1.53	0.09	0.10	0.11	0.12	0.16	0.19
	3	0.25	9.7	2007	1.53	0.09	0.09	0.10	0.11	0.14	0.17
	4	0.25	12.3	1973	1.54	0.09	0.10	0.11	0.12	0.15	0.18
	6	0.25	19.8	1975	1.56	0.09	0.10	0.10	0.12	0.15	0.18
	8	0.25	25.4	1995	1.57	0.09	0.10	0.10	0.12	0.15	0.19
	12	0.25	35.5	1975	1.59	0.09	0.10	0.10	0.12	0.15	0.19
	20	0.25	54.4	1929	1.64	0.09	0.09	0.10	0.12	0.15	0.19
0.05	**1**	0.13	3.0	1391	2.32	0.12	0.14	0.15	0.17	0.22	0.28
	2	0.13	7.0	1472	2.33	0.12	0.13	0.14	0.17	0.23	0.28
	3	0.13	9.0	1325	2.33	0.12	0.13	0.14	0.17	0.22	0.28
	4	0.13	13.9	1421	2.34	0.12	0.13	0.14	0.17	0.22	0.29
	6	0.13	20.3	1514	2.36	0.12	0.13	0.14	0.17	0.22	0.28
	8	0.13	27.0	1389	2.36	0.12	0.13	0.14	0.17	0.22	0.28
	12	0.13	39.1	1363	2.40	0.12	0.13	0.14	0.17	0.22	0.28
	20	0.13	56.9	1388	2.47	0.11	0.13	0.14	0.17	0.22	0.28
0.10	**1**	0.063	3.1	1126	3.02	0.13	0.15	0.17	0.20	0.28	0.36
	2	0.063	6.4	1007	3.03	0.14	0.16	0.18	0.22	0.29	0.38
	3	0.063	8.4	1105	3.03	0.14	0.16	0.17	0.21	0.29	0.37
	4	0.063	10.5	1070	3.03	0.14	0.16	0.18	0.22	0.31	0.40
	6	0.063	17.2	1026	3.06	0.14	0.16	0.18	0.22	0.30	0.39
	8	0.063	22.7	1068	3.07	0.14	0.16	0.18	0.22	0.30	0.39
	12	0.063	32.5	1032	3.09	0.14	0.16	0.18	0.22	0.30	0.39
	20	0.063	47.9	1001	3.16	0.14	0.16	0.18	0.22	0.30	0.39
0.20	**1**	0.015	1.9	703	3.69	0.14	0.16	0.18	0.23	0.33	0.44
	2	0.015	3.8	614	3.70	0.14	0.17	0.19	0.24	0.35	0.46
	3	0.015	5.1	737	3.70	0.14	0.17	0.19	0.25	0.36	0.48
	4	0.015	6.0	677	3.69	0.15	0.18	0.21	0.26	0.39	0.53
	6	0.015	9.7	670	3.71	0.15	0.18	0.20	0.26	0.37	0.49
	8	0.015	12.6	718	3.72	0.15	0.18	0.20	0.26	0.37	0.50
	12	0.015	18.6	661	3.73	0.15	0.18	0.20	0.26	0.37	0.50
	20	0.015	29.9	656	3.76	0.15	0.18	0.20	0.26	0.38	0.51
0.50	**1**	0.015	0.7	434	4.38	0.19	0.23	0.27	0.36	0.55	0.74
	2	0.015	1.4	415	4.38	0.17	0.21	0.25	0.33	0.49	0.65
	3	0.015	1.8	461	4.38	0.18	0.22	0.26	0.35	0.53	0.72
	4	0.015	1.7	512	4.38	0.18	0.21	0.25	0.33	0.51	0.70
	6	0.015	3.4	487	4.39	0.18	0.22	0.26	0.35	0.52	0.70
	8	0.015	4.6	423	4.39	0.18	0.22	0.26	0.34	0.52	0.70
	12	0.015	6.0	451	4.40	0.18	0.22	0.26	0.34	0.52	0.70
	20	0.015	9.9	427	4.41	0.18	0.22	0.26	0.35	0.53	0.72

B.2 Precipitation Trigered Pollution

Table B.24: Detection probability in case of $\sigma^2_{\ln K} = 0.0$, $\sigma^2_{\ln K} = 1.0$ and $\sigma^2_{\ln K} = 2.0$, for different transverse coefficients and sampling frequencies

		$\sigma^2_{\ln K}$				0.00								1.00								2.00				
α_T(m)	nws	No Wells	nfds(max)	ED	1M	2M	3M	4M	6M	12M	nfds(max)	ED	1M	2M	3M	4M	6M	12M	nfds(max)	ED	1M	2M	3M	4M	6M	12M
	1.00	**1**	3.00	7.5	7.4	7.3	7.1	6.9	6.8	6.6	1.75	8.2	8.0	7.9	7.8	7.9	7.7	7.7	0.75	6.9	6.6	6.5	6.3	6.3	6.2	6.1
	0.50	**2**	3.00	16.3	16.1	15.9	15.7	15.6	14.7	14.6	1.75	18.2	17.8	17.2	17.1	16.8	16.7	16.3	0.75	16.5	16.1	16.0	15.7	15.5	15.2	15.1
	0.33	**3**	3.00	24.3	24.1	24.0	23.6	23.3	22.7	22.4	1.75	24.5	24.0	23.6	23.2	23.3	22.7	22.0	0.75	18.6	18.0	17.8	17.3	17.4	17.0	17.0
0.001	**0.25**	**4**	3.00	31.5	31.2	30.7	30.6	29.8	29.3	28.2	1.75	31.4	30.4	29.9	29.7	29.4	28.8	28.3	0.75	23.8	23.3	22.9	22.6	22.7	22.1	21.7
	0.17	**6**	3.00	48.8	48.5	47.6	46.8	46.3	44.8	44.0	1.75	46.5	45.4	44.4	44.1	43.8	43.0	42.0	0.75	39.0	37.9	37.7	37.0	36.9	36.2	35.9
	0.12	**8**	3.00	62.3	62.0	61.4	60.6	60.0	58.3	57.8	1.75	56.2	54.8	54.1	53.8	53.1	52.5	51.4	0.75	44.7	42.9	42.3	41.6	41.5	41.0	40.8
	0.08	**12**	3.00	92.5	91.8	90.4	89.2	87.5	86.0	84.0	1.75	71.3	69.7	69.3	68.6	68.4	67.9	67.2	0.75	61.5	60.0	59.2	58.3	58.4	57.7	57.3
	0.05	**20**	3.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	1.75	82.7	82.3	82.0	81.8	81.7	81.2	80.6	0.75	76.9	75.8	75.4	74.9	74.7	74.5	74.0
	1.00	**1**	2.25	19.9	19.8	19.7	19.2	19.1	18.5	18.1	1.25	22.2	22.0	21.8	21.3	21.3	20.8	20.1	0.50	16.2	15.8	15.5	15.3	14.9	14.9	14.4
	0.50	**2**	2.25	40.0	39.5	38.9	38.1	38.0	36.5	35.3	1.25	41.1	40.5	39.9	39.2	39.0	38.3	36.6	0.50	29.1	28.3	27.9	27.4	27.3	26.6	26.0
	0.33	**3**	2.25	59.9	59.2	58.6	57.1	56.6	55.0	53.4	1.25	55.8	54.6	54.2	53.1	52.6	51.6	50.3	0.50	43.5	42.5	41.6	41.3	40.6	40.0	39.0
0.010	**0.25**	**4**	2.25	79.5	79.1	77.8	76.8	75.8	74.2	72.1	1.25	66.8	65.7	64.9	64.3	64.1	63.1	62.3	0.50	50.6	49.3	48.4	48.0	47.0	46.7	45.3
	0.17	**6**	2.25	100.0	100.0	100.0	100.0	100.0	99.9	99.7	1.25	80.6	80.0	79.4	78.8	78.4	77.7	76.7	0.50	65.3	64.1	63.4	62.9	62.2	61.5	59.9
	0.12	**8**	2.25	97.4	97.3	97.1	96.9	96.8	96.6	96.2	1.25	82.5	82.0	81.5	81.3	80.9	80.7	80.0	0.50	74.8	73.8	73.1	72.6	72.3	71.8	70.5
	0.08	**12**	2.25	100.0	100.0	100.0	100.0	100.0	100.0	100.0	1.25	90.7	90.4	90.1	90.0	89.9	89.7	89.1	0.50	84.9	83.9	83.4	83.1	83.0	82.7	82.0
	0.05	**20**	2.25	100.0	100.0	100.0	100.0	100.0	100.0	100.0	1.25	92.5	92.4	92.2	92.0	92.0	91.8	91.6	0.50	87.9	87.7	87.6	87.6	87.4	87.3	86.9
	1.00	**1**	0.50	26.1	25.5	25.1	24.3	24.5	23.8	22.7	0.125	21.1	20.6	20.1	19.6	19.6	19.1	18.3	0.125	21.8	21.1	20.5	20.3	19.7	19.4	18.9
	0.50	**2**	0.50	50.3	49.4	48.6	47.9	47.0	46.6	45.2	0.125	42.0	41.0	40.3	39.9	39.6	38.9	37.6	0.125	45.1	43.7	42.7	42.2	41.2	40.8	38.9
	0.33	**3**	0.50	76.4	74.8	73.7	71.9	71.6	70.0	67.2	0.125	58.6	56.8	55.9	55.1	54.8	53.8	51.3	0.125	61.3	59.7	58.8	57.9	57.3	56.5	55.1
0.05	**0.25**	**4**	0.50	96.7	95.6	94.8	93.8	93.0	92.0	89.7	0.125	71.7	70.2	69.3	67.8	67.6	66.4	63.8	0.125	72.4	70.8	70.2	69.0	68.7	67.9	65.1
	0.17	**6**	0.50	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.125	91.1	89.3	88.5	88.0	88.0	86.7	85.4	0.125	88.5	87.2	86.3	85.9	85.3	84.1	83.0
	0.12	**8**	0.50	99.3	99.1	99.0	98.7	98.8	98.6	98.4	0.125	92.3	91.9	91.6	91.4	91.3	91.0	90.4	0.125	90.7	90.3	89.7	89.6	88.9	88.7	87.7
	0.08	**12**	0.50	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.125	97.1	97.1	97.0	97.0	97.0	96.8	96.8	0.125	95.9	95.8	95.7	95.4	95.4	95.3	95.0
	0.05	**20**	0.50	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.125	97.9	97.7	97.7	97.7	97.7	97.5	97.6	0.125	97.3	97.0	97.0	96.8	96.7	96.6	96.1
	1.00	**1**	0.125	27.2	26.3	25.8	25.2	25.0	24.7	23.3	0.0625	28.5	27.4	27.0	26.6	26.1	25.6	24.2	0.0625	29.9	28.5	28.0	27.3	27.3	26.0	25.3
	0.50	**2**	0.125	53.6	52.0	50.9	49.6	49.6	48.3	47.0	0.0625	56.2	54.4	53.4	53.1	52.6	50.9	49.2	0.0625	60.4	57.9	56.6	55.4	54.9	54.0	52.8
	0.33	**3**	0.125	79.5	77.3	75.9	74.8	74.2	72.4	69.0	0.0625	76.9	74.3	73.2	72.1	71.5	70.3	67.9	0.0625	78.5	76.2	74.9	73.8	73.6	72.0	69.5
0.10	**0.25**	**4**	0.125	96.0	94.6	93.7	93.0	92.2	91.4	89.4	0.0625	88.6	86.8	85.9	84.3	83.8	82.7	80.1	0.0625	88.0	86.7	85.4	85.3	83.8	83.0	81.6
	0.17	**6**	0.125	100.0	100.0	100.0	100.0	100.0	100.0	99.9	0.0625	98.0	97.8	97.5	97.0	97.0	96.4	96.0	0.0625	96.7	95.9	95.6	95.3	95.0	94.3	93.3
	0.12	**8**	0.125	99.5	99.4	99.3	99.3	99.2	99.0	98.7	0.0625	96.2	95.8	95.7	95.5	95.4	95.3	94.8	0.0625	95.0	94.9	94.6	94.5	94.2	94.0	93.9
	0.08	**12**	0.125	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0625	99.5	99.2	99.2	99.2	99.1	99.1	98.9	0.0625	98.9	98.6	98.5	98.4	98.5	98.2	98.0
	0.05	**20**	0.125	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0625	99.7	99.7	99.6	99.5	99.6	99.5	99.4	0.0625	99.3	99.2	99.1	99.1	98.9	99.0	98.6
	1.00	**1**	0.015	72.4	67.4	64.9	63.1	61.5	59.8	57.2	0.015	91.1	86.9	84.6	82.3	81.4	78.8	75.4	0.015	92.5	89.7	87.9	86.0	85.3	82.6	79.6
	0.50	**2**	0.015	100.0	100.0	99.7	99.5	99.5	99.0	97.9	0.015	99.9	99.8	99.7	99.7	99.6	99.6	99.1	0.015	100.0	99.8	99.6	99.6	99.6	99.3	99.1
	0.33	**3**	0.015	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.015	100.0	100.0	100.0	100.0	99.9	99.9	99.9	0.015	100.0	100.0	100.0	100.0	99.9	100.0	99.8
0.50	**0.25**	**4**	0.015	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.015	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.015	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	0.17	**6**	0.015	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.015	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.015	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	0.12	**8**	0.015	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.015	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.015	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	0.08	**12**	0.015	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.015	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.015	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	0.05	**20**	0.015	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.015	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.015	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table B.25: Precipitation triggered pollution detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area for various RADTi in case of $\sigma^2_{\ln K} = 0.0$ assuming daily (ED) and monthly (1M) sampling frequencies

$\sigma^2_{\ln K}$										0.00										
α_T(m)	**now**	**nfds(max)**	**P_d (ED)**	**<$T_{(DET.)}$> (DAYS)**	**AREA ON FAILURE**	**(AREA ON DET.)/L**	**(3M. RADTi)/L**	**(6M. RADTi)/L**	**(12M. RADTi)/L**	**(24M. RADTi/L)**	**(36M. RADTi)/L**	**P_d (1M)**	**<$T_{(DET.)}$> (DAYS)**	**AREA ON FAILURE**	**(AREA ON DET.)/L**	**(3M. RADTi)/L**	**(6M. RADTi)/L**	**(12M. RADTi)/L**	**(24M. RADTi/L)**	**(36M. RADTi)/L**
0.001	**1**	3.00	7.5	9405	0.36	0.29	0.30	0.29	0.30	0.29	0.21	7.4	9402	0.36	0.29	0.30	0.30	0.30	0.29	0.19
	2	3.00	16.3	9586	0.36	0.30	0.30	0.31	0.31	0.31	0.23	16.1	9598	0.36	0.30	0.30	0.31	0.31	0.31	0.23
	3	3.00	24.3	9556	0.36	0.30	0.30	0.30	0.31	0.31	0.25	24.1	9569	0.36	0.30	0.30	0.31	0.31	0.31	0.25
	4	3.00	31.5	9555	0.36	0.30	0.30	0.31	0.31	0.31	0.24	31.2	9569	0.36	0.30	0.31	0.31	0.31	0.31	0.24
	6	3.00	48.8	9587	0.36	0.30	0.30	0.31	0.31	0.31	0.24	48.5	9601	0.36	0.30	0.30	0.31	0.31	0.31	0.23
	8	3.00	62.3	9560	0.35	0.30	0.31	0.31	0.31	0.31	0.25	62.0	9576	0.35	0.30	0.31	0.31	0.31	0.31	0.24
	12	3.00	92.5	9579	NAV	0.30	0.31	0.31	0.31	0.31	0.24	91.8	9593	NAV	0.30	0.31	0.31	0.31	0.31	0.24
	20	3.00	100.0	9457	NAV	0.30	0.30	0.30	0.31	0.33	0.27	100.0	9472	NAV	0.30	0.30	0.30	0.31	0.33	0.27
0.01	**1**	2.25	19.9	7254	0.80	0.46	0.46	0.47	0.49	0.52	0.54	19.8	7296	0.80	0.46	0.47	0.47	0.49	0.52	0.54
	2	2.25	40.0	7242	0.80	0.46	0.47	0.47	0.49	0.51	0.54	39.5	7265	0.80	0.46	0.47	0.47	0.49	0.51	0.54
	3	2.25	59.9	7251	0.80	0.46	0.47	0.47	0.48	0.51	0.54	59.2	7268	0.80	0.46	0.47	0.47	0.49	0.52	0.54
	4	2.25	79.5	7215	0.80	0.46	0.46	0.47	0.48	0.51	0.54	79.1	7238	0.80	0.46	0.46	0.47	0.48	0.51	0.54
	6	2.25	100.0	7007	NAV	0.44	0.44	0.45	0.47	0.50	0.53	100.0	7032	NAV	0.44	0.45	0.45	0.47	0.50	0.53
	8	2.25	97.4	6935	NAV	0.43	0.44	0.45	0.46	0.49	0.52	97.3	6955	NAV	0.43	0.44	0.45	0.46	0.49	0.53
	12	2.25	100.0	6854	NAV	0.42	0.43	0.44	0.46	0.49	0.52	100.0	6874	NAV	0.43	0.43	0.44	0.46	0.49	0.52
	20	2.25	100.0	6823	NAV	0.42	0.43	0.44	0.45	0.48	0.52	100.0	6842	NAV	0.42	0.43	0.44	0.45	0.49	0.52
0.05	**1**	0.50	26.1	2397	1.52	0.22	0.22	0.23	0.25	0.29	0.32	25.5	2430	1.52	0.22	0.23	0.24	0.25	0.29	0.32
	2	0.50	50.3	2183	1.52	0.19	0.20	0.20	0.22	0.26	0.31	49.4	2252	1.52	0.19	0.20	0.21	0.23	0.27	0.31
	3	0.50	76.4	2285	1.52	0.20	0.21	0.22	0.24	0.28	0.31	74.8	2329	1.52	0.21	0.22	0.22	0.24	0.28	0.32
	4	0.50	96.7	2086	NAV	0.17	0.18	0.19	0.21	0.25	0.29	95.6	2137	NAV	0.18	0.19	0.20	0.22	0.25	0.29
	6	0.50	100.0	1669	NAV	0.12	0.13	0.14	0.16	0.20	0.24	100.0	1705	NAV	0.13	0.14	0.15	0.16	0.20	0.25
	8	0.50	99.3	1649	NAV	0.12	0.13	0.14	0.16	0.20	0.24	99.1	1683	NAV	0.13	0.14	0.14	0.16	0.20	0.24
	12	0.50	100.0	1553	NAV	0.11	0.12	0.13	0.15	0.19	0.23	100.0	1584	NAV	0.12	0.12	0.13	0.15	0.19	0.23
	20	0.50	100.0	1526	NAV	0.11	0.12	0.13	0.15	0.18	0.22	100.0	1556	NAV	0.11	0.12	0.13	0.15	0.19	0.23
0.10	**1**	0.13	27.2	1383	1.97	0.16	0.17	0.18	0.19	0.23	0.29	26.3	1412	1.97	0.16	0.17	0.18	0.20	0.24	0.29
	2	0.13	53.6	1377	1.97	0.16	0.17	0.17	0.20	0.24	0.29	52.0	1375	1.97	0.16	0.16	0.17	0.19	0.23	0.28
	3	0.13	79.5	1289	1.97	0.14	0.15	0.16	0.18	0.22	0.27	77.3	1340	1.97	0.15	0.16	0.17	0.19	0.23	0.28
	4	0.13	96.0	1064	1.97	0.11	0.12	0.13	0.15	0.19	0.24	94.6	1138	1.97	0.12	0.13	0.14	0.16	0.20	0.25
	6	0.13	100.0	657	NAV	0.05	0.06	0.07	0.09	0.13	0.18	100.0	702	NAV	0.06	0.07	0.08	0.10	0.14	0.19
	8	0.13	99.5	634	NAV	0.05	0.06	0.07	0.09	0.13	0.18	99.4	676	NAV	0.06	0.07	0.08	0.10	0.14	0.18
	12	0.13	100.0	535	NAV	0.04	0.05	0.06	0.08	0.12	0.16	100.0	566	NAV	0.05	0.05	0.06	0.08	0.12	0.17
	20	0.13	100.0	510	NAV	0.04	0.05	0.06	0.08	0.12	0.16	100.0	540	NAV	0.04	0.05	0.06	0.08	0.12	0.16
0.50	**1**	0.015	72.4	1843	NAV	1.13	1.17	1.23	1.36	1.60	1.85	67.4	1856	6.78	1.21	1.26	1.33	1.46	1.68	1.95
	2	0.015	100.0	743	NAV	0.39	0.45	0.51	0.63	0.88	1.14	100.0	908	NAV	0.48	0.54	0.60	0.73	0.98	1.23
	3	0.015	100.0	390	NAV	0.17	0.22	0.28	0.41	0.66	0.91	100.0	463	NAV	0.21	0.27	0.34	0.46	0.71	0.96
	4	0.015	100.0	278	NAV	0.11	0.16	0.22	0.35	0.60	0.86	100.0	334	NAV	0.15	0.21	0.27	0.40	0.64	0.89
	6	0.015	100.0	202	NAV	0.07	0.11	0.17	0.30	0.54	0.81	100.0	244	NAV	0.09	0.14	0.21	0.34	0.58	0.84
	8	0.015	100.0	186	NAV	0.07	0.11	0.16	0.30	0.54	0.81	100.0	226	NAV	0.09	0.14	0.20	0.33	0.57	0.84
	12	0.015	100.0	156	NAV	0.05	0.09	0.14	0.28	0.52	0.79	100.0	189	NAV	0.07	0.12	0.18	0.31	0.55	0.82
	20	0.015	100.0	144	NAV	0.05	0.08	0.13	0.26	0.51	0.78	100.0	174	NAV	0.06	0.10	0.16	0.30	0.54	0.80

Table B.26: Precipitation triggered pollution detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area for various RADTi in case of $\sigma^2_{\ln K} = 0.0$ assuming bimonthly (2M) and quarterly (3M) sampling frequencies

	$\sigma^2_{\ln K}$									0.00										
α_T(m)	now	nfds(max)	P_d (2M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L	P_d (3M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	1	3.00	7.3	9408	0.36	0.29	0.30	0.29	0.30	0.29	0.20	7.1	9399	0.36	0.29	0.30	0.30	0.31	0.30	0.20
	2	3.00	15.9	9610	0.36	0.30	0.31	0.31	0.32	0.31	0.23	15.7	9632	0.36	0.30	0.30	0.31	0.31	0.31	0.22
	3	3.00	24.0	9583	0.36	0.30	0.30	0.30	0.31	0.31	0.25	23.6	9586	0.36	0.30	0.31	0.31	0.31	0.31	0.25
	4	3.00	30.7	9577	0.36	0.30	0.31	0.31	0.31	0.31	0.24	30.6	9602	0.36	0.30	0.31	0.31	0.31	0.31	0.23
	6	3.00	47.6	9612	0.36	0.30	0.31	0.31	0.31	0.31	0.23	46.8	9627	0.36	0.30	0.31	0.31	0.31	0.31	0.23
	8	3.00	61.4	9588	0.35	0.30	0.31	0.31	0.31	0.32	0.25	60.6	9604	0.35	0.30	0.31	0.31	0.31	0.31	0.24
	12	3.00	90.4	9603	NAV	0.30	0.31	0.31	0.31	0.31	0.24	89.2	9620	NAV	0.30	0.31	0.31	0.31	0.31	0.23
	20	3.00	100.0	9488	NAV	0.30	0.30	0.30	0.31	0.33	0.27	100.0	9503	NAV	0.30	0.30	0.31	0.31	0.33	0.26
0.01	1	2.25	19.7	7340	0.80	0.47	0.47	0.48	0.49	0.52	0.54	19.2	7324	0.80	0.47	0.47	0.48	0.49	0.52	0.55
	2	2.25	38.9	7293	0.80	0.46	0.47	0.48	0.49	0.51	0.54	38.1	7314	0.80	0.46	0.47	0.48	0.49	0.52	0.54
	3	2.25	58.6	7303	0.80	0.46	0.47	0.47	0.49	0.52	0.54	57.1	7290	0.80	0.46	0.47	0.48	0.49	0.52	0.55
	4	2.25	77.8	7250	0.80	0.46	0.47	0.47	0.49	0.51	0.54	76.8	7288	0.80	0.46	0.47	0.48	0.49	0.51	0.54
	6	2.25	100.0	7062	NAV	0.44	0.45	0.46	0.47	0.50	0.54	100.0	7101	NAV	0.45	0.45	0.46	0.48	0.51	0.54
	8	2.25	97.1	6978	NAV	0.43	0.44	0.45	0.47	0.50	0.53	96.9	7001	NAV	0.44	0.44	0.45	0.47	0.50	0.53
	12	2.25	100.0	6898	NAV	0.43	0.44	0.44	0.46	0.49	0.52	100.0	6922	NAV	0.43	0.44	0.45	0.46	0.49	0.52
	20	2.25	100.0	6866	NAV	0.43	0.43	0.44	0.46	0.49	0.52	100.0	6889	NAV	0.43	0.43	0.44	0.46	0.49	0.52
0.05	1	0.50	25.1	2449	1.52	0.22	0.23	0.24	0.26	0.30	0.34	24.3	2355	1.52	0.21	0.22	0.22	0.24	0.28	0.32
	2	0.50	48.6	2314	1.52	0.20	0.21	0.22	0.24	0.28	0.32	47.9	2336	1.52	0.21	0.21	0.22	0.24	0.28	0.32
	3	0.50	73.7	2373	1.52	0.21	0.22	0.23	0.25	0.29	0.32	71.9	2343	1.52	0.21	0.21	0.22	0.24	0.28	0.32
	4	0.50	94.8	2211	1.52	0.19	0.20	0.21	0.23	0.27	0.31	93.8	2225	NAV	0.19	0.20	0.21	0.23	0.27	0.31
	6	0.50	100.0	1741	NAV	0.13	0.14	0.15	0.17	0.21	0.25	100.0	1764	NAV	0.13	0.14	0.15	0.17	0.21	0.25
	8	0.50	99.0	1720	NAV	0.13	0.14	0.15	0.17	0.21	0.25	98.7	1736	NAV	0.13	0.14	0.15	0.17	0.21	0.25
	12	0.50	100.0	1610	NAV	0.12	0.13	0.14	0.15	0.19	0.23	100.0	1632	NAV	0.12	0.13	0.14	0.16	0.20	0.24
	20	0.50	100.0	1581	NAV	0.12	0.12	0.13	0.15	0.19	0.23	100.0	1601	NAV	0.12	0.13	0.14	0.15	0.19	0.23
0.10	1	0.13	25.8	1483	1.97	0.17	0.18	0.19	0.21	0.25	0.29	25.2	1534	1.97	0.18	0.19	0.20	0.21	0.25	0.30
	2	0.13	50.9	1421	1.97	0.16	0.17	0.18	0.20	0.24	0.29	49.6	1424	1.97	0.16	0.17	0.18	0.20	0.24	0.29
	3	0.13	75.9	1398	1.97	0.16	0.17	0.18	0.20	0.24	0.29	74.8	1441	1.97	0.16	0.17	0.18	0.20	0.24	0.29
	4	0.13	93.7	1187	1.97	0.13	0.14	0.14	0.16	0.21	0.26	93.0	1235	1.97	0.13	0.14	0.15	0.17	0.22	0.26
	6	0.13	100.0	737	NAV	0.06	0.07	0.08	0.10	0.14	0.19	100.0	764	NAV	0.06	0.07	0.08	0.10	0.15	0.19
	8	0.13	99.3	704	NAV	0.06	0.07	0.08	0.10	0.14	0.19	99.3	735	NAV	0.07	0.07	0.08	0.10	0.14	0.19
	12	0.13	100.0	587	NAV	0.05	0.06	0.06	0.08	0.12	0.17	100.0	607	NAV	0.05	0.06	0.07	0.09	0.13	0.17
	20	0.13	100.0	561	NAV	0.04	0.05	0.06	0.08	0.12	0.17	100.0	578	NAV	0.05	0.05	0.06	0.08	0.12	0.17
0.50	1	0.015	64.9	1878	6.71	1.31	1.36	1.40	1.50	1.72	1.99	63.1	1871	6.77	1.26	1.33	1.40	1.53	1.78	2.04
	2	0.015	99.7	985	NAV	0.54	0.59	0.66	0.78	1.03	1.29	99.5	1059	NAV	0.58	0.64	0.70	0.83	1.08	1.33
	3	0.015	100.0	508	NAV	0.25	0.31	0.37	0.50	0.74	0.99	100.0	540	NAV	0.27	0.33	0.39	0.52	0.76	1.01
	4	0.015	100.0	366	NAV	0.17	0.23	0.29	0.42	0.67	0.92	100.0	391	NAV	0.19	0.25	0.31	0.44	0.69	0.93
	6	0.015	100.0	269	NAV	0.11	0.17	0.23	0.36	0.60	0.86	100.0	288	NAV	0.12	0.18	0.25	0.37	0.62	0.88
	8	0.015	100.0	250	NAV	0.11	0.16	0.22	0.35	0.60	0.85	100.0	267	NAV	0.12	0.18	0.24	0.37	0.61	0.87
	12	0.015	100.0	210	NAV	0.08	0.13	0.19	0.33	0.56	0.83	100.0	228	NAV	0.09	0.15	0.21	0.34	0.58	0.84
	20	0.015	100.0	195	NAV	0.07	0.12	0.18	0.31	0.55	0.82	100.0	214	NAV	0.08	0.13	0.19	0.33	0.56	0.83

Table B.27: Precipitation triggered pollution detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area for various RADTi in case of $\sigma^2_{\ln K} = 0.0$ assuming every 4 months (4M) and biannually (6M) sampling frequencies

$\sigma^2_{\ln K}$											0.00									
α_T(m)	now	nfds(max)	P_d (4M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L	P_d (6M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	**1**	3.00	6.9	9390	0.36	0.29	0.30	0.30	0.31	0.31	0.21	6.8	9415	0.36	0.29	0.30	0.30	0.30	0.29	0.18
	2	3.00	15.6	9650	0.36	0.31	0.31	0.31	0.31	0.31	0.23	14.7	9645	0.36	0.30	0.31	0.31	0.32	0.31	0.20
	3	3.00	23.3	9608	0.36	0.30	0.30	0.31	0.31	0.31	0.25	22.7	9614	0.36	0.30	0.31	0.31	0.31	0.31	0.23
	4	3.00	29.8	9601	0.36	0.30	0.31	0.31	0.32	0.31	0.24	29.3	9627	0.36	0.30	0.31	0.31	0.31	0.30	0.22
	6	3.00	46.3	9645	0.36	0.30	0.31	0.31	0.31	0.31	0.23	44.8	9660	0.36	0.31	0.31	0.31	0.31	0.30	0.21
	8	3.00	60.0	9617	0.35	0.30	0.31	0.31	0.32	0.32	0.25	58.3	9632	0.36	0.31	0.31	0.31	0.31	0.30	0.22
	12	3.00	87.5	9628	0.35	0.30	0.31	0.31	0.32	0.31	0.24	86.0	9649	0.35	0.31	0.31	0.31	0.31	0.30	0.21
	20	3.00	100.0	9520	NAV	0.30	0.30	0.31	0.31	0.33	0.27	100.0	9549	NAV	0.30	0.30	0.31	0.31	0.32	0.24
0.01	**1**	2.25	19.1	7379	0.80	0.47	0.47	0.48	0.50	0.52	0.55	18.5	7369	0.80	0.47	0.48	0.48	0.50	0.53	0.55
	2	2.25	38.0	7350	0.80	0.47	0.47	0.48	0.49	0.51	0.54	36.5	7344	0.80	0.47	0.47	0.48	0.49	0.52	0.54
	3	2.25	56.6	7332	0.80	0.47	0.47	0.48	0.49	0.52	0.54	55.0	7347	0.80	0.47	0.47	0.48	0.49	0.52	0.54
	4	2.25	75.8	7299	0.80	0.46	0.47	0.47	0.49	0.51	0.54	74.2	7322	0.80	0.46	0.47	0.48	0.49	0.52	0.54
	6	2.25	100.0	7125	NAV	0.45	0.45	0.46	0.48	0.51	0.54	99.9	7178	NAV	0.45	0.46	0.47	0.48	0.51	0.55
	8	2.25	96.8	7022	NAV	0.44	0.45	0.45	0.47	0.50	0.53	96.6	7054	NAV	0.44	0.45	0.46	0.47	0.50	0.53
	12	2.25	100.0	6944	NAV	0.43	0.44	0.45	0.46	0.49	0.53	100.0	6976	NAV	0.43	0.44	0.45	0.47	0.50	0.53
	20	2.25	100.0	6907	NAV	0.43	0.44	0.44	0.46	0.49	0.52	100.0	6940	NAV	0.43	0.44	0.45	0.46	0.49	0.53
0.05	**1**	0.50	24.5	2481	1.52	0.22	0.23	0.24	0.26	0.30	0.34	23.8	2457	1.52	0.22	0.23	0.24	0.26	0.30	0.33
	2	0.50	47.0	2327	1.52	0.20	0.21	0.22	0.24	0.28	0.32	46.6	2403	1.52	0.21	0.22	0.23	0.25	0.29	0.33
	3	0.50	71.6	2402	1.52	0.21	0.22	0.23	0.25	0.29	0.33	70.0	2410	1.52	0.21	0.22	0.23	0.25	0.29	0.33
	4	0.50	93.0	2271	1.51	0.20	0.20	0.21	0.23	0.27	0.31	92.0	2327	1.51	0.20	0.21	0.22	0.24	0.28	0.32
	6	0.50	100.0	1791	NAV	0.14	0.15	0.15	0.17	0.21	0.26	100.0	1829	NAV	0.14	0.15	0.16	0.18	0.22	0.26
	8	0.50	98.8	1755	NAV	0.13	0.14	0.15	0.17	0.21	0.25	98.6	1791	NAV	0.14	0.15	0.16	0.17	0.21	0.25
	12	0.50	100.0	1651	NAV	0.12	0.13	0.14	0.16	0.20	0.24	100.0	1687	NAV	0.13	0.13	0.14	0.16	0.20	0.24
	20	0.50	100.0	1619	NAV	0.12	0.13	0.14	0.16	0.19	0.24	100.0	1652	NAV	0.12	0.13	0.14	0.16	0.20	0.24
0.10	**1**	0.13	25.0	1560	1.97	0.18	0.19	0.20	0.22	0.26	0.30	24.7	1624	1.97	0.19	0.20	0.21	0.22	0.26	0.31
	2	0.13	49.6	1509	1.97	0.18	0.18	0.19	0.21	0.25	0.30	48.3	1512	1.97	0.17	0.18	0.19	0.21	0.25	0.29
	3	0.13	74.2	1481	1.97	0.17	0.18	0.19	0.21	0.26	0.30	72.4	1502	1.97	0.17	0.18	0.19	0.21	0.25	0.30
	4	0.13	92.2	1244	1.97	0.13	0.14	0.15	0.17	0.22	0.27	91.4	1288	1.97	0.14	0.15	0.16	0.18	0.22	0.27
	6	0.13	100.0	791	NAV	0.07	0.08	0.09	0.11	0.15	0.20	100.0	834	NAV	0.07	0.08	0.09	0.11	0.16	0.20
	8	0.13	99.2	747	NAV	0.07	0.07	0.08	0.10	0.15	0.19	99.0	779	NAV	0.07	0.08	0.09	0.11	0.15	0.20
	12	0.13	100.0	622	NAV	0.05	0.06	0.07	0.09	0.13	0.17	100.0	654	NAV	0.05	0.06	0.07	0.09	0.13	0.18
	20	0.13	100.0	596	NAV	0.05	0.06	0.07	0.08	0.13	0.17	100.0	627	NAV	0.05	0.06	0.07	0.09	0.13	0.18
0.50	**1**	0.015	61.5	1838	NAV	1.26	1.31	1.38	1.51	1.76	2.01	59.8	1863	NAV	1.30	1.37	1.43	1.57	1.81	2.08
	2	0.015	99.5	1117	NAV	0.62	0.68	0.74	0.87	1.12	1.37	99.0	1200	NAV	0.67	0.73	0.79	0.92	1.17	1.43
	3	0.015	100.0	567	NAV	0.29	0.35	0.42	0.54	0.79	1.03	100.0	613	NAV	0.31	0.38	0.44	0.56	0.81	1.05
	4	0.015	100.0	411	NAV	0.21	0.27	0.33	0.46	0.71	0.95	100.0	450	NAV	0.23	0.29	0.35	0.47	0.73	0.96
	6	0.015	100.0	308	NAV	0.14	0.20	0.26	0.39	0.63	0.89	100.0	337	NAV	0.16	0.22	0.28	0.41	0.66	0.90
	8	0.015	100.0	287	NAV	0.14	0.19	0.25	0.38	0.63	0.88	100.0	320	NAV	0.15	0.21	0.27	0.40	0.65	0.90
	12	0.015	100.0	246	NAV	0.10	0.16	0.22	0.35	0.59	0.86	100.0	284	NAV	0.13	0.19	0.25	0.38	0.62	0.88
	20	0.015	100.0	232	NAV	0.09	0.15	0.21	0.34	0.58	0.84	100.0	272	NAV	0.12	0.17	0.23	0.36	0.61	0.86

Table B.28: Precipitation triggered pollution detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area for various RADTi in case of $\sigma^2_{\ln K} = 0.0$ assuming annually sampling frequency

$\sigma^2_{\ln K}$						0.00					
α_T(m)	now	nfds(max)	P_d (12M)	<T(DET.)> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	1	3.00	6.6	9488	0.36	0.30	0.30	0.30	0.31	0.32	0.23
	2	3.00	14.6	9735	0.36	0.31	0.31	0.31	0.32	0.32	0.24
	3	3.00	22.4	9719	0.36	0.31	0.31	0.31	0.32	0.32	0.27
	4	3.00	28.2	9716	0.36	0.31	0.31	0.31	0.32	0.32	0.26
	6	3.00	44.0	9759	0.36	0.31	0.31	0.31	0.32	0.32	0.25
	8	3.00	57.8	9741	0.36	0.31	0.31	0.31	0.32	0.32	0.25
	12	3.00	84.0	9750	0.35	0.31	0.31	0.31	0.32	0.32	0.25
	20	3.00	100.0	9652	NAV	0.30	0.31	0.31	0.32	0.33	0.28
0.01	1	2.25	18.1	7477	0.80	0.48	0.48	0.49	0.50	0.53	0.55
	2	2.25	35.3	7453	0.80	0.48	0.47	0.48	0.50	0.53	0.55
	3	2.25	53.4	7435	0.80	0.47	0.48	0.48	0.50	0.53	0.55
	4	2.25	72.1	7422	0.80	0.47	0.48	0.48	0.50	0.53	0.56
	6	2.25	99.7	7316	NAV	0.46	0.47	0.48	0.49	0.53	0.56
	8	2.25	96.2	7152	NAV	0.45	0.46	0.46	0.48	0.51	0.54
	12	2.25	100.0	7074	NAV	0.44	0.45	0.46	0.47	0.51	0.54
	20	2.25	100.0	7042	NAV	0.44	0.45	0.46	0.47	0.50	0.54
0.05	1	0.50	22.7	2582	1.52	0.23	0.24	0.25	0.27	0.31	0.34
	2	0.50	45.2	2513	1.52	0.23	0.23	0.24	0.26	0.30	0.34
	3	0.50	67.2	2494	1.52	0.22	0.23	0.24	0.26	0.30	0.34
	4	0.50	89.7	2426	1.51	0.21	0.22	0.23	0.25	0.29	0.33
	6	0.50	100.0	1931	NAV	0.15	0.16	0.17	0.19	0.23	0.27
	8	0.50	98.4	1887	NAV	0.15	0.16	0.17	0.18	0.22	0.27
	12	0.50	100.0	1778	NAV	0.13	0.14	0.15	0.17	0.21	0.25
	20	0.50	100.0	1742	NAV	0.13	0.14	0.15	0.17	0.21	0.25
0.10	1	0.13	23.3	1574	1.97	0.18	0.19	0.20	0.22	0.27	0.31
	2	0.13	47.0	1656	1.97	0.20	0.20	0.21	0.24	0.28	0.33
	3	0.13	69.0	1584	1.97	0.18	0.19	0.20	0.22	0.27	0.31
	4	0.13	89.4	1446	1.97	0.16	0.17	0.18	0.20	0.25	0.30
	6	0.13	99.9	945	NAV	0.09	0.09	0.11	0.13	0.17	0.22
	8	0.13	98.7	878	NAV	0.08	0.09	0.10	0.12	0.16	0.21
	12	0.13	100.0	741	NAV	0.06	0.07	0.08	0.10	0.14	0.19
	20	0.13	100.0	715	NAV	0.06	0.07	0.08	0.10	0.14	0.19
0.50	1	0.015	57.2	2063	6.79	1.50	1.50	1.57	1.70	1.93	2.18
	2	0.015	97.9	1439	NAV	0.83	0.89	0.95	1.07	1.33	1.58
	3	0.015	100.0	739	NAV	0.40	0.46	0.52	0.64	0.90	1.13
	4	0.015	100.0	561	NAV	0.31	0.37	0.43	0.55	0.80	1.03
	6	0.015	100.0	445	NAV	0.25	0.30	0.36	0.48	0.75	0.96
	8	0.015	100.0	435	NAV	0.24	0.29	0.35	0.47	0.73	0.96
	12	0.015	100.0	406	NAV	0.21	0.26	0.32	0.44	0.70	0.93
	20	0.015	100.0	395	NAV	0.18	0.23	0.29	0.42	0.68	0.92

Table B.29: Precipitation triggered pollution detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area for various RADTi in case of $\sigma^2_{\ln K} = 1.0$ assuming daily (ED) and monthly (1M) sampling frequencies

$\sigma^2_{\ln K}$											1.00											
α_T(m)	now	nfds(max)	P_d (ED)	$<T_{(DET.)}>$ (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L	P_d (1M)	$<T_{(DET.)}>$ (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	1	1.75	8.4	5827	0.61	0.22	0.23	0.23	0.24	0.25	0.26	8.2	5824	0.61	0.22	0.23	0.23	0.24	0.25	0.26
	2	1.75	18.2	5770	0.59	0.23	0.23	0.24	0.24	0.26	0.27	17.8	5805	0.59	0.23	0.23	0.24	0.24	0.26	0.27
	3	1.75	24.9	5686	0.61	0.22	0.23	0.23	0.24	0.25	0.27	24.4	5699	0.61	0.22	0.23	0.23	0.24	0.26	0.27
	4	1.75	31.4	5688	0.57	0.22	0.22	0.23	0.24	0.25	0.27	30.4	5685	0.57	0.22	0.22	0.23	0.23	0.26	0.27
	6	1.75	46.4	5614	0.59	0.21	0.22	0.22	0.23	0.25	0.27	45.2	5614	0.59	0.21	0.22	0.22	0.23	0.25	0.27
	8	1.75	56.7	5557	0.65	0.20	0.21	0.21	0.22	0.24	0.26	55.3	5585	0.65	0.21	0.21	0.22	0.22	0.24	0.26
	12	1.75	71.8	5496	0.54	0.20	0.20	0.20	0.21	0.23	0.26	70.3	5496	0.59	0.20	0.20	0.20	0.21	0.23	0.25
	20	1.75	83.0	5340	NAV	0.18	0.19	0.19	0.20	0.22	0.24	82.7	5384	NAV	0.19	0.19	0.20	0.20	0.22	0.24
0.01	1	1.25	22.2	4430	1.32	0.32	0.33	0.34	0.36	0.39	0.43	21.9	4505	1.32	0.33	0.34	0.35	0.37	0.40	0.44
	2	1.25	41.1	4237	1.26	0.31	0.32	0.33	0.35	0.39	0.43	40.5	4266	1.26	0.31	0.32	0.33	0.35	0.39	0.43
	3	1.25	55.8	4211	1.29	0.30	0.31	0.32	0.34	0.38	0.42	54.7	4263	1.29	0.31	0.32	0.33	0.35	0.38	0.43
	4	1.25	67.3	4123	1.23	0.28	0.29	0.30	0.32	0.36	0.40	66.2	4139	1.22	0.29	0.30	0.31	0.33	0.37	0.41
	6	1.25	80.7	3955	1.25	0.26	0.27	0.27	0.29	0.33	0.37	80.2	3996	1.25	0.26	0.27	0.28	0.30	0.34	0.38
	8	1.25	82.8	3848	1.29	0.24	0.24	0.25	0.27	0.31	0.35	82.3	3892	1.29	0.24	0.25	0.26	0.28	0.32	0.36
	12	1.25	90.9	3751	1.30	0.22	0.23	0.24	0.26	0.30	0.34	90.6	3793	1.29	0.23	0.24	0.25	0.27	0.31	0.35
	20	1.25	92.6	3676	1.26	0.22	0.23	0.23	0.25	0.29	0.33	92.5	3714	NAV	0.22	0.23	0.24	0.26	0.29	0.34
0.05	1	0.13	21.3	1420	2.20	0.14	0.15	0.16	0.18	0.23	0.28	20.8	1514	2.20	0.16	0.17	0.18	0.20	0.25	0.30
	2	0.13	42.0	1401	2.21	0.13	0.13	0.14	0.16	0.20	0.25	41.0	1501	2.21	0.15	0.16	0.17	0.18	0.22	0.27
	3	0.13	58.4	1412	2.22	0.13	0.14	0.15	0.17	0.21	0.26	56.7	1510	2.24	0.14	0.15	0.16	0.18	0.23	0.28
	4	0.13	71.6	1355	2.24	0.13	0.14	0.15	0.16	0.21	0.26	70.0	1389	2.26	0.13	0.14	0.15	0.17	0.21	0.27
	6	0.13	91.0	1108	2.22	0.08	0.09	0.10	0.12	0.17	0.21	89.2	1143	2.23	0.09	0.10	0.11	0.13	0.17	0.22
	8	0.13	92.3	898	NAV	0.06	0.06	0.07	0.09	0.13	0.18	91.9	947	2.21	0.06	0.07	0.08	0.10	0.14	0.19
	12	0.13	97.1	771	NAV	0.04	0.05	0.06	0.08	0.12	0.16	97.1	807	NAV	0.05	0.05	0.06	0.08	0.12	0.17
	20	0.13	97.9	741	NAV	0.04	0.05	0.06	0.07	0.11	0.16	97.7	768	NAV	0.04	0.05	0.06	0.08	0.12	0.16
0.10	1	0.06	28.5	1343	2.60	0.18	0.19	0.20	0.23	0.29	0.35	27.4	1459	2.60	0.20	0.21	0.23	0.26	0.31	0.38
	2	0.06	56.3	1320	2.61	0.17	0.18	0.19	0.22	0.27	0.33	54.4	1328	2.61	0.17	0.18	0.19	0.22	0.27	0.33
	3	0.06	76.5	1205	2.60	0.15	0.16	0.17	0.20	0.25	0.31	74.1	1259	2.61	0.15	0.16	0.18	0.20	0.26	0.32
	4	0.06	88.4	1086	NAV	0.12	0.13	0.15	0.17	0.23	0.28	86.6	1190	2.71	0.14	0.15	0.16	0.19	0.25	0.30
	6	0.06	98.0	720	NAV	0.06	0.07	0.08	0.10	0.16	0.22	97.8	786	2.22	0.07	0.08	0.09	0.12	0.17	0.23
	8	0.06	96.2	612	NAV	0.05	0.06	0.07	0.09	0.14	0.20	95.9	651	2.48	0.05	0.06	0.07	0.09	0.15	0.20
	12	0.06	99.6	521	NAV	0.04	0.05	0.06	0.08	0.13	0.18	99.3	556	NAV	0.04	0.05	0.06	0.08	0.13	0.19
	20	0.06	99.8	477	NAV	0.03	0.04	0.05	0.07	0.12	0.18	99.7	511	NAV	0.04	0.05	0.06	0.08	0.13	0.18
0.50	1	0.015	90.9	1872	NAV	1.10	1.15	1.20	1.30	1.53	1.77	86.9	2006	NAV	1.19	1.25	1.30	1.43	1.65	1.89
	2	0.015	99.9	662	NAV	0.29	0.34	0.40	0.52	0.77	1.02	99.8	777	NAV	0.36	0.41	0.47	0.60	0.84	1.10
	3	0.015	100.0	424	NAV	0.17	0.21	0.27	0.39	0.64	0.89	100.0	498	NAV	0.22	0.27	0.32	0.45	0.69	0.95
	4	0.015	100.0	322	NAV	0.12	0.16	0.20	0.33	0.58	0.83	100.0	383	NAV	0.15	0.20	0.25	0.38	0.62	0.88
	6	0.015	100.0	241	NAV	0.08	0.11	0.16	0.28	0.52	0.78	100.0	289	NAV	0.10	0.14	0.19	0.32	0.56	0.82
	8	0.015	100.0	230	NAV	0.08	0.11	0.16	0.27	0.52	0.78	100.0	275	NAV	0.10	0.14	0.19	0.31	0.56	0.82
	12	0.015	100.0	188	NAV	0.06	0.09	0.13	0.25	0.49	0.75	100.0	226	NAV	0.08	0.12	0.16	0.28	0.53	0.79
	20	0.015	100.0	174	NAV	0.05	0.08	0.12	0.24	0.48	0.74	100.0	208	NAV	0.07	0.11	0.15	0.27	0.51	0.77

Table B.30: Precipitation triggered pollution detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area for various RADTi in case of $\sigma^2_{\ln K} = 1.0$ assuming bimonthly (2M) and quarterly (3M) sampling frequencies

	$\sigma^2_{\ln K}$									1.00										
α_T(m)	now	nfds(max)	P_d (2M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L	P_d (3M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	1	1.75	8.1	5788	0.61	0.22	0.22	0.22	0.23	0.25	0.26	8.0	5800	0.61	0.22	0.22	0.23	0.24	0.25	0.26
	2	1.75	17.2	5781	0.59	0.23	0.23	0.24	0.24	0.26	0.27	17.2	5850	0.59	0.23	0.24	0.24	0.25	0.26	0.27
	3	1.75	23.8	5690	0.61	0.22	0.23	0.23	0.24	0.26	0.27	23.5	5704	0.61	0.22	0.23	0.23	0.24	0.26	0.27
	4	1.75	29.9	5725	0.57	0.22	0.22	0.23	0.24	0.26	0.28	29.7	5746	0.57	0.22	0.23	0.23	0.24	0.26	0.28
	6	1.75	44.2	5631	0.59	0.21	0.22	0.22	0.23	0.25	0.27	43.9	5685	0.59	0.22	0.22	0.23	0.23	0.25	0.27
	8	1.75	54.6	5630	0.65	0.21	0.21	0.22	0.23	0.24	0.26	54.3	5651	0.65	0.21	0.22	0.22	0.23	0.25	0.27
	12	1.75	69.8	5531	0.59	0.20	0.20	0.21	0.22	0.24	0.26	69.1	5554	0.59	0.20	0.20	0.21	0.22	0.24	0.26
	20	1.75	82.4	5411	NAV	0.19	0.19	0.20	0.21	0.23	0.25	82.1	5432	NAV	0.19	0.19	0.20	0.21	0.23	0.25
0.01	1	1.25	21.7	4558	1.32	0.34	0.35	0.36	0.37	0.41	0.45	21.3	4577	1.32	0.34	0.35	0.36	0.37	0.41	0.45
	2	1.25	40.0	4331	1.28	0.32	0.33	0.34	0.36	0.40	0.43	39.2	4351	1.26	0.33	0.33	0.34	0.36	0.40	0.44
	3	1.25	54.2	4321	1.29	0.32	0.33	0.34	0.36	0.39	0.43	53.1	4308	1.29	0.31	0.32	0.33	0.35	0.39	0.44
	4	1.25	65.3	4161	1.22	0.29	0.30	0.31	0.33	0.37	0.42	64.7	4212	1.23	0.30	0.31	0.32	0.34	0.38	0.42
	6	1.25	79.5	4042	1.31	0.27	0.27	0.28	0.30	0.34	0.38	78.9	4055	1.25	0.27	0.28	0.29	0.31	0.35	0.39
	8	1.25	81.8	3925	1.28	0.25	0.25	0.26	0.28	0.32	0.36	81.6	3963	1.29	0.25	0.26	0.27	0.29	0.33	0.37
	12	1.25	90.3	3826	1.28	0.23	0.24	0.25	0.27	0.31	0.35	90.2	3850	1.28	0.23	0.24	0.25	0.27	0.31	0.35
	20	1.25	92.3	3747	NAV	0.22	0.23	0.24	0.26	0.30	0.34	92.1	3770	NAV	0.22	0.23	0.24	0.26	0.30	0.34
0.05	1	0.13	20.3	1503	2.21	0.15	0.16	0.17	0.19	0.24	0.30	19.9	1522	2.21	0.15	0.16	0.17	0.19	0.24	0.30
	2	0.13	40.3	1592	2.21	0.16	0.17	0.18	0.20	0.24	0.29	39.9	1592	2.21	0.16	0.17	0.17	0.19	0.23	0.28
	3	0.13	55.8	1562	2.24	0.15	0.16	0.17	0.19	0.24	0.29	54.9	1573	2.23	0.16	0.16	0.17	0.20	0.24	0.29
	4	0.13	69.1	1467	2.26	0.14	0.15	0.16	0.18	0.23	0.28	67.6	1432	2.26	0.13	0.14	0.15	0.17	0.22	0.27
	6	0.13	88.4	1186	2.21	0.10	0.11	0.11	0.13	0.18	0.23	87.9	1202	2.22	0.10	0.10	0.11	0.14	0.18	0.23
	8	0.13	91.6	978	2.21	0.06	0.07	0.08	0.10	0.14	0.19	91.4	1003	2.25	0.07	0.08	0.08	0.10	0.15	0.20
	12	0.13	97.0	834	NAV	0.05	0.06	0.06	0.08	0.12	0.17	97.0	853	NAV	0.05	0.06	0.07	0.08	0.13	0.17
	20	0.13	97.7	793	NAV	0.05	0.05	0.06	0.08	0.12	0.17	97.7	810	NAV	0.05	0.06	0.06	0.08	0.12	0.17
0.10	1	0.06	27.0	1505	2.60	0.21	0.22	0.24	0.26	0.31	0.38	26.5	1531	2.60	0.21	0.22	0.24	0.27	0.32	0.38
	2	0.06	53.4	1369	2.61	0.18	0.19	0.20	0.22	0.28	0.34	53.0	1436	2.61	0.19	0.20	0.22	0.24	0.29	0.35
	3	0.06	73.0	1317	2.61	0.16	0.18	0.19	0.21	0.26	0.32	71.8	1344	2.62	0.17	0.18	0.19	0.22	0.27	0.33
	4	0.06	85.7	1261	2.70	0.16	0.17	0.18	0.21	0.27	0.32	84.3	1276	2.70	0.16	0.17	0.18	0.21	0.25	0.31
	6	0.06	97.4	824	2.29	0.08	0.09	0.10	0.12	0.18	0.24	97.0	844	NAV	0.08	0.09	0.10	0.12	0.18	0.24
	8	0.06	95.8	698	2.48	0.06	0.07	0.08	0.10	0.15	0.21	95.6	718	NAV	0.06	0.07	0.08	0.11	0.16	0.21
	12	0.06	99.3	581	NAV	0.04	0.05	0.06	0.08	0.13	0.19	99.3	597	NAV	0.05	0.05	0.06	0.09	0.14	0.20
	20	0.06	99.7	529	NAV	0.04	0.05	0.06	0.08	0.13	0.18	99.6	545	NAV	0.04	0.05	0.06	0.08	0.13	0.19
0.50	1	0.015	84.6	2087	NAV	1.25	1.31	1.36	1.49	1.73	1.97	82.4	2056	NAV	1.25	1.31	1.37	1.50	1.76	1.99
	2	0.015	99.7	839	NAV	0.40	0.46	0.52	0.64	0.89	1.14	99.7	894	NAV	0.43	0.49	0.55	0.68	0.93	1.18
	3	0.015	100.0	541	NAV	0.24	0.29	0.35	0.48	0.72	0.98	100.0	573	NAV	0.27	0.32	0.38	0.50	0.75	1.00
	4	0.015	100.0	417	NAV	0.17	0.22	0.27	0.40	0.65	0.90	100.0	445	NAV	0.19	0.24	0.30	0.42	0.67	0.93
	6	0.015	100.0	316	NAV	0.12	0.16	0.21	0.34	0.58	0.84	100.0	338	NAV	0.13	0.18	0.23	0.36	0.60	0.86
	8	0.015	100.0	302	NAV	0.12	0.16	0.21	0.33	0.58	0.84	100.0	322	NAV	0.13	0.17	0.23	0.35	0.59	0.85
	12	0.015	100.0	249	NAV	0.09	0.13	0.18	0.30	0.55	0.81	100.0	269	NAV	0.10	0.14	0.19	0.32	0.56	0.82
	20	0.015	100.0	230	NAV	0.08	0.12	0.16	0.29	0.53	0.79	100.0	248	NAV	0.09	0.13	0.18	0.30	0.54	0.80

Table B.31: Precipitation triggered pollution detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area for various RADTi in case of $\sigma^2_{\ln K} = 1.0$ assuming every 4 months (4M) and biannually (6M) sampling frequencies

$\sigma^2_{\ln K}$										1.00										
α_T(m)	now	nfds(max)	P_d (4M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L	P_d (6M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	1	1.75	8.0	5845	0.61	0.22	0.23	0.23	0.24	0.25	0.27	7.8	5808	0.61	0.22	0.23	0.23	0.24	0.25	0.27
	2	1.75	16.8	5805	0.59	0.23	0.24	0.24	0.25	0.27	0.28	16.7	5883	0.59	0.24	0.24	0.24	0.25	0.27	0.28
	3	1.75	23.5	5726	0.61	0.22	0.23	0.23	0.24	0.26	0.28	22.9	5749	0.61	0.23	0.23	0.23	0.24	0.26	0.28
	4	1.75	29.4	5762	0.57	0.22	0.23	0.23	0.24	0.26	0.28	28.8	5794	0.57	0.23	0.23	0.23	0.24	0.27	0.28
	6	1.75	43.6	5702	0.59	0.22	0.22	0.23	0.24	0.26	0.27	42.8	5719	0.59	0.22	0.23	0.23	0.24	0.26	0.28
	8	1.75	53.6	5667	0.65	0.21	0.22	0.22	0.23	0.25	0.27	53.0	5691	0.65	0.21	0.22	0.22	0.23	0.25	0.27
	12	1.75	68.9	5577	0.59	0.20	0.20	0.21	0.22	0.24	0.26	68.4	5626	0.59	0.21	0.21	0.21	0.22	0.24	0.26
	20	1.75	82.0	5446	NAV	0.19	0.20	0.20	0.21	0.23	0.25	81.6	5472	NAV	0.19	0.20	0.20	0.21	0.23	0.25
0.01	1	1.25	21.3	4591	1.32	0.34	0.35	0.36	0.38	0.42	0.45	20.8	4580	1.32	0.34	0.35	0.36	0.38	0.42	0.46
	2	1.25	39.0	4369	1.28	0.32	0.33	0.34	0.36	0.39	0.44	38.4	4421	1.28	0.33	0.34	0.35	0.37	0.41	0.44
	3	1.25	52.6	4325	1.29	0.32	0.33	0.34	0.36	0.40	0.44	51.6	4355	1.29	0.32	0.33	0.34	0.36	0.40	0.45
	4	1.25	64.5	4247	1.23	0.30	0.31	0.32	0.34	0.38	0.43	63.6	4280	1.23	0.31	0.32	0.33	0.35	0.39	0.43
	6	1.25	78.5	4106	1.31	0.27	0.28	0.29	0.31	0.35	0.39	77.8	4134	1.31	0.28	0.29	0.30	0.32	0.36	0.40
	8	1.25	81.2	3975	1.28	0.25	0.26	0.27	0.29	0.33	0.37	81.1	4036	1.28	0.26	0.27	0.28	0.30	0.34	0.38
	12	1.25	90.1	3882	1.28	0.24	0.25	0.26	0.28	0.32	0.36	89.9	3914	1.27	0.24	0.25	0.26	0.28	0.32	0.36
	20	1.25	92.1	3803	NAV	0.23	0.24	0.25	0.27	0.30	0.35	91.9	3835	NAV	0.23	0.24	0.25	0.27	0.31	0.35
0.05	1	0.13	19.9	1608	2.21	0.17	0.18	0.19	0.21	0.26	0.31	19.4	1535	2.20	0.15	0.16	0.17	0.19	0.24	0.30
	2	0.13	39.6	1609	2.21	0.16	0.17	0.18	0.20	0.25	0.30	38.9	1669	2.21	0.17	0.18	0.19	0.21	0.26	0.30
	3	0.13	54.6	1614	2.23	0.16	0.17	0.18	0.20	0.25	0.30	53.6	1644	2.23	0.16	0.17	0.18	0.20	0.25	0.30
	4	0.13	67.4	1479	2.26	0.14	0.15	0.16	0.18	0.23	0.28	66.2	1546	2.25	0.15	0.16	0.17	0.19	0.24	0.28
	6	0.13	88.0	1265	2.20	0.11	0.12	0.13	0.15	0.19	0.24	86.6	1277	2.23	0.11	0.12	0.12	0.15	0.19	0.24
	8	0.13	91.3	1031	2.21	0.07	0.08	0.09	0.11	0.15	0.20	90.9	1077	2.24	0.08	0.09	0.10	0.12	0.16	0.21
	12	0.13	97.0	878	NAV	0.05	0.06	0.07	0.09	0.13	0.18	96.8	907	NAV	0.05	0.06	0.07	0.09	0.13	0.18
	20	0.13	97.7	829	NAV	0.05	0.06	0.07	0.08	0.13	0.17	97.5	850	NAV	0.05	0.06	0.07	0.08	0.13	0.17
0.10	1	0.06	26.1	1546	2.60	0.22	0.24	0.25	0.27	0.33	0.39	25.6	1552	2.60	0.22	0.23	0.24	0.27	0.33	0.39
	2	0.06	52.6	1504	2.61	0.20	0.21	0.23	0.25	0.30	0.36	50.8	1420	2.62	0.18	0.19	0.20	0.23	0.29	0.35
	3	0.06	71.3	1372	2.62	0.17	0.19	0.20	0.22	0.27	0.34	70.0	1390	2.61	0.17	0.19	0.20	0.23	0.28	0.35
	4	0.06	83.8	1283	2.68	0.16	0.17	0.18	0.20	0.26	0.32	82.6	1345	2.68	0.17	0.18	0.19	0.22	0.27	0.33
	6	0.06	97.0	894	2.51	0.09	0.10	0.11	0.13	0.19	0.25	96.4	930	2.51	0.09	0.10	0.11	0.14	0.19	0.25
	8	0.06	95.4	733	2.54	0.06	0.07	0.08	0.11	0.16	0.22	95.3	756	2.54	0.07	0.08	0.09	0.11	0.16	0.22
	12	0.06	99.2	616	NAV	0.05	0.06	0.07	0.09	0.14	0.20	99.2	655	NAV	0.05	0.06	0.07	0.10	0.15	0.21
	20	0.06	99.7	565	NAV	0.04	0.05	0.06	0.08	0.13	0.19	99.6	600	NAV	0.05	0.05	0.06	0.09	0.14	0.20
0.50	1	0.015	81.4	2147	NAV	1.33	1.39	1.45	1.58	1.82	2.06	78.8	2138	NAV	1.35	1.42	1.47	1.60	1.83	2.05
	2	0.015	99.5	941	NAV	0.46	0.52	0.58	0.71	0.95	1.21	99.6	1018	NAV	0.51	0.57	0.63	0.75	1.00	1.26
	3	0.015	99.9	597	NAV	0.28	0.33	0.39	0.52	0.77	1.02	99.9	647	NAV	0.31	0.36	0.42	0.55	0.80	1.05
	4	0.015	100.0	467	NAV	0.20	0.25	0.31	0.43	0.68	0.94	100.0	511	NAV	0.23	0.28	0.34	0.47	0.72	0.97
	6	0.015	100.0	357	NAV	0.14	0.19	0.24	0.37	0.61	0.87	100.0	393	NAV	0.16	0.21	0.27	0.39	0.64	0.90
	8	0.015	100.0	343	NAV	0.14	0.18	0.24	0.36	0.61	0.87	100.0	381	NAV	0.16	0.21	0.26	0.39	0.63	0.89
	12	0.015	100.0	286	NAV	0.11	0.15	0.21	0.33	0.57	0.83	100.0	326	NAV	0.13	0.18	0.23	0.36	0.60	0.86
	20	0.015	100.0	268	NAV	0.10	0.14	0.19	0.31	0.56	0.82	100.0	307	NAV	0.11	0.16	0.21	0.34	0.58	0.84

Table B.32: Precipitation triggered pollution detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area for various RADTi in case of $\sigma^2_{\ln K} = 1.0$ assuming annually sampling frequency

$\sigma^2_{\ln K}$						1.00					
α_T(m)	now	nfds(max)	P_d (12M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	1	1.75	7.8	5968	0.61	0.23	0.23	0.24	0.25	0.26	0.28
	2	1.75	16.3	6003	0.59	0.24	0.24	0.25	0.26	0.27	0.28
	3	1.75	22.2	5823	0.61	0.23	0.23	0.24	0.25	0.26	0.28
	4	1.75	28.3	5927	0.57	0.23	0.24	0.24	0.25	0.27	0.29
	6	1.75	41.8	5840	0.59	0.23	0.23	0.23	0.25	0.26	0.28
	8	1.75	51.9	5806	0.64	0.22	0.22	0.23	0.24	0.26	0.28
	12	1.75	67.6	5748	0.58	0.21	0.21	0.22	0.23	0.25	0.27
	20	1.75	81.0	5550	NAV	0.20	0.20	0.21	0.22	0.24	0.26
0.01	1	1.25	20.1	4720	1.32	0.35	0.36	0.37	0.39	0.43	0.47
	2	1.25	36.6	4451	1.29	0.33	0.34	0.35	0.37	0.41	0.45
	3	1.25	50.3	4502	1.29	0.34	0.34	0.35	0.37	0.41	0.45
	4	1.25	62.6	4400	1.29	0.32	0.33	0.34	0.36	0.40	0.44
	6	1.25	76.9	4256	1.35	0.29	0.30	0.31	0.33	0.37	0.42
	8	1.25	80.4	4130	1.29	0.27	0.27	0.28	0.30	0.34	0.39
	12	1.25	89.3	4022	1.28	0.25	0.26	0.27	0.29	0.33	0.38
	20	1.25	91.7	3934	1.32	0.24	0.25	0.26	0.28	0.32	0.36
0.05	1	0.13	18.5	1616	2.21	0.16	0.17	0.18	0.21	0.26	0.31
	2	0.13	37.6	1710	2.21	0.17	0.18	0.19	0.21	0.26	0.31
	3	0.13	51.1	1695	2.23	0.17	0.17	0.19	0.21	0.26	0.31
	4	0.13	63.5	1628	2.25	0.16	0.17	0.18	0.20	0.24	0.29
	6	0.13	85.5	1412	2.22	0.12	0.13	0.14	0.16	0.21	0.26
	8	0.13	90.3	1193	2.24	0.09	0.10	0.11	0.13	0.18	0.23
	12	0.13	96.8	1008	NAV	0.07	0.07	0.08	0.10	0.15	0.19
	20	0.13	97.6	951	NAV	0.06	0.07	0.08	0.10	0.14	0.19
0.10	1	0.06	24.3	1718	2.60	0.26	0.26	0.27	0.30	0.36	0.43
	2	0.06	49.2	1550	2.62	0.20	0.20	0.21	0.24	0.30	0.36
	3	0.06	67.6	1586	2.60	0.22	0.23	0.24	0.27	0.32	0.39
	4	0.06	79.9	1397	2.68	0.17	0.18	0.19	0.22	0.28	0.34
	6	0.06	95.9	1064	2.43	0.11	0.12	0.13	0.16	0.22	0.28
	8	0.06	94.7	846	2.55	0.07	0.08	0.09	0.12	0.17	0.23
	12	0.06	99.0	747	NAV	0.06	0.07	0.08	0.11	0.16	0.22
	20	0.06	99.4	701	NAV	0.06	0.07	0.08	0.10	0.15	0.21
0.50	1	0.015	75.3	2321	NAV	1.46	1.50	1.57	1.70	1.94	2.19
	2	0.015	99.0	1203	NAV	0.62	0.67	0.74	0.86	1.11	1.36
	3	0.015	99.9	775	NAV	0.39	0.45	0.51	0.64	0.89	1.13
	4	0.015	100.0	625	NAV	0.29	0.35	0.41	0.54	0.79	1.03
	6	0.015	100.0	502	NAV	0.21	0.27	0.33	0.46	0.71	0.95
	8	0.015	100.0	501	NAV	0.21	0.27	0.33	0.46	0.70	0.95
	12	0.015	100.0	453	NAV	0.18	0.23	0.29	0.42	0.67	0.92
	20	0.015	100.0	433	NAV	0.16	0.21	0.28	0.41	0.65	0.90

Table B.33: Precipitation triggered pollution detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area for various RADTi in case of $\sigma^2_{\ln K} = 2.0$ assuming daily (ED) and monthly (1M) sampling frequencies

	σ^2_{lnK}										2.00										
α_T(m)	now	nfds(max)	P_d (ED)	$<T_{(DET.)}>$ (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L	P_d (1M)	$<T_{(DET.)}>$ (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	**1**	0.75	6.6	3315	1.50	0.12	0.12	0.13	0.14	0.16	0.17	6.6	3225	1.49	0.11	0.12	0.12	0.13	0.15	0.18
	2	0.75	16.5	3220	1.47	0.11	0.11	0.12	0.13	0.15	0.17	16.1	3229	1.46	0.11	0.11	0.12	0.13	0.15	0.17
	3	0.75	18.6	3293	1.53	0.13	0.14	0.15	0.17	0.22	0.26	18.0	3279	1.55	0.11	0.12	0.12	0.13	0.15	0.17
	4	0.75	23.8	3113	1.35	0.11	0.11	0.12	0.13	0.15	0.17	23.3	3100	1.35	0.11	0.11	0.12	0.13	0.15	0.17
	6	0.75	39.0	3185	1.56	0.10	0.11	0.11	0.12	0.14	0.16	37.9	3162	1.55	0.10	0.11	0.11	0.12	0.14	0.16
	8	0.75	44.7	3197	1.54	0.11	0.12	0.13	0.14	0.17	0.21	42.9	3175	1.55	0.10	0.11	0.11	0.12	0.14	0.16
	12	0.75	61.5	3025	1.56	0.09	0.09	0.10	0.11	0.13	0.15	60.0	3065	1.55	0.09	0.10	0.10	0.11	0.13	0.16
	20	0.75	76.9	2956	1.61	0.08	0.09	0.09	0.10	0.12	0.15	75.8	2981	1.62	0.08	0.09	0.09	0.10	0.12	0.14
0.01	**1**	0.50	16.2	2820	2.31	0.18	0.19	0.20	0.22	0.26	0.31	15.8	2952	2.31	0.20	0.21	0.22	0.23	0.28	0.32
	2	0.50	29.1	2460	2.36	0.16	0.17	0.18	0.20	0.25	0.29	28.3	2493	2.35	0.17	0.17	0.18	0.20	0.25	0.29
	3	0.50	43.5	2598	2.29	0.16	0.17	0.18	0.20	0.24	0.29	42.5	2701	2.27	0.19	0.20	0.21	0.23	0.27	0.32
	4	0.50	50.6	2475	2.12	0.15	0.16	0.17	0.19	0.22	0.27	49.3	2570	2.11	0.17	0.17	0.18	0.20	0.24	0.28
	6	0.50	65.3	2327	2.64	0.13	0.14	0.14	0.16	0.20	0.24	64.1	2386	2.60	0.13	0.14	0.15	0.17	0.21	0.25
	8	0.50	74.8	2240	2.11	0.11	0.11	0.12	0.14	0.18	0.22	73.8	2324	2.13	0.12	0.13	0.14	0.16	0.20	0.24
	12	0.50	84.9	2136	2.30	0.10	0.10	0.11	0.13	0.17	0.21	83.9	2172	2.31	0.10	0.11	0.12	0.13	0.17	0.21
	20	0.50	87.9	2063	2.26	0.08	0.09	0.10	0.11	0.15	0.19	87.7	2102	2.26	0.09	0.09	0.10	0.12	0.15	0.19
0.05	**1**	0.13	21.8	1652	3.03	0.16	0.17	0.18	0.21	0.26	0.33	21.1	1759	3.03	0.17	0.18	0.20	0.22	0.28	0.32
	2	0.13	45.1	1514	3.05	0.16	0.17	0.18	0.20	0.25	0.31	43.7	1655	3.06	0.18	0.19	0.20	0.22	0.28	0.34
	3	0.13	61.3	1461	3.02	0.14	0.15	0.16	0.19	0.24	0.30	59.7	1563	3.02	0.16	0.17	0.18	0.21	0.25	0.30
	4	0.13	72.4	1442	3.00	0.13	0.14	0.16	0.18	0.24	0.30	70.8	1535	2.99	0.18	0.19	0.17	0.20	0.25	0.31
	6	0.13	88.5	1199	3.32	0.09	0.10	0.11	0.13	0.18	0.24	87.2	1281	3.26	0.10	0.11	0.12	0.14	0.19	0.25
	8	0.13	90.7	1053	3.73	0.06	0.07	0.08	0.10	0.15	0.21	90.3	1138	3.70	0.08	0.09	0.09	0.12	0.17	0.22
	12	0.13	95.9	933	3.03	0.05	0.06	0.07	0.09	0.14	0.19	95.8	976	3.04	0.06	0.06	0.07	0.09	0.14	0.20
	20	0.13	97.3	881	0.00	0.05	0.05	0.06	0.08	0.13	0.18	97.0	910	0.00	0.05	0.06	0.06	0.09	0.13	0.19
0.10	**1**	0.06	29.9	1672	3.26	0.24	0.25	0.27	0.30	0.36	0.43	28.5	1706	3.25	0.25	0.26	0.28	0.32	0.37	0.45
	2	0.06	60.4	1484	3.46	0.19	0.21	0.22	0.25	0.31	0.38	57.9	1499	3.44	0.20	0.21	0.22	0.25	0.31	0.37
	3	0.06	78.5	1316	3.44	0.16	0.18	0.19	0.22	0.28	0.35	76.2	1407	3.42	0.19	0.20	0.21	0.24	0.30	0.38
	4	0.06	88.0	1104	3.50	0.12	0.13	0.14	0.17	0.23	0.30	86.7	1236	3.51	0.15	0.16	0.17	0.20	0.26	0.33
	6	0.06	96.7	853	NAV	0.07	0.08	0.10	0.12	0.18	0.25	95.9	920	NAV	0.08	0.09	0.11	0.13	0.19	0.26
	8	0.06	95.0	696	NAV	0.05	0.06	0.07	0.10	0.15	0.22	94.9	762	NAV	0.06	0.07	0.08	0.11	0.17	0.24
	12	0.06	98.9	620	NAV	0.05	0.05	0.06	0.09	0.14	0.21	98.6	654	NAV	0.05	0.06	0.07	0.09	0.15	0.21
	20	0.06	99.3	565	NAV	0.04	0.05	0.06	0.08	0.13	0.19	99.2	607	NAV	0.04	0.05	0.06	0.08	0.14	0.20
0.50	**1**	0.015	92.5	1750	NAV	0.99	1.05	1.11	1.24	1.49	1.75	89.7	1986	NAV	1.16	1.19	1.26	1.40	1.66	1.93
	2	0.015	100.0	704	NAV	0.31	0.36	0.42	0.55	0.80	1.06	99.8	804	NAV	0.37	0.43	0.48	0.62	0.87	1.13
	3	0.015	100.0	469	NAV	0.17	0.21	0.26	0.39	0.65	0.91	100.0	552	NAV	0.22	0.26	0.32	0.46	0.71	0.97
	4	0.015	100.0	361	NAV	0.12	0.15	0.20	0.33	0.58	0.84	100.0	423	NAV	0.15	0.19	0.24	0.38	0.63	0.89
	6	0.015	100.0	286	NAV	0.09	0.12	0.16	0.28	0.54	0.80	100.0	339	NAV	0.11	0.15	0.19	0.33	0.58	0.84
	8	0.015	100.0	273	NAV	0.08	0.12	0.16	0.28	0.53	0.79	100.0	322	NAV	0.11	0.14	0.19	0.32	0.57	0.83
	12	0.015	100.0	221	NAV	0.06	0.09	0.13	0.24	0.50	0.76	100.0	263	NAV	0.08	0.11	0.16	0.28	0.54	0.80
	20	0.015	100.0	203	NAV	0.06	0.09	0.12	0.23	0.49	0.75	100.0	243	NAV	0.07	0.11	0.15	0.27	0.52	0.78

Table B.34: Precipitation triggered pollution detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area for various RADTi in case of $\sigma^2_{\ln K} = 2.0$ assuming bimonthly (2M) and quarterly (3M) sampling frequencies

	$\sigma^2_{\ln K}$									2.00										
α_T(m)	now	nfds(max)	P_d (2M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L	P_d (3M)	<$T_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi/L)	(36M. RADTi)/L
0.001	**1**	0.75	6.5	3334	1.50	0.12	0.12	0.13	0.14	0.16	0.18	6.3	3171	1.49	0.11	0.11	0.12	0.13	0.15	0.17
	2	0.75	16.0	3331	1.48	0.12	0.12	0.12	0.14	0.16	0.18	15.7	3376	1.46	0.12	0.12	0.13	0.14	0.16	0.18
	3	0.75	17.8	3343	1.55	0.12	0.12	0.13	0.14	0.16	0.18	17.3	3298	1.55	0.11	0.12	0.12	0.13	0.15	0.17
	4	0.75	22.9	3121	1.34	0.11	0.12	0.12	0.13	0.15	0.18	22.6	3105	1.34	0.11	0.11	0.12	0.13	0.15	0.17
	6	0.75	37.7	3219	1.57	0.10	0.11	0.11	0.12	0.14	0.17	37.0	3232	1.54	0.11	0.11	0.12	0.13	0.15	0.17
	8	0.75	42.3	3178	1.55	0.10	0.11	0.11	0.12	0.14	0.16	41.6	3168	1.53	0.10	0.11	0.11	0.12	0.14	0.16
	12	0.75	59.2	3086	1.54	0.00	0.10	0.10	0.11	0.13	0.16	58.3	3078	1.53	0.09	0.10	0.10	0.11	0.13	0.15
	20	0.75	75.4	3011	1.58	0.00	0.09	0.09	0.10	0.12	0.15	74.9	3008	1.56	0.09	0.09	0.09	0.10	0.12	0.15
0.01	**1**	0.50	15.5	2997	2.31	0.20	0.21	0.22	0.23	0.28	0.32	15.3	3019	2.31	0.20	0.21	0.22	0.24	0.28	0.33
	2	0.50	27.9	2578	2.35	0.18	0.19	0.20	0.22	0.27	0.31	27.4	2610	2.35	0.19	0.20	0.21	0.23	0.27	0.31
	3	0.50	41.6	2717	2.27	0.19	0.20	0.21	0.23	0.27	0.32	41.3	2713	2.29	0.17	0.18	0.19	0.21	0.25	0.30
	4	0.50	48.4	2591	2.14	0.00	0.18	0.19	0.21	0.24	0.28	48.0	2608	2.10	0.17	0.18	0.19	0.21	0.25	0.30
	6	0.50	63.4	2462	2.59	0.00	0.16	0.17	0.18	0.22	0.26	62.9	2488	2.57	0.15	0.16	0.17	0.19	0.22	0.26
	8	0.50	73.1	2342	2.22	0.00	0.13	0.14	0.16	0.20	0.24	72.6	2379	2.30	0.13	0.13	0.14	0.16	0.20	0.24
	12	0.50	83.4	2197	2.42	0.00	0.11	0.12	0.14	0.17	0.21	83.1	2224	2.28	0.11	0.11	0.12	0.14	0.18	0.22
	20	0.50	87.6	2124	2.32	0.00	0.10	0.10	0.12	0.16	0.20	87.6	2145	2.25	0.09	0.10	0.10	0.12	0.16	0.20
0.05	**1**	0.13	20.5	1747	3.03	0.16	0.18	0.19	0.20	0.26	0.32	20.3	1793	3.04	0.17	0.18	0.19	0.21	0.26	0.33
	2	0.13	42.7	1689	3.08	0.18	0.19	0.20	0.23	0.28	0.34	42.2	1782	3.08	0.21	0.22	0.23	0.26	0.29	0.35
	3	0.13	58.8	1606	3.01	0.16	0.18	0.19	0.21	0.25	0.31	57.9	1604	3.02	0.16	0.17	0.18	0.20	0.25	0.31
	4	0.13	70.2	1608	2.97	0.20	0.22	0.20	0.21	0.27	0.33	69.0	1617	3.04	0.16	0.18	0.19	0.21	0.27	0.33
	6	0.13	86.3	1307	3.24	0.00	0.11	0.12	0.14	0.20	0.25	85.9	1357	3.22	0.11	0.12	0.13	0.15	0.20	0.26
	8	0.13	89.7	1173	3.64	0.00	0.09	0.10	0.12	0.17	0.22	89.6	1219	3.62	0.09	0.10	0.11	0.13	0.18	0.24
	12	0.13	95.7	1007	2.99	0.00	0.07	0.08	0.10	0.15	0.20	95.4	1012	3.15	0.06	0.07	0.07	0.10	0.15	0.20
	20	0.13	97.0	938	0.00	0.00	0.06	0.07	0.09	0.14	0.19	96.8	957	0.00	0.05	0.06	0.07	0.09	0.14	0.19
0.10	**1**	0.06	28.0	1781	3.25	0.26	0.28	0.29	0.32	0.38	0.47	27.3	1760	3.26	0.24	0.25	0.27	0.30	0.36	0.42
	2	0.06	56.6	1534	3.44	0.20	0.21	0.22	0.25	0.32	0.38	55.4	1533	3.45	0.20	0.21	0.22	0.26	0.32	0.38
	3	0.06	74.9	1454	3.38	0.20	0.21	0.22	0.25	0.31	0.39	73.8	1465	3.43	0.19	0.21	0.22	0.25	0.31	0.38
	4	0.06	85.4	1267	3.52	0.00	0.16	0.17	0.20	0.27	0.33	85.3	1335	3.47	0.16	0.17	0.19	0.22	0.28	0.35
	6	0.06	95.6	981	NAV	0.00	0.11	0.12	0.14	0.20	0.27	95.3	1014	NAV	0.10	0.11	0.12	0.15	0.21	0.28
	8	0.06	94.6	791	NAV	0.00	0.07	0.08	0.11	0.17	0.24	94.5	825	NAV	0.07	0.08	0.09	0.12	0.18	0.25
	12	0.06	98.5	681	NAV	0.00	0.06	0.07	0.09	0.15	0.22	98.4	697	NAV	0.05	0.06	0.07	0.09	0.15	0.22
	20	0.06	99.1	622	NAV	0.00	0.05	0.06	0.08	0.14	0.21	99.1	650	NAV	0.05	0.06	0.07	0.09	0.15	0.21
0.50	**1**	0.015	87.9	2078	NAV	1.27	1.34	1.40	1.52	1.79	2.03	86.0	2099	NAV	1.23	1.29	1.36	1.49	1.75	2.02
	2	0.015	99.6	879	NAV	0.00	0.48	0.54	0.67	0.93	1.19	99.6	939	NAV	0.46	0.52	0.58	0.72	0.97	1.23
	3	0.015	100.0	594	NAV	0.24	0.29	0.35	0.49	0.74	1.01	100.0	627	NAV	0.26	0.32	0.38	0.51	0.77	1.03
	4	0.015	100.0	458	NAV	0.17	0.21	0.27	0.40	0.65	0.92	100.0	490	NAV	0.19	0.24	0.29	0.43	0.68	0.95
	6	0.015	100.0	369	NAV	0.12	0.16	0.21	0.35	0.60	0.87	100.0	393	NAV	0.14	0.18	0.23	0.37	0.62	0.89
	8	0.015	100.0	348	NAV	0.12	0.16	0.21	0.34	0.59	0.85	100.0	376	NAV	0.13	0.18	0.23	0.36	0.61	0.88
	12	0.015	100.0	289	NAV	0.09	0.13	0.17	0.30	0.56	0.82	100.0	309	NAV	0.10	0.14	0.19	0.32	0.57	0.84
	20	0.015	100.0	266	NAV	0.08	0.12	0.16	0.29	0.54	0.81	100.0	288	NAV	0.09	0.13	0.18	0.30	0.56	0.82

Table B.35: Precipitation triggered pollution detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area for various RADTi in case of $\sigma^2_{\ln K} = 2.0$ assuming every 4 months (4M) and biannually (6M) sampling frequencies

$\sigma^2_{\ln K}$											2.00										
α_T(m)	now	nfds(max)	P_d (4M)	<T$_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi)/L	(36M. RADTi)/L	P_d (6M)	<T$_{(DET.)}$> (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi)/L	(36M. RADTi)/L
0.001	**1**	0.75	6.3	3334	1.49	0.12	0.12	0.13	0.14	0.16	0.18	6.2	3325	1.49	0.12	0.12	0.13	0.14	0.16	0.18
	2	0.75	15.5	3337	1.48	0.12	0.12	0.13	0.14	0.16	0.18	15.2	3430	1.48	0.12	0.12	0.13	0.14	0.16	0.18
	3	0.75	17.4	3389	1.55	0.12	0.13	0.13	0.14	0.16	0.18	17.0	3413	1.54	0.12	0.13	0.13	0.14	0.16	0.18
	4	0.75	22.7	3171	1.34	0.11	0.12	0.12	0.13	0.16	0.18	22.1	3178	1.36	0.11	0.12	0.12	0.13	0.16	0.18
	6	0.75	36.9	3229	1.56	0.11	0.11	0.12	0.13	0.15	0.17	36.2	3307	1.56	0.11	0.12	0.12	0.13	0.15	0.17
	8	0.75	41.5	3227	1.54	0.10	0.11	0.11	0.12	0.14	0.17	41.0	3217	1.53	0.10	0.11	0.11	0.12	0.14	0.17
	12	0.75	58.4	3139	1.53	0.10	0.10	0.11	0.12	0.14	0.16	57.7	3157	1.54	0.10	0.10	0.11	0.12	0.14	0.16
	20	0.75	74.7	3036	1.55	0.09	0.09	0.10	0.11	0.13	0.15	74.5	3072	1.54	0.10	0.11	0.11	0.11	0.13	0.15
0.01	**1**	0.50	14.9	2992	2.30	0.19	0.20	0.21	0.23	0.27	0.32	14.9	3076	2.31	0.21	0.22	0.23	0.25	0.28	0.33
	2	0.50	27.3	2645	2.35	0.19	0.20	0.21	0.23	0.27	0.31	26.6	2708	2.34	0.20	0.21	0.22	0.24	0.28	0.32
	3	0.50	40.6	2747	2.28	0.18	0.19	0.20	0.22	0.26	0.30	40.0	2759	2.28	0.18	0.19	0.20	0.22	0.26	0.30
	4	0.50	47.0	2629	2.14	0.17	0.18	0.19	0.21	0.25	0.29	46.7	2675	2.20	0.18	0.19	0.20	0.22	0.26	0.30
	6	0.50	62.2	2515	2.56	0.15	0.16	0.17	0.19	0.23	0.27	61.5	2552	2.56	0.16	0.17	0.18	0.20	0.24	0.28
	8	0.50	72.3	2424	2.20	0.13	0.14	0.15	0.17	0.21	0.25	71.8	2457	2.35	0.13	0.14	0.15	0.17	0.21	0.25
	12	0.50	83.0	2266	2.40	0.11	0.12	0.13	0.14	0.18	0.22	82.7	2296	2.39	0.11	0.12	0.13	0.15	0.19	0.23
	20	0.50	87.4	2155	2.29	0.09	0.10	0.11	0.12	0.16	0.20	87.3	2186	2.30	0.09	0.10	0.11	0.13	0.16	0.21
0.05	**1**	0.13	19.7	1768	3.03	0.17	0.18	0.19	0.22	0.28	0.34	19.4	1868	3.03	0.18	0.19	0.21	0.23	0.28	0.34
	2	0.13	41.2	1715	3.07	0.18	0.19	0.20	0.23	0.27	0.33	40.8	1779	3.07	0.21	0.22	0.23	0.25	0.29	0.35
	3	0.13	57.3	1662	3.00	0.18	0.19	0.20	0.23	0.27	0.34	56.5	1705	3.01	0.18	0.19	0.20	0.22	0.27	0.33
	4	0.13	68.7	1657	3.07	0.17	0.18	0.19	0.22	0.27	0.33	67.9	1734	3.02	0.20	0.22	0.23	0.24	0.29	0.36
	6	0.13	85.3	1373	3.27	0.11	0.12	0.13	0.15	0.20	0.26	84.1	1390	3.28	0.11	0.12	0.14	0.16	0.20	0.26
	8	0.13	88.9	1213	3.57	0.08	0.09	0.10	0.13	0.18	0.24	88.7	1282	3.55	0.10	0.11	0.12	0.14	0.19	0.25
	12	0.13	95.4	1045	3.09	0.06	0.07	0.08	0.10	0.15	0.21	95.3	1073	3.14	0.06	0.07	0.08	0.11	0.16	0.21
	20	0.13	96.7	981	0.00	0.06	0.06	0.07	0.09	0.14	0.20	96.6	1007	0.00	0.06	0.07	0.08	0.10	0.15	0.20
0.10	**1**	0.06	27.3	1875	3.25	0.29	0.30	0.31	0.35	0.41	0.49	26.0	1832	3.26	0.25	0.26	0.27	0.30	0.36	0.43
	2	0.06	54.9	1554	3.47	0.20	0.21	0.22	0.26	0.32	0.39	54.0	1584	3.45	0.20	0.22	0.23	0.26	0.32	0.38
	3	0.06	73.6	1526	3.39	0.21	0.23	0.24	0.27	0.33	0.41	72.0	1591	3.39	0.22	0.23	0.24	0.27	0.33	0.40
	4	0.06	83.8	1308	3.50	0.16	0.17	0.18	0.21	0.27	0.34	83.0	1393	3.44	0.17	0.18	0.20	0.23	0.29	0.37
	6	0.06	95.0	1047	NAV	0.10	0.12	0.13	0.16	0.22	0.29	94.3	1088	NAV	0.11	0.12	0.14	0.16	0.22	0.29
	8	0.06	94.2	827	NAV	0.06	0.07	0.08	0.11	0.17	0.24	94.0	869	NAV	0.07	0.08	0.10	0.12	0.18	0.25
	12	0.06	98.5	719	NAV	0.05	0.06	0.07	0.10	0.16	0.22	98.2	748	NAV	0.05	0.06	0.08	0.10	0.16	0.23
	20	0.06	98.9	659	NAV	0.05	0.06	0.07	0.09	0.15	0.21	99.0	701	NAV	0.05	0.06	0.07	0.10	0.16	0.22
0.50	**1**	0.015	85.3	2200	NAV	1.31	1.38	1.44	1.59	1.86	2.08	82.6	2200	NAV	1.33	1.40	1.46	1.60	1.86	2.13
	2	0.015	99.6	988	NAV	0.49	0.54	0.61	0.74	1.00	1.26	99.3	1052	NAV	0.52	0.58	0.65	0.78	1.03	1.29
	3	0.015	99.9	654	NAV	0.28	0.34	0.40	0.54	0.79	1.05	100.0	710	NAV	0.32	0.37	0.43	0.57	0.82	1.09
	4	0.015	100.0	513	NAV	0.20	0.25	0.31	0.44	0.70	0.96	100.0	558	NAV	0.22	0.28	0.34	0.47	0.73	0.99
	6	0.015	100.0	413	NAV	0.15	0.19	0.25	0.38	0.63	0.90	100.0	453	NAV	0.17	0.22	0.28	0.41	0.66	0.93
	8	0.015	100.0	396	NAV	0.14	0.19	0.24	0.37	0.63	0.89	100.0	438	NAV	0.16	0.21	0.27	0.40	0.65	0.92
	12	0.015	100.0	332	NAV	0.11	0.15	0.20	0.34	0.59	0.85	100.0	372	NAV	0.13	0.18	0.23	0.37	0.62	0.88
	20	0.015	100.0	307	NAV	0.10	0.14	0.18	0.32	0.57	0.83	100.0	347	NAV	0.12	0.16	0.21	0.35	0.59	0.86

Table B.36: Precipitation triggered pollution detection probability, average detection time, contaminated area in case of detection failure and relative contaminated area to control area for various RADTi in case of $\sigma^2_{\ln K} = 2.0$ assuming annually sampling frequency

$\sigma^2_{\ln K}$				2.00							
α_T(m)	now	nfds(max)	P_d (12M)	$\langle T_{(DET.)}\rangle$ (DAYS)	AREA ON FAILURE	(AREA ON DET.)/L	(3M. RADTi)/L	(6M. RADTi)/L	(12M. RADTi)/L	(24M. RADTi)/L)	(36M. RADTi)/L
0.001	1	0.75	6.1	3409	1.49	0.12	0.12	0.13	0.14	0.16	0.19
	2	0.75	15.1	3607	1.46	0.17	0.18	0.19	0.22	0.27	0.19
	3	0.75	17.0	3438	1.54	0.12	0.13	0.13	0.14	0.17	0.19
	4	0.75	21.7	3387	1.34	0.13	0.13	0.14	0.15	0.17	0.20
	6	0.75	35.9	3515	1.53	0.14	0.15	0.16	0.18	0.22	0.18
	8	0.75	40.8	3403	1.53	0.12	0.12	0.12	0.14	0.16	0.18
	12	0.75	57.3	3303	1.50	0.11	0.11	0.12	0.13	0.15	0.17
	20	0.75	74.0	3207	1.64	0.10	0.10	0.11	0.12	0.14	0.16
0.01	1	0.50	14.4	3203	2.30	0.25	0.26	0.27	0.30	0.36	0.43
	2	0.50	26.0	2800	2.35	0.21	0.21	0.22	0.24	0.28	0.33
	3	0.50	39.0	2940	2.27	0.21	0.22	0.23	0.26	0.30	0.36
	4	0.50	45.3	2741	2.17	0.18	0.19	0.20	0.22	0.26	0.31
	6	0.50	59.9	2689	2.53	0.18	0.19	0.20	0.22	0.26	0.31
	8	0.50	70.5	2602	2.29	0.15	0.16	0.17	0.19	0.22	0.27
	12	0.50	82.0	2404	2.36	0.12	0.13	0.14	0.16	0.20	0.24
	20	0.50	86.9	2294	2.29	0.10	0.11	0.12	0.14	0.18	0.22
0.05	1	0.13	18.9	1984	3.02	0.22	0.23	0.24	0.27	0.33	0.40
	2	0.13	38.9	1779	3.04	0.19	0.20	0.21	0.24	0.30	0.36
	3	0.13	55.1	1863	3.01	0.20	0.22	0.23	0.26	0.30	0.37
	4	0.13	65.1	1740	3.06	0.17	0.18	0.19	0.22	0.28	0.34
	6	0.13	83.0	1497	3.23	0.13	0.14	0.15	0.18	0.23	0.29
	8	0.13	87.7	1396	3.60	0.11	0.12	0.13	0.15	0.21	0.27
	12	0.13	95.0	1171	3.31	0.07	0.08	0.09	0.12	0.17	0.23
	20	0.13	96.1	1090	0.00	0.07	0.07	0.09	0.11	0.16	0.21
0.10	1	0.06	25.3	1975	3.26	0.28	0.29	0.30	0.34	0.40	0.47
	2	0.06	52.8	1771	3.40	0.25	0.25	0.27	0.30	0.37	0.43
	3	0.06	69.5	1607	3.34	0.24	0.22	0.24	0.27	0.34	0.41
	4	0.06	81.6	1536	3.59	0.20	0.20	0.22	0.25	0.32	0.39
	6	0.06	93.3	1218	NAV	0.13	0.14	0.16	0.19	0.25	0.32
	8	0.06	93.9	989	NAV	0.09	0.10	0.11	0.14	0.20	0.27
	12	0.06	98.0	854	NAV	0.07	0.08	0.09	0.12	0.18	0.25
	20	0.06	98.6	797	NAV	0.06	0.07	0.08	0.11	0.17	0.24
0.50	1	0.015	79.6	2391	NAV	1.59	1.54	1.61	1.76	1.95	2.21
	2	0.015	99.1	1224	NAV	0.65	0.71	0.78	0.91	1.16	1.42
	3	0.015	99.8	837	NAV	0.40	0.46	0.53	0.66	0.92	1.18
	4	0.015	100.0	679	NAV	0.30	0.36	0.43	0.56	0.81	1.07
	6	0.015	100.0	570	NAV	0.22	0.28	0.35	0.49	0.73	0.99
	8	0.015	100.0	567	NAV	0.23	0.29	0.36	0.49	0.74	1.00
	12	0.015	100.0	501	NAV	0.19	0.24	0.31	0.45	0.69	0.95
	20	0.015	100.0	481	NAV	0.17	0.22	0.29	0.43	0.67	0.94

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