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Subsurface Stormflow Modeling with Sensitivity Analysis Using a Latin-Hypercube Sampling Technique

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Environmental Sciences Division
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Environmental Sciences Division

SUBSURFACE STORMFLOW MODELING WITH SENSITIVITY ANALYSIS USING A LATIN-HYPERCUBE SAMPLING TECHNIQUE

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CONTENTS

	Page
LIST OF TABLES	v
LIST OF FIGURES	vii
ACKNOWLEDGMENT	ix
EXECUTIVE SUMMARY	xi
1. INTRODUCTION	1
2. METHODOLOGY	3
3. CONCEPTUAL AND NUMERICAL MODELS	8
3.1 CONCEPTUAL MODEL	8
3.2 NUMERICAL MODELS AND SIMULATION SCENARIOS	8
4. RESULTS AND DISCUSSION	16
5. SUMMARY AND CONCLUSIONS	26
6. REFERENCES	27

LIST OF TABLES

Table Page

1 Ranges and distributions of input data. 13

2 Model parameters and target variables for scenarios 1-4. 14

3 Model parameters and target variables for scenario 5. 15

4 Coefficients and statistics of regression equations on ranks. 18

LIST OF FIGURES

Figure Page

1 A risk assessment framework that consists of the Latin-hypercube simulation and the regression on ranks 4

2 A conceptual subsurface flow model of the ORR (Moore 1988). 9

3 A cross section used for the numerical models in this study 10

4 Soil property functions of the soil horizons: (a) water retention curves and (b) relative hydraulic conductivity relations 12

5 Perched water table development in the stormflow and vadose zones for realization 5 with scenarios: (a) no remediation design, (b) a cap on thehill top, and (c) a cap on the middle hillslope 17

6 Relation between groundwater discharge and hydraulic conductivity: (a) layer cross section with no clay lenses, and (b) cross section with clay lenses 19

7 Darcy velocity distribution for realization 15 with a cap at the middle hillslope. . 20

8 Comparison of unsaturated areas (a) before and (b) after a French drain was placed on the hillslope 21

9 Pressure head distribution for the cross section with clay lenses. 22

10 Effect of caps on the change of unsaturated areas beneath and downslope of a cap on the hilltop 23

11 Estimated cumulative distribution of groundwater flux (as percentage of total flux) for (a) layer cross section with no clay lenses and remediation designs and (b) cross section with clay lenses and without remediation designs. 24

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EXECUTIVE SUMMARY

Subsurface stormflow, because of its dynamic and nonlinear features, has been a very challenging process in both field experiments and modeling studies. The disposal of wastes in subsurface stormflow and vadose zones at Oak Ridge National Laboratory, however, demands more effort to characterize these flow zones and to study their dynamic flow processes. Field data and modeling studies for these flow zones are relatively scarce, and the effect of engineering designs on the flow processes is poorly understood. On the basis of a risk assessment framework and a conceptual model for the Oak Ridge Reservation area, numerical models of a proposed waste disposal site were built, and a Latin-hypercube simulation technique was used to study the uncertainty of model parameters. Four scenarios, with three engineering designs, were simulated, and the effectiveness of the engineering designs was evaluated. Sensitivity analyses of model parameters suggested that hydraulic conductivity was the most influential parameter. However, local heterogeneities (e.g., clay lenses in the vadose zone) may alter flow patterns and result in complex recharge and discharge patterns. Hydraulic conductivity, therefore, may not be used as the only reference for subsurface flow monitoring and engineering operations. Neither of the two engineering designs, capping and French drains, was found to be effective in hydrologically isolating downslope waste trenches. However, pressure head contours indicated that combinations of both designs may prove more effective than either one alone.

1. INTRODUCTION

Waste disposal by shallow land burial in heterogeneous geological formations located in high precipitation areas usually poses a school of questions, if not problems, regarding environmental safety and restoration. For example, at the only active low-level radioactive waste (LLW) disposal site at Oak Ridge National Laboratory (ORNL), LLW was generally disposed of in unlined trenches and auger holes until 1986 (ORNL 1993). During storm events, these shallow disposal facilities become inundated, and subsurface stormflow water may intermittently extract radionuclides from both the surrounding soils and the wastes themselves. Numerous field investigations on the migration of LLW in the groundwater zone have been conducted at ORNL (Moore and Toran 1992) while relatively less field work has been done on subsurface stormflow because of its highly dynamic feature and the higher cost of obtaining field data. It is estimated, however, that more than 90% of the rainwater infiltrating the soil horizons becomes subsurface stormflow (Moore 1988; Solomon et al. 1992; Moore and Toran 1992). Therefore, imminent needs exist to study subsurface stormflow and its effect on off-site migration of LLW at ORNL. The objectives of this study are (1) to investigate the effect of heterogeneities on subsurface water movement using a conceptual model developed by Moore (1988) and field data obtained from a proposed waste disposal site, the Melton Branch Watershed, at ORNL; (2) to identify important model parameters by conducting sensitivity analysis using a Latin-hypercube simulation technique (McKay et al. 1979; Iman and Conover 1980); and (3) to evaluate the effectiveness of remediation designs using the numerical model developed for the aforementioned purposes and a variably saturated subsurface flow code 3DFEMWATER (Yeh 1987).

Previous investigations of subsurface stormflow were usually conducted using a vertical cross section and did not consider the storage of the partially saturated region (e.g., Beven 1981). Further simplification sometimes were introduced by invoking the Dupuit-Forchheimer assumption, and, with Darcy's law, an extended Boussinesq equation can be obtained to account for gravity-driven flow in a vertical cross section (e.g., Koussis 1992). The equation was nonlinear and one-dimensional (1-D) and can be solved analytically or numerically. Two-dimensional (2-D) cross-section models were also used to investigate lateral downslope vadose flow (Jackson 1992), in which a surface no-flow boundary condition was related to subsurface flow after the rain ceased. For the present study, we similarly assume that the problem domain is a wide planar hillslope that can be

represented by a 2-D cross-section. We consider, however, the storage in the partially saturated regions of the cross section, and the Richard's equation with nonlinear soil property functions is solved numerically by a finite element code 3DFEMWATER (Yeh 1987):

$$\frac{\partial \theta}{\partial t} = \nabla \cdot \boldsymbol{K} \nabla (h + z) + q \ , \tag{1}$$

where

h = pressure head (L);

z = elevation (L);

q = external source/sink (L^3/L^3T);

t = time (T);

$\theta = \theta(h)$ is water content that can be represented by a nonlinear function of pressure head;

$\boldsymbol{K} = \begin{bmatrix} K_{xx} & K_{xz} \\ K_{zx} & K_{zz} \end{bmatrix} K_r$ is the hydraulic conductivity tensor, in which K_{xx}, K_{zz}, $K_{xz} = K_{zx}$ are the saturated scalar hydraulic conductivity components (L/T) and $K_r(h)$ is the relative hydraulic conductivity that can be represented by a nonlinear function of pressure head.

The numerical model developed by using 3DFEMWATER was adapted as a module of a Latin-hypercube simulation framework, to be discussed in the next section, that can later become the basis for uncertainty analysis and risk assessment. Within the framework for the present study, three engineering designs were simulated to evaluate the effectiveness of the designs in isolating the disposal facilities from stormflow water. The alteration of flow processes in the stormflow zone by each of the engineering designs is examined and discussed. Field observations at the study site suggest that clay lenses exist in the vadose zone and may also alter stormflow processes. Therefore, a cross-section with clay lenses in the vadose zone was also simulated to investigate the effect of local heterogeneities on subsurface stormflow.

2. METHODOLOGY

The present study is one of the components that will be used as a decision-making tool for the management of wastes and the remediation and restoration of disposal sites at ORNL. Development of numerical models (Gamliel et al. 1993; West and Toran 1994) is one of the major efforts for this purpose and has provided decision makers with very useful information for remediation operations. We therefore start from the methodology of risk assessment but later restrict our discussion to uncertainty analysis.

In conducting risk assessment, one typically formulates objective functions in terms of monetary cost/benefit or human health risk (Freeze et al. 1990). The target variables needed for these functions can be obtained from numerical model simulations. Before obtaining the target variables, however, one needs to determine engineering designs that may be implemented on a disposal site and to formulate simulation scenarios corresponding to the engineering designs. Uncertainty analysis such as Monte Carlo simulations or stochastic approaches is then invoked to carry out numerical simulations for the scenarios and to obtain output variables needed for the calculation of target variables (Freeze et al. 1990). Risk of the individual engineering design can then be calculated and the corresponding objective function determined (Fig. 1).

For the present study, we use a Latin-hypercube method (McKay et al. 1979), a modified Monte Carlo simulation technique, to sample the input variable space. The vector of input variables can be represented as

$$\boldsymbol{X} = (x_1, x_2, \ldots, x_k) \tag{2}$$

and an output variable as

$$Y_i = H(\boldsymbol{X}) \tag{3}$$

where $H(\boldsymbol{X})$ is a deterministic but unknown function of the input variables and x_i, $i=1,\ldots,k$, are model parameters (e.g., hydraulic conductivities and recharge rates). To sample N vectors of input variables, we can divide the range of each input variable into N intervals, and one observation on the input variable is selected randomly in each interval. Thus, there are N observations on each of the k input variables. One of the observations

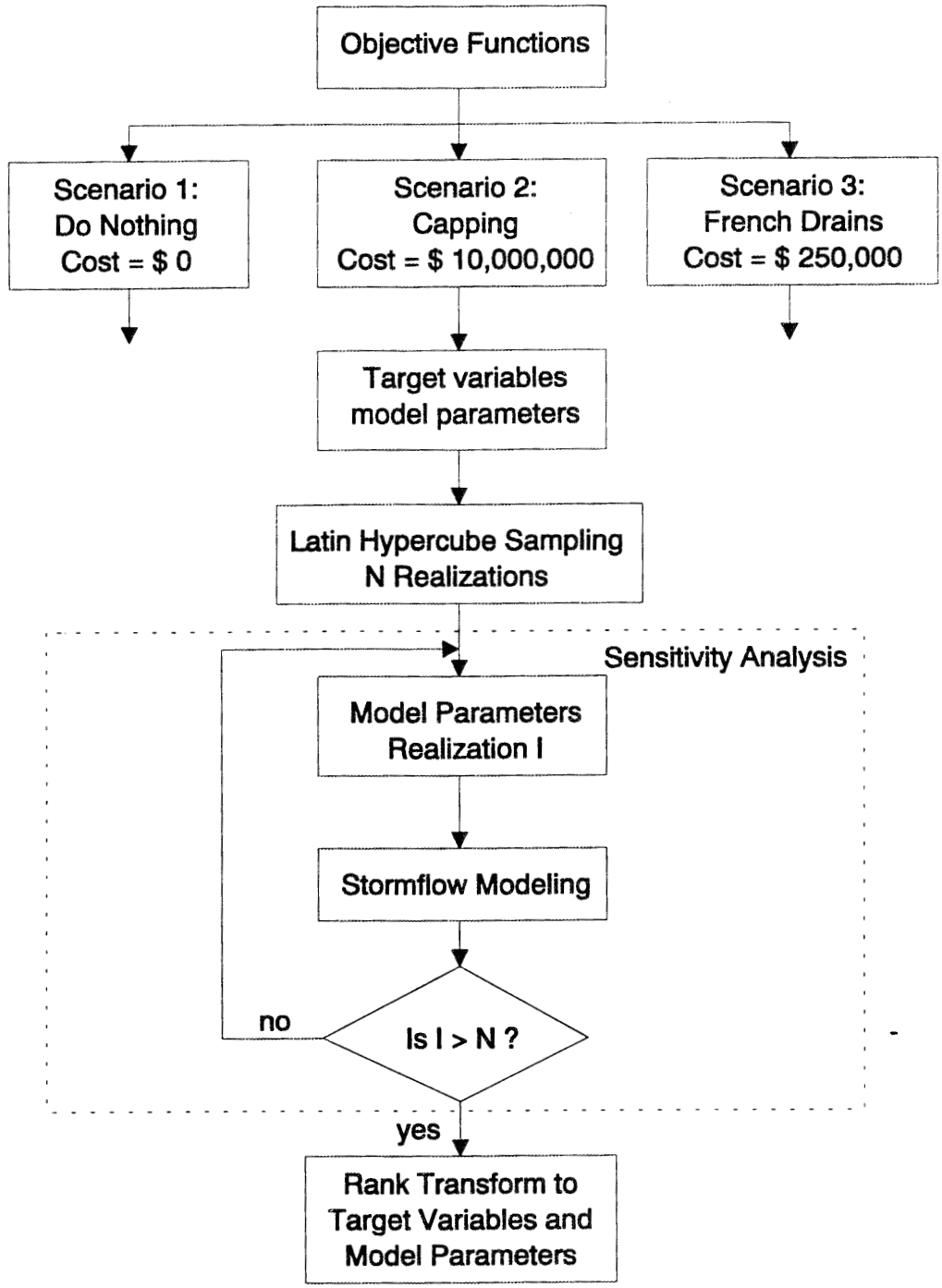

Fig. 1. A risk assessment framework that consists of the Latin-hypercube simulation and the regression on ranks. The Latin-hypercube simulation can be further divided into sampling and numerical simulations.

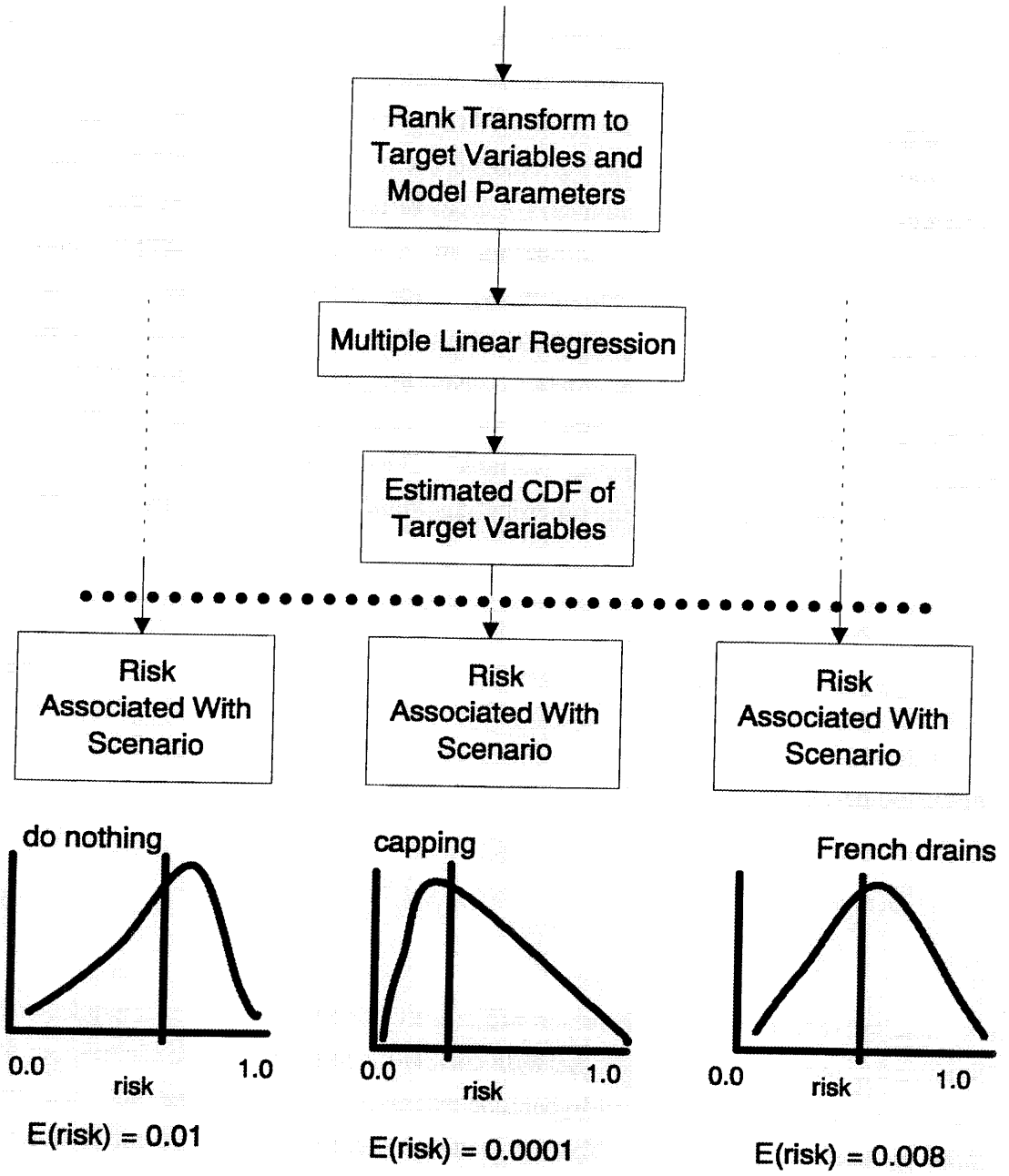

Fig. 1. (continued)

on x_1 is then randomly selected and matched with a randomly selected observation on x_2, and so on, through x_k. We thus obtain the first vector of input variables. One of the remaining observations on x_1 is then matched randomly with one of the remaining observations on x_2, and so on, to get the second vector of variables. This procedure is repeated until all of the observations on the input variables are exhausted and N Latin-hypercube samples are obtained. Comparing with an exhaustive sampling technique, which will result in N^k samples, the Latin-hypercube sampling technique is far more efficient and may provide an uncertainty estimate with comparable accuracy (McKay et al. 1979). Because the samples are obtained according to underlying probabilistic distributions, output from the numerical simulations can be easily translated into probabilistic distributions of the target variables. For example, for a Latin-hypercube simulation with N realizations, the empirical distribution function *S(y)* can be represented by

$$S(y) = \frac{1}{N}\sum_{i=1}^{N} u(y - Y_i) \ , \tag{4}$$

where the unitary function is

$$\begin{aligned} u(t) &= 1 \ \text{ if } \ t \geq 0 \\ &= 0 \ \text{ if } \ t < 0 \ . \end{aligned} \tag{5}$$

For detailed description and discussion of Latin-hypercube sampling techniques, refer to Iman and Conover (1980). Since pairwise correlation may exist when the number of realizations sampled by the Latin-hypercube technique is small, scatter plots of every two input variables are examined graphically to ensure that there is no such correlation. In the present study, this suggests that the correlation of the model parameters is minimal. For the purpose of analyzing off-site waste movement and studying development of stormflow zones, discharge rates and the horizontal extent of the perched water table were chosen as target variables.

To conduct statistical analysis on the realizations, we apply a rank transform to the input and output variables. Rank transform is a simple procedure that replaces raw data with their corresponding ranks. It has been shown that rank transform is a repeatable process that compares favorably with other methods in conducting statistical analyses to the raw

data (Iman and Conover 1979). Studies by Iman and Conover (1979) also indicated that regression on ranks worked quite well on monotonic data. Multiple linear regression on the ranks is therefore performed to obtain relationships between input and output variables in the present study. Coefficients of the regression equations, or the response surface equations (McKay et al. 1979), are correlated with the coefficients of determination and can be used to screen influential model parameters (Iman and Conover 1980). Estimated distribution functions on ranks can then be obtained according to eqs. (4) and (5) and may be used later for risk assessment (Fig. 1).

The uncertainty analysis module in the risk assessment framework (Fig. 1) consists of the Latin-hypercube simulation and the regression on ranks. The Latin-hypercube simulation can be further divided into sampling and numerical simulations. For the latter task, one needs to build a conceptual model of the disposal site and to translate the conceptual model into workable numerical models.

3. CONCEPTUAL AND NUMERICAL MODELS

3.1 CONCEPTUAL MODEL

On the basis of field data and technical studies on the Oak Ridge Reservation (ORR), a conceptual model of the reservation has been proposed by previous investigators (Moore 1988; Solomon et al. 1992). This model represents an integration of data, information, and concepts that is intended to describe water flux and water chemistry on the ORR as they vary in location and time. According to this conceptual model, the subsurface flow system can be divided into the stormflow zone, the vadose zone, the groundwater zone, and the aquiclude (Fig. 2). The groundwater zone can be subdivided into the water table interval, the intermediate interval, and the deep interval. Fluxes of these hydrologic subsystems decrease with depth, and no discrete interface or lithological boundaries are defined between subsystems (Solomon et al. 1992). Because detailed lithological data, which agree very well with the conceptual model, are available at an experiment site, the Melton Branch Watershed at ORNL, the conceptual model of ORR is further modified to adapt the soil horizons or layered structure of the experiment site (Fig. 3). In addition to the soil horizons, clay lenses in the vadose zone result in local heterogeneities (Fig. 3). Clay lenses, though very often found in the B and C horizons on the ORR, have not been considered in the conceptual model. To investigate the effect of these local heterogeneities, we simulated both cross-sections with and without the clay lenses and compared the resultant flow fields. A conceptual model of the site therefore consists of three soil horizons and the clay lenses (Fig. 3). The A horizon is a very thin layer of decomposed organic matter and is highly macroporous; the B horizon is composed of weathered soils less than 1 m in thickness; and the C horizon is composed of highly fractured saprolites partially weathered from parent materials (Luxmoore and Abner 1987; Wilson et al. 1993).

3.2 NUMERICAL MODELS AND SIMULATION SCENARIOS

To numerically define a model that can be simulated using a subsurface flow code, in addition to the lithological structure of a site, one needs to define boundary conditions and model parameters such as hydraulic conductivity and water content or porosity. The

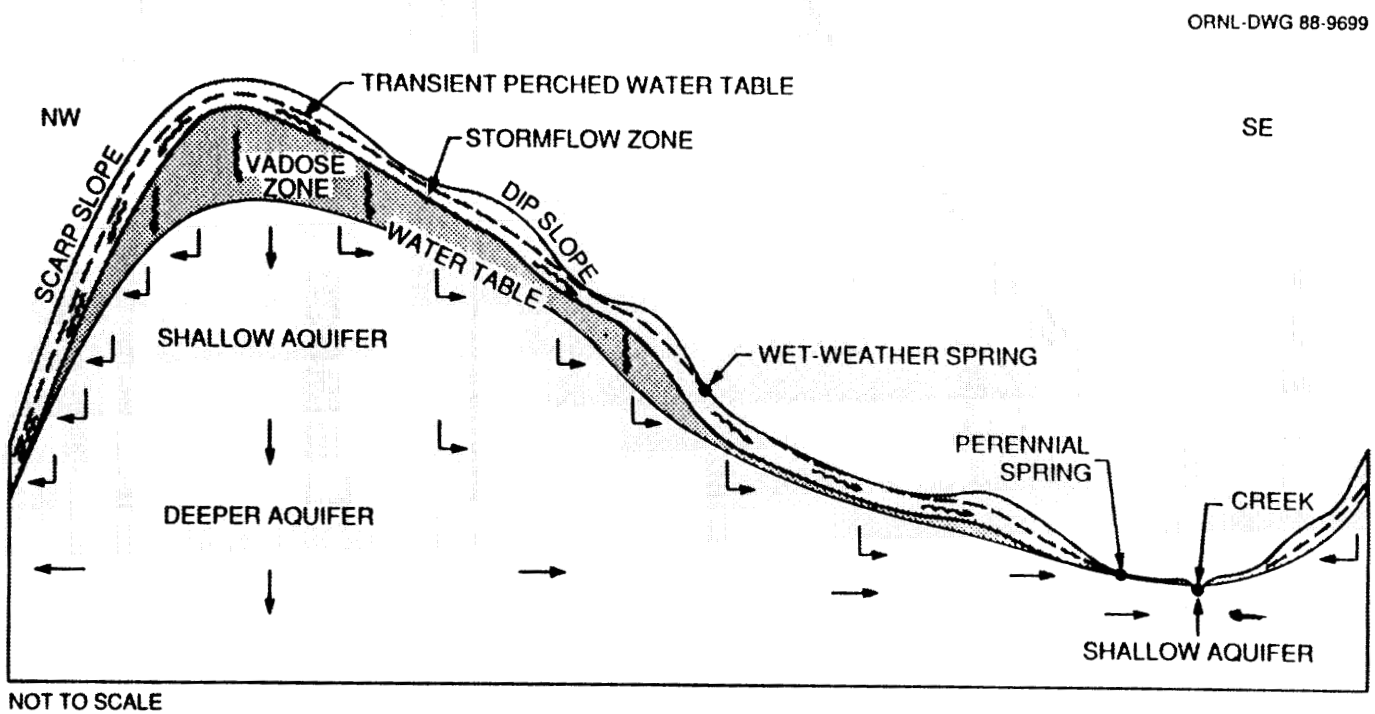

Fig. 2. A conceptual subsurface flow model of the ORR (Moore 1988) . The conceptual model consists of three flow zones: stormflow, vadose, and groundwater flow zones.

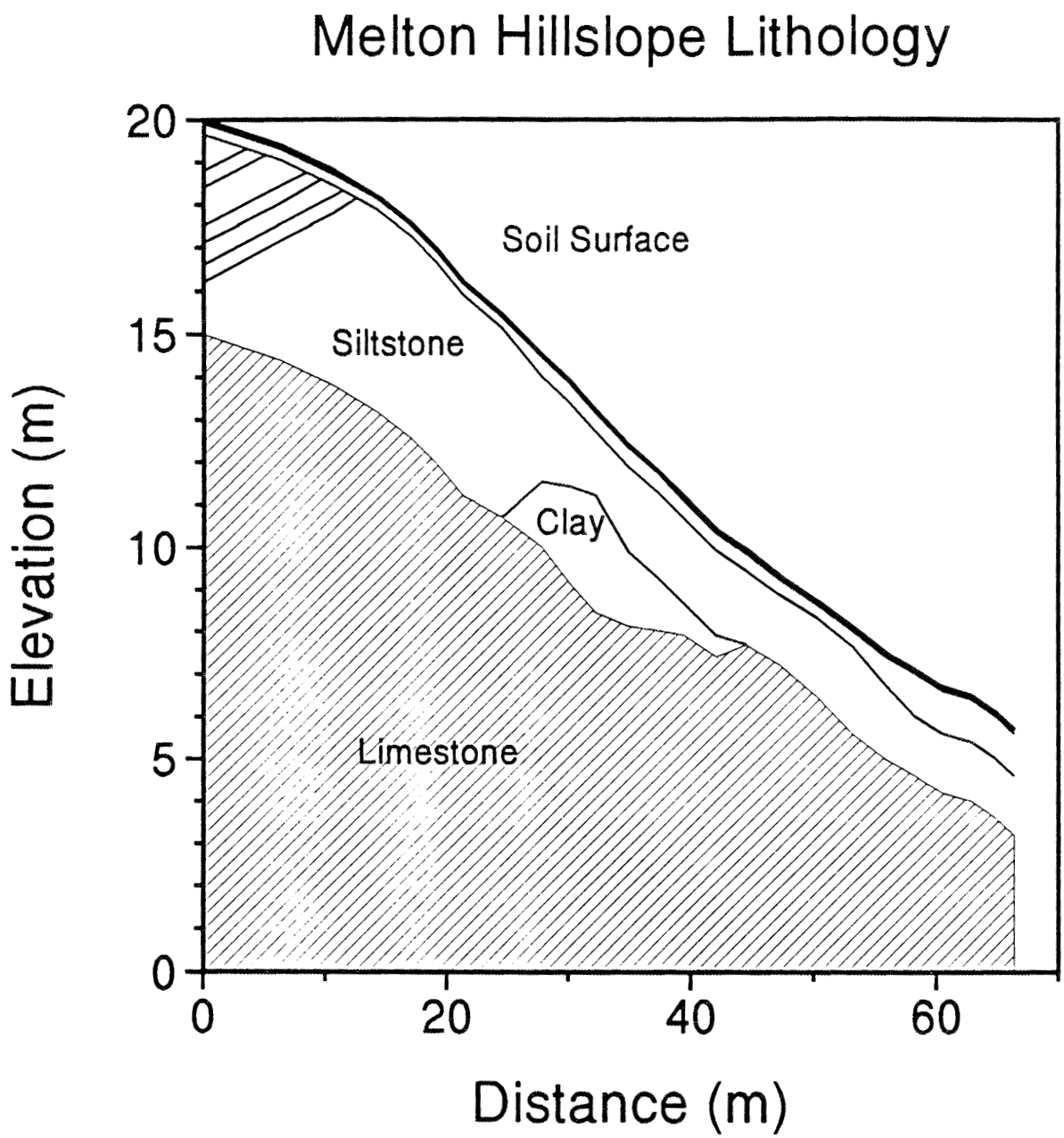

Fig. 3. A cross section used for the numerical models in this study. The cross section consists of A, B, and C soil horizons and clay lenses.

right boundary of the problem domain was assumed to be a stream with a 3 m seepage face. Because of symmetry, the boundary from 3 m down to the bottom of the domain was set up as a no-flux boundary. Similarly, the left boundary was a no-flux boundary and so was the bottom of the domain, which was assumed interfaced at the impermeable aquiclude. The top boundary, or the ground surface, was assigned a evapotranspiration-infiltration-seepage boundary or a variable boundary that allowed evapotranspiration, infiltration, and seepage depending on weather conditions (Yeh 1987). Because the present study is intended to analyze both spatial and temporal variations of subsurface flow fields, one also needs to determine water retention and hydraulic conductivity relations. The determination of these relations, however, involves large uncertainties associated with parameterization of the relations. We therefore assumed that the relations were the same for all of the realizations. These relations for the soil horizons are shown in Fig. 4. The parameters that are considered as random are saturated hydraulic conductivities of the soils, rainfall intensities on the surface, and the anisotropy ratio, which is defined as K_{xx}/K_{zz}. A trend of conductivity variation with depth has been observed in the aquifers on the ORR, which suggested that hydraulic conductivities of aquifers decreased with depth (Solomon et al. 1992). We therefore further assumed that hydraulic conductivities of the soil horizons are perfectly correlated. Hence, only one hydraulic conductivity was sampled, and the others were calculated proportionally according to the ranges of available field data and observations (Table 1). Field and laboratory data ranges of the parameters and their assumed probabilistic distributions are also listed in Table 1. Input variable vectors sampled by a Latin-hypercube technique (Iman and Conover 1980) are listed in Table 1 for all the simulation scenarios. Upon determining the rainfall intensity, the rainfall duration was obtained from a rainfall-frequency-duration chart for the Oak Ridge area (McMaster 1967) by fixing the return period at 30 years, which corresponds to the history of waste disposal at ORNL.

For consistence of numerical models and the comparison of engineering designs, 20 realizations were sampled for the cross-section without clay lenses (Table 2), and 30 realizations were sampled for the cross-section with clay lenses (Table 3). Four scenarios were investigated for the cross section without clay lenses: without caps (scenario 1), with a single cap on the upper hillslope (scenario 2), with a single cap on middle the hillslope (scenario 3), and with a French drain on the upper hillslope (scenario 4). Only one scenario without any engineering designs was simulated for the cross section with

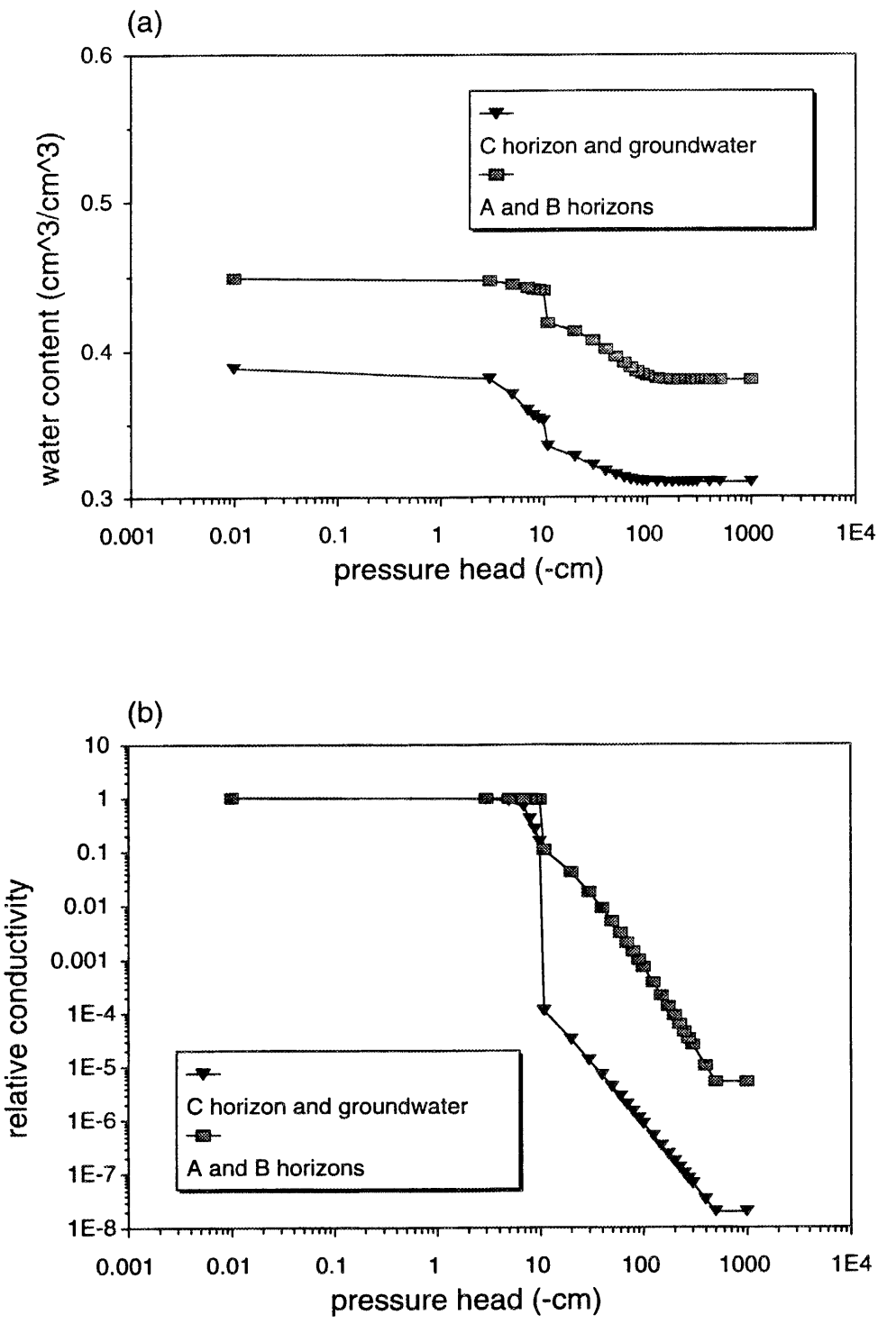

Fig. 4. Soil property functions of the soil horizons: (a) water retention curves and (b) relative hydraulic conductivity relations.

Table 1. Ranges and distributions of input data

Parameters	Minimum	Maximum	Distribution
K_s, A horizon, m/s[a]	1.27×10^{-5}[b]	1.84×10^{-4}[c]	log-uniform
K_s, B horizon, m/s	7.78×10^{-7}[b]	1.6×10^{-4}[c]	log-uniform
K_s, C horizon, m/s	3.50×10^{-8}[d]	2.5×10^{-3}[c]	log-uniform
K_s, groundwater, m/s	2.00×10^{-9}[b]	2.08×10^{-6}[b]	log-uniform
infiltration rates, m/s	1.85×10^{-6}[e]	2.89×10^{-5}[e]	uniform
anisotropy ratio	1.0	10.0	uniform

[a]K_s = saturated hydraulic conductivity.

[b]W. de Laguna, T. Tamura, H. O. Weeren, E. G. Struxness, W. C. McClain, and R. C. Sexton. 1968. Engineering Development of Hydraulic Fracturing as a Method for Permanent Disposal of Radioactive Wastes. ORNL-4259. Oak Ridge National Laboratory.

[c]G. V. Wilson, P. M. Jardine, and J. P. Gwo. 1992. Modeling the hydraulic properties of a multiregion soil. Soil Sci. Soc. Am. J. 56: 1731-1737.

[d]Luxmoore, R. J. 1993. personal communication.

[e]W. M. McMaster. 1967. Hydrologic Data for the Oak Ridge Area, Tennessee, U.S. Geological Survey Water-Supply Paper 1839-N.

clay lenses (scenario 5). Further investigations of engineering designs on the latter cross section will be scheduled later once the effect of the clay lenses has been more thoroughly studied.

In summary, 110 transient variably saturated subsurface flow simulations were executed. The 80 simulations without clay lenses were run on DEC (Digital Equipment Corporation) and HP (Hewlett-Packard) workstations because of their smaller number of finite element nodes and simpler material type distributions. The 30 simulations with clay lenses were run on an Intel Hypercube IPSC860 parallel computer using a parallel version of 3DFEMWATER, PFEM (E. D'Azevedo. 1994. personal communication) because of their large problem size and more complicated distributions of soil types within the problem domain.

Table 2. Model parameters and target variables for scenarios 1-4.

realization	K_s (m/s)[a]	infiltration rate (m/s)	anisotropy ratio	groundwater flux as % of total flux (%) (scenario 1)	perched water length in stormflow zone (m) (scenario 1)
1	6.88×10^{-5}	3.40×10^{-6}	9.53	1.67	2.21
2	1.39×10^{-4}	1.47×10^{-6}	2.42	2.85	0.00
3	1.69×10^{-5}	4.04×10^{-6}	8.58	0.06	32.00
4	2.96×10^{-5}	1.30×10^{-5}	1.47	0.30	14.74
5	1.47×10^{-5}	6.61×10^{-6}	5.74	0.03	41.00
6	1.60×10^{-4}	1.17×10^{-5}	4.32	3.18	0.00
7	1.21×10^{-4}	4.68×10^{-6}	2.90	2.73	0.00
8	1.27×10^{-5}	1.05×10^{-5}	7.63	0.01	47.00
9	9.11×10^{-5}	8.33×10^{-7}	3.84	2.43	0.00
10	3.41×10^{-5}	9.17×10^{-6}	1.00	0.54	5.37
11	1.84×10^{-4}	9.81×10^{-6}	10.00	3.34	0.00
12	4.51×10^{-5}	5.96×10^{-6}	3.37	0.97	6.58
13	5.19×10^{-5}	1.11×10^{-5}	7.16	1.06	16.63
14	5.98×10^{-5}	2.12×10^{-6}	8.11	1.49	0.00
15	1.94×10^{-5}	8.53×10^{-6}	1.95	0.05	22.74
16	3.92×10^{-5}	5.32×10^{-6}	6.21	0.69	10.47
17	2.23×10^{-5}	2.76×10^{-6}	5.26	0.23	5.21
18	7.92×10^{-5}	7.89×10^{-6}	9.05	1.87	13.16
19	1.05×10^{-4}	7.24×10^{-6}	6.68	2.63	0.00
20	2.57×10^{-5}	1.24×10^{-5}	4.79	0.21	35.68

[a]Ks = saturated hydraulic conductivity of A horizon. Saturated hydraulic conductivities of other soil horizons were calculated proportionately.

Table 3. Model parameters and target variables for scenario 5.

realization	K_s (m/s)[a]	infiltration rate (m/s)	anisotropy ratio	groundwater flux as % of total flux (%)
1	3.19×10^{-5}	1.09×10^{-6}	4.72	0.03
2	2.21×10^{-5}	2.52×10^{-6}	3.48	0.11
3	6.08×10^{-5}	1.22×10^{-6}	8.76	0.01
4	1.16×10^{-4}	7.97×10^{-7}	2.55	1.33
5	2.43×10^{-5}	3.86×10^{-6}	9.38	0.12
6	1.39×10^{-4}	3.03×10^{-6}	4.10	0.60
7	3.50×10^{-5}	1.10×10^{-6}	3.17	0.02
8	1.27×10^{-5}	1.14×10^{-6}	5.66	0.12
9	1.84×10^{-5}	2.00×10^{-6}	8.45	0.12
10	1.53×10^{-5}	5.64×10^{-6}	7.21	0.09
11	2.66×10^{-5}	3.75×10^{-5}	6.90	0.16
12	9.67×10^{-5}	9.56×10^{-7}	9.07	0.27
13	1.84×10^{-4}	1.19×10^{-6}	8.14	0.81
14	2.02×10^{-5}	1.39×10^{-6}	3.79	0.04
15	4.61×10^{-5}	7.53×10^{-7}	6.28	0.01
16	1.53×10^{-4}	8.97×10^{-7}	6.59	0.86
17	7.33×10^{-5}	2.03×10^{-5}	1.62	0.20
18	1.40×10^{-5}	6.44×10^{-7}	2.24	0.02
19	1.68×10^{-4}	1.66×10^{-6}	5.97	0.95
20	3.83×10^{-5}	6.39×10^{-6}	1.00	0.02
21	1.27×10^{-4}	8.89×10^{-7}	7.83	0.62
22	8.81×10^{-5}	3.97×10^{-7}	4.41	0.61
23	2.92×10^{-5}	9.19×10^{-7}	2.86	0.27
24	4.22×10^{-5}	8.61×10^{-7}	7.52	0.01
25	1.68×10^{-5}	2.18×10^{-6}	1.31	0.02
26	5.06×10^{-5}	1.80×10^{-6}	10.00	0.06
27	5.56×10^{-5}	1.06×10^{-6}	9.69	0.00
28	1.06×10^{-4}	1.18×10^{-6}	1.93	0.99
29	8.03×10^{-5}	1.12×10^{-6}	5.34	0.19
30	6.69×10^{-5}	9.83×10^{-7}	5.03	0.09

[a]Ks = saturated hydraulic conductivity of A horizon. Saturated hydraulic conductivities of other soil horizons were calculated proportionately.

4. RESULTS AND DISCUSSION

Among the 20 realizations of scenario 1 (no engineering designs), 13 of them developed perched water tables in the stormflow zone (Table 2) (e.g., realization 5 as shown in Fig. 5). Those that did not develop perched water tables typically had high hydraulic conductivity, which indicated that development of perched water tables was inversely related to the parameter. Regression on ranks of perched water tables indeed suggested that the horizontal extent of perched water tables was inversely correlated with hydraulic conductivity and weakly positively correlated with rainfall rates (Table 4).

Velocity in the stormflow zone was higher because of the higher conductivity in the associated soil horizons A and B relative to vadose and groundwater zones that largely consisted of the C horizon (not shown). Discharge rates near the bottom of the hillslope, in fact, suggested that less than 3% of the outflow was contributed by groundwater (Table 3). Regression on ranks of discharge rates indicated that hydraulic conductivity was the most influential parameter (Table 4). A plot of discharge rates vs hydraulic conductivities suggested a strong correlation between the target variable and the parameter (Fig. 6).

For scenarios 2 and 3, in which one single cap was placed on the hilltop and the middle hillslope, respectively, the caps generally resulted in disappearance of the perched water table in the stormflow zone right beneath the caps and/or water table depression in the vadose zone (Fig. 5). Scenario 3, with a single cap on the middle hillslope, however, may not be effective in isolating the underlying trenches, as suggested by velocity plots of the realizations (e.g., Figure 7 for realization 15). High velocity in the stormflow zone may result in inundation of trenches because rainwater may reach the trenches laterally from underneath the cap.

A French drain (scenario 4) alone was not an effective design to isolate waste trenches (e.g., realization 15, shown in Fig. 8). The unsaturated area was further extended downslope of the drain, but surface infiltration may result in recharge to the trenches and leakage of waste to underlying saturated zones. Combinations of engineering designs are beyond the scope of the current study, but on the basis of the results from cap and French drain simulations, the use of both French drains and caps should prove very effective in lowering or eliminating perched water tables and in isolating areas downslope of the

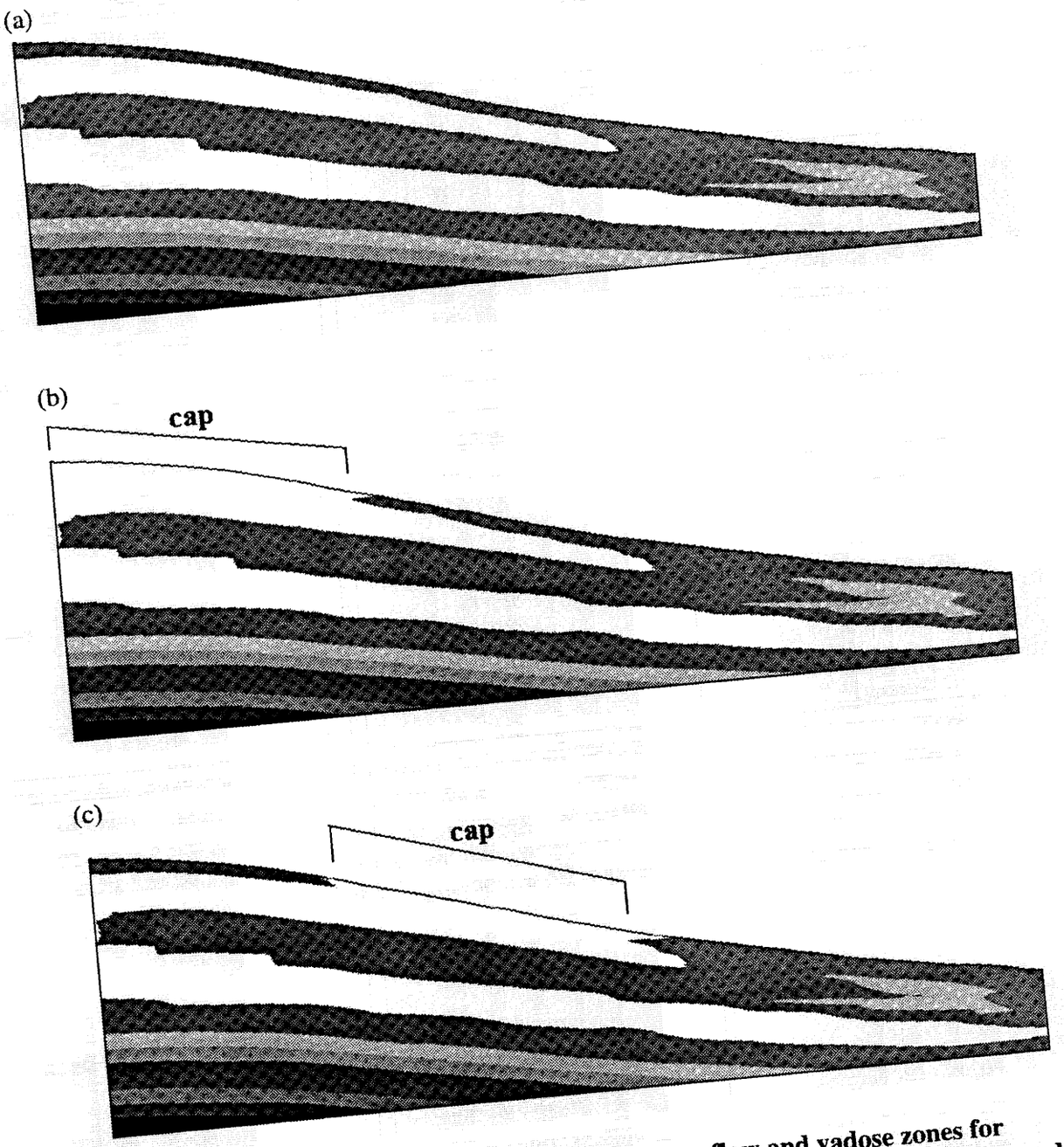

Fig. 5. Perched water table development in the stormflow and vadose zones for realization 5 with scenarios: (a) no remediation design, (b) a cap on the hill top, and (c) a cap on the middle hillslope. The unshaded areas are unsaturated.

Table 4. Coefficients and statistics of regression equations on ranks.

target variable (rank)	intercept	K_s[a]	infiltration rate[a]	anisotropy ratio[a]	multiple correlation coefficient
groundwater flux %, scenario 1	0.236	0.990 (0.997)	-0.033 (-0.194)	0.020 (0.107)	0.998
perched water table, scenario 1	14.191	-0.809 (-0.867)	0.315 (-0.441)	0.143 (-0.045)	0.930
groundwater flux %, scenario 2	0.758	0.967 (0.983)	-0.080 (-0.239)	0.040 (-0.129)	0.988
groundwater flux %, scenario 3	0.758	0.967 (0.983)	-0.080 (-0.239)	0.040 (-0.129)	0.988
groundwater flux %, scenario 4	0.236	0.990 (0.997)	-0.033 (-0.194)	0.020 (0.107)	0.998
groundwater flux %,scenario 5	5.773	0.656 (0.598)	0.144 (-0.014)	-0.173 (-0.091)	0.637
unsaturated area change, under the cap, scenario 2	16.7052	-0.866 (-0.866)	0.096 (0.218)	0.179 (0.096)	0.888
unsaturated area change, downslope of the cap, scenario 2	3.806	0.877 (0.875)	-0.062 (-0.186)	-0.178 (-0.098)	0.894

[a]Ks = rank of saturated hydraulic conductivity of A horizon. Parameters were substituted by ranks before multiple linear regression. Values in parentheses are linear correlation coefficients associated with the parameters.drains. Questions regarding the relationship between the depth of drain and the designed increase of downslope unsaturated areas, however, remain to be answered by further modeling studies.

Clay lenses in the unsaturated zones (scenario 5) resulted in alteration of flow patterns in these regions. The clay lens at the middle hillslope divided the flow processes into largely recharge to groundwater at the upper hillslope and discharge to surface water at the lower hillslope (e.g., realization 28, shown in Fig. 9). While realizations with low recharge rates still resulted in perched water tables in the stormflow zone (not shown), realizations similar to that of Fig. 9 suggested that the midslope clay lens became a barrier for downslope movement of water in the vadose zone. Infiltration upslope of the clay lens recharged directly to local groundwater. The clay lenses near the top of the hill also diverted infiltration in an opposite direction to the hillslope and, in fact, suggested that

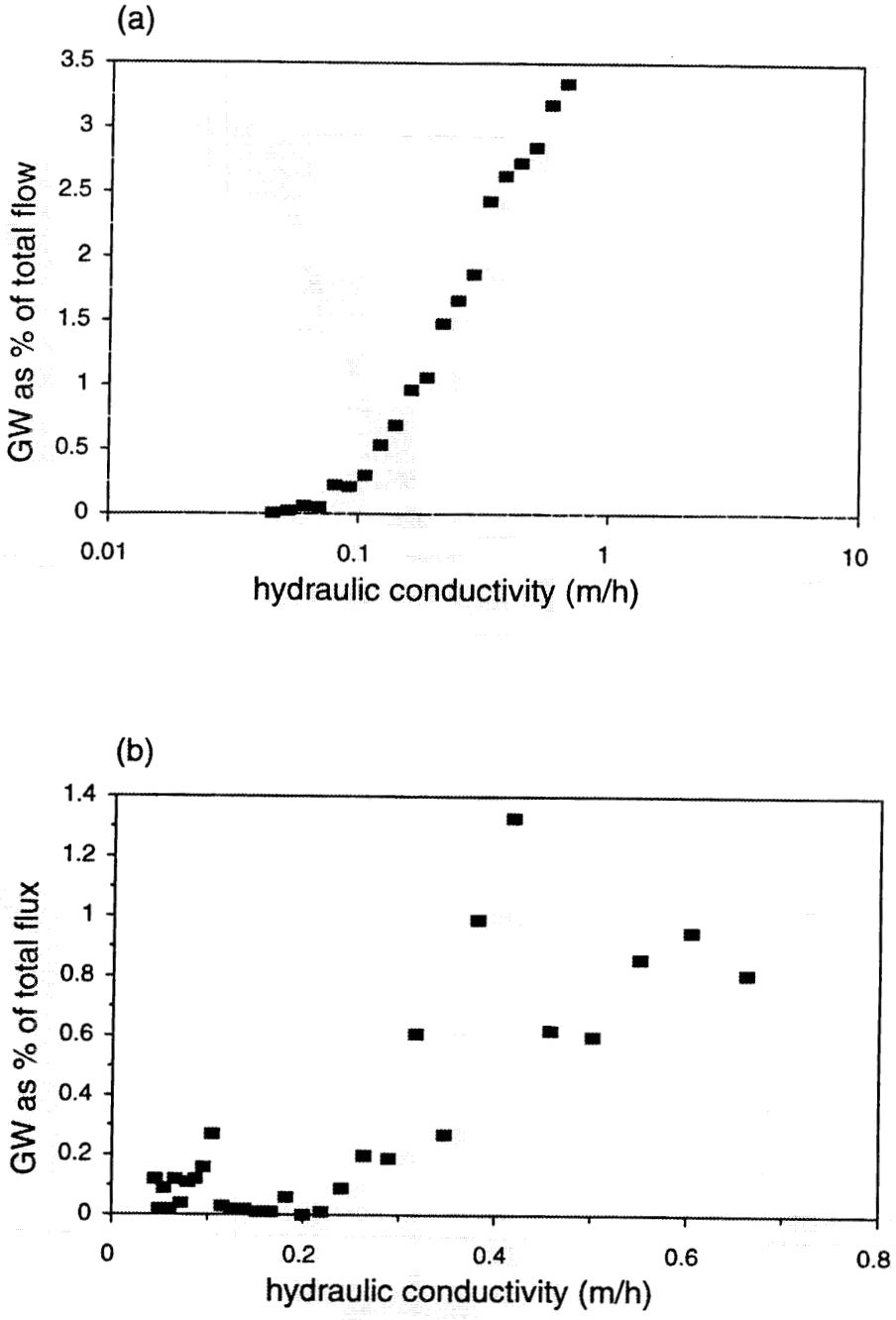

Fig. 6. Relation between groundwater discharge and hydraulic conductivity: (a) layer cross section with no clay lenses, and (b) cross section with clay lenses. Groundwater discharge is expressed as percentage of total flux that includes discharge from stormflow and vadose zones.

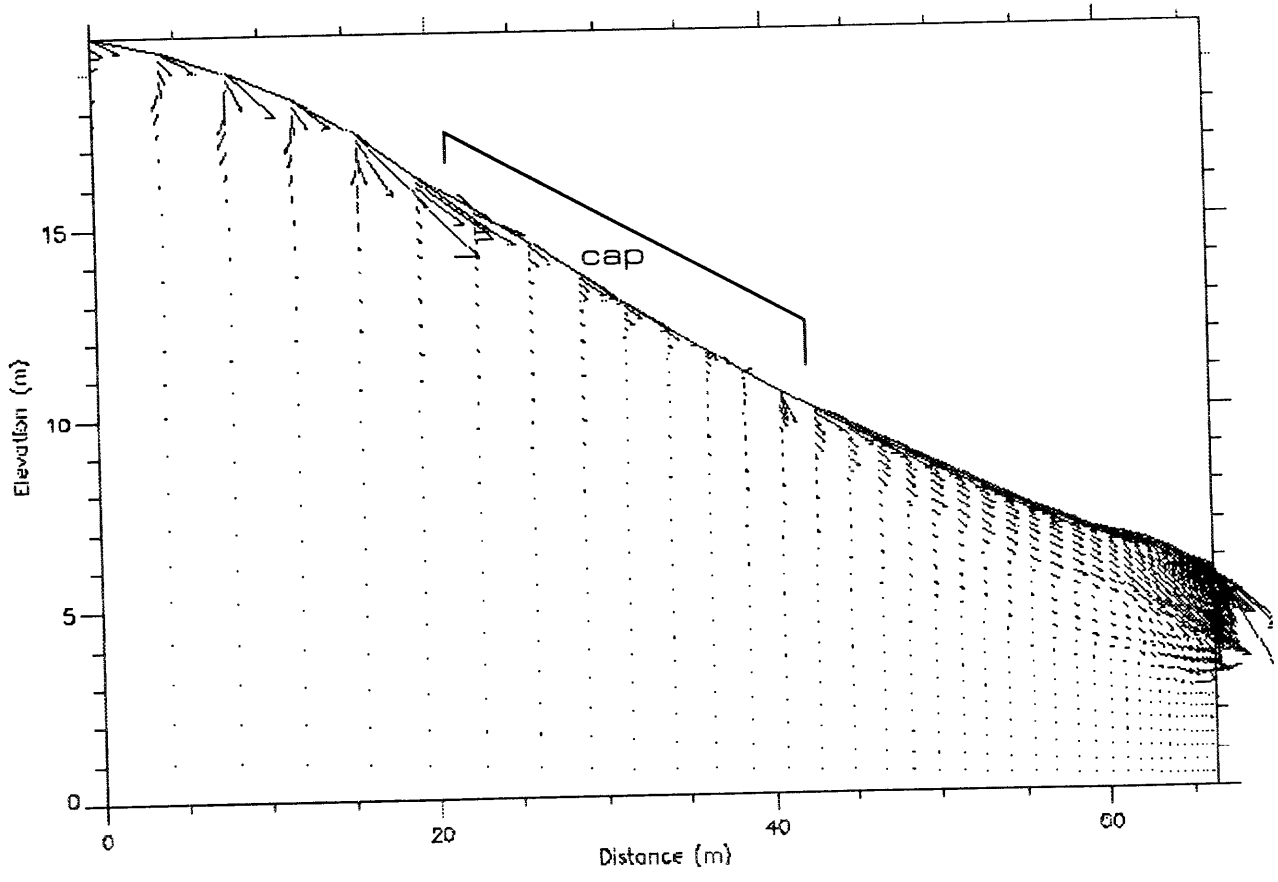

Fig. 7. Darcy velocity distribution for realization 15 with a cap at the middle hillslope

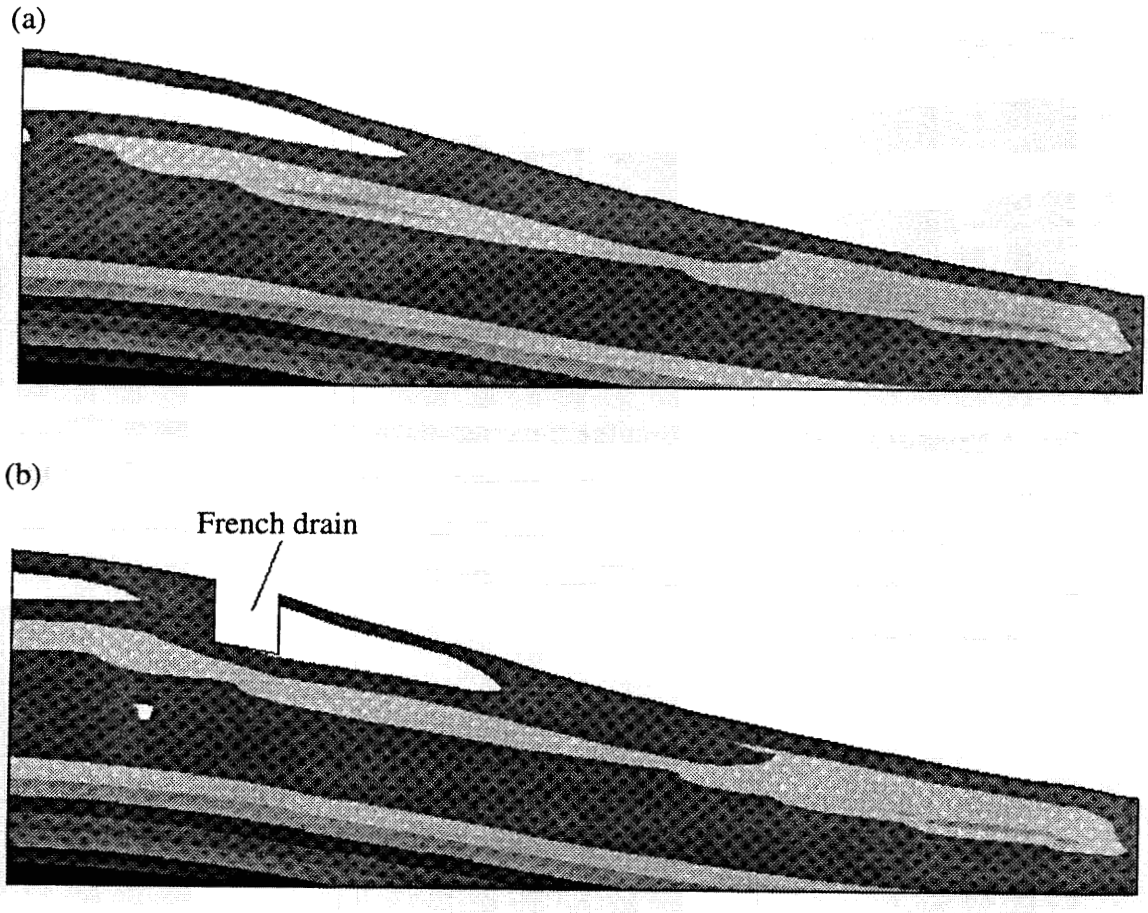

Fig. 8. Comparison of unsaturated areas (a) before and (b) after a French drain was placed on the hillslope. The unsaturated areas downslope of the French drain increased and lengthened after the remediation design.

no-flow vertical boundary at the hilltop may not be representative of the geological structure of the slope. Lithological structures will need to be accounted for if flow processes are to be studied for small-scale problems. Local heterogeneities such as the clay lenses in this scenario are very expensive to characterize, but their effect on groundwater recharge and discharge to surface water cannot be overemphasized.

Regression on ranks suggested that, for scenarios 1 to 4, the most important parameter with respect to discharge rates near the stream was hydraulic conductivity (Table 4). The target variable and the parameter were highly correlated (Table 4) with linear correlation coefficients greater than 0.98 (Table 4). For the horizontal extent of perched water tables

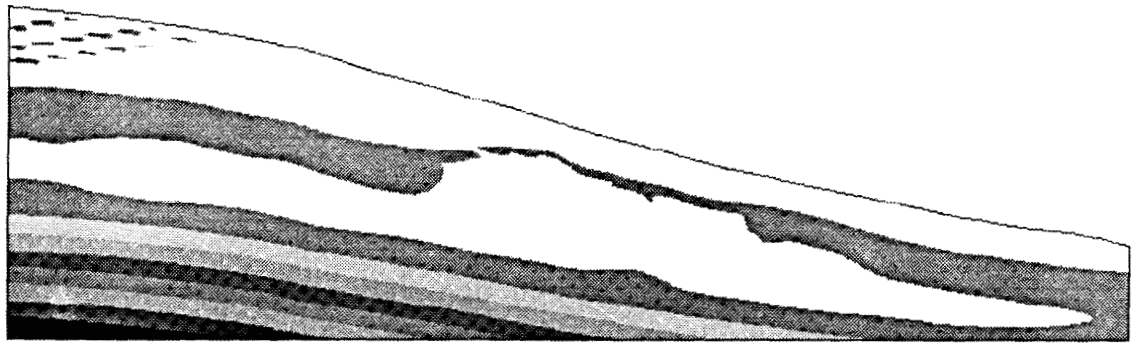

Fig. 9. Pressure head distribution for the cross section with clay lenses. The clay lens at the middle hillslope was a barrier for downslope movement of water infiltrating through the upper half of the slope. As a result, this water recharged directly to the groundwater flow zone and water infiltrating through the other half of the slope discharged to surface streams.

(scenario 1 only), the target variable was inversely related to hydraulic conductivity, and the contribution of rainfall intensity was more noticeable (Table 4). Anisotropy was relatively the least important parameter for all the target variables.

The effect of the caps on various sections of the hillslope can be measured either by the depression of perched water tables or the increase of unsaturated areas. Generally speaking, the perched water table in the stormflow zone right beneath the caps disappeared and the unsaturated areas increased. However, a noticeable difference in the change of unsaturated areas existed between the area underneath and downslope of the cap. For example, the change of these unsaturated areas for scenario 2 was not sensitive to hydraulic conductivity until it was higher than 0.3 m/h (Fig. 10). The unsaturated areas underneath and downslope of the cap were also related to hydraulic conductivity differently. Unsaturated areas under the cap decreased with hydraulic conductivity, while they increased with hydraulic conductivity downslope of the cap. This implied that the effectiveness of the cap was not only location dependent (comparing scenarios 2 and 3) but also conductivity dependent. To implement a cap, one will need to consider the topography and the hydraulic conductivity of the capping areas. For scenario 4, with a French drain on the upper hillslope, no relationship was observed between the extent of unsaturated areas and the parameters.

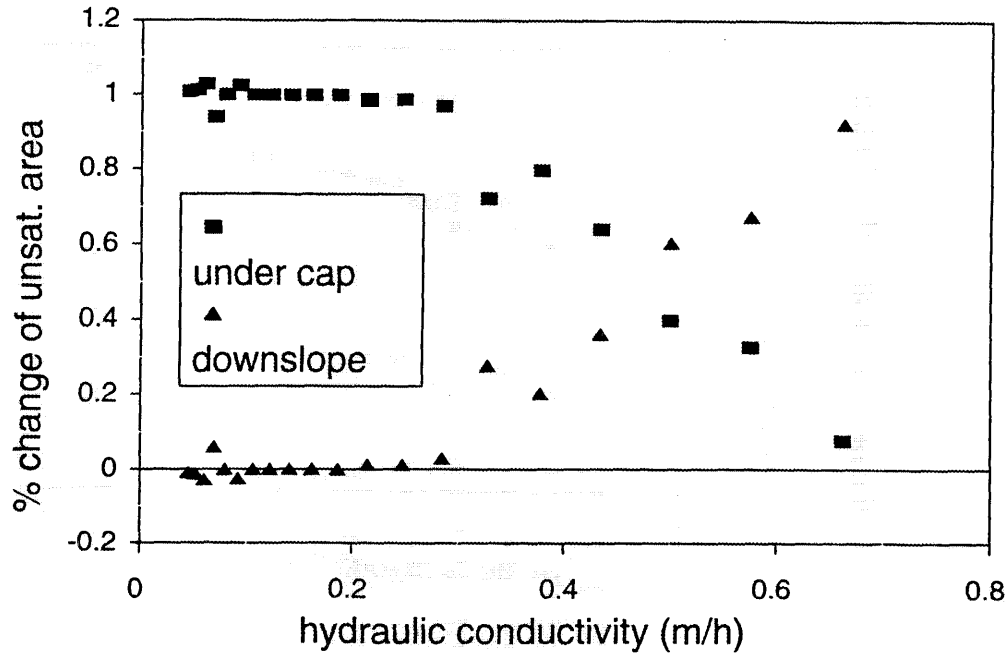

Fig. 10. Effect of caps on the change of unsaturated areas beneath and downslope of a cap on the hilltop. The change of unsaturated areas was sensitive to hydraulic conductivity only when it was lower than 0.3 m/h.

The discharge rates of the cross-section with clay lenses were not correlated with hydraulic conductivity as much as those of the cross-section without clay lenses (Fig. 6). The three parameters accounted for only 64% of the variation (Table 4). This result indicated that hydraulic conductivity can no longer be used as the sole controlling parameter for stormflow designs or data acquisition prioritization. Large-scale models that are based on the simple layered conceptual model (e.g., West and Toran, 1994), although they can be used to provide watershed management information, will need to be modified if subsurface discharge rates are to be obtained locally from the models.

Based on the Latin-hypercube simulations, estimated distributions of the discharge rates are shown for the hillslope with and without clay lenses in Fig. 11. Because the underlying distributions of the parameters were assumed either uniform or log-uniform,

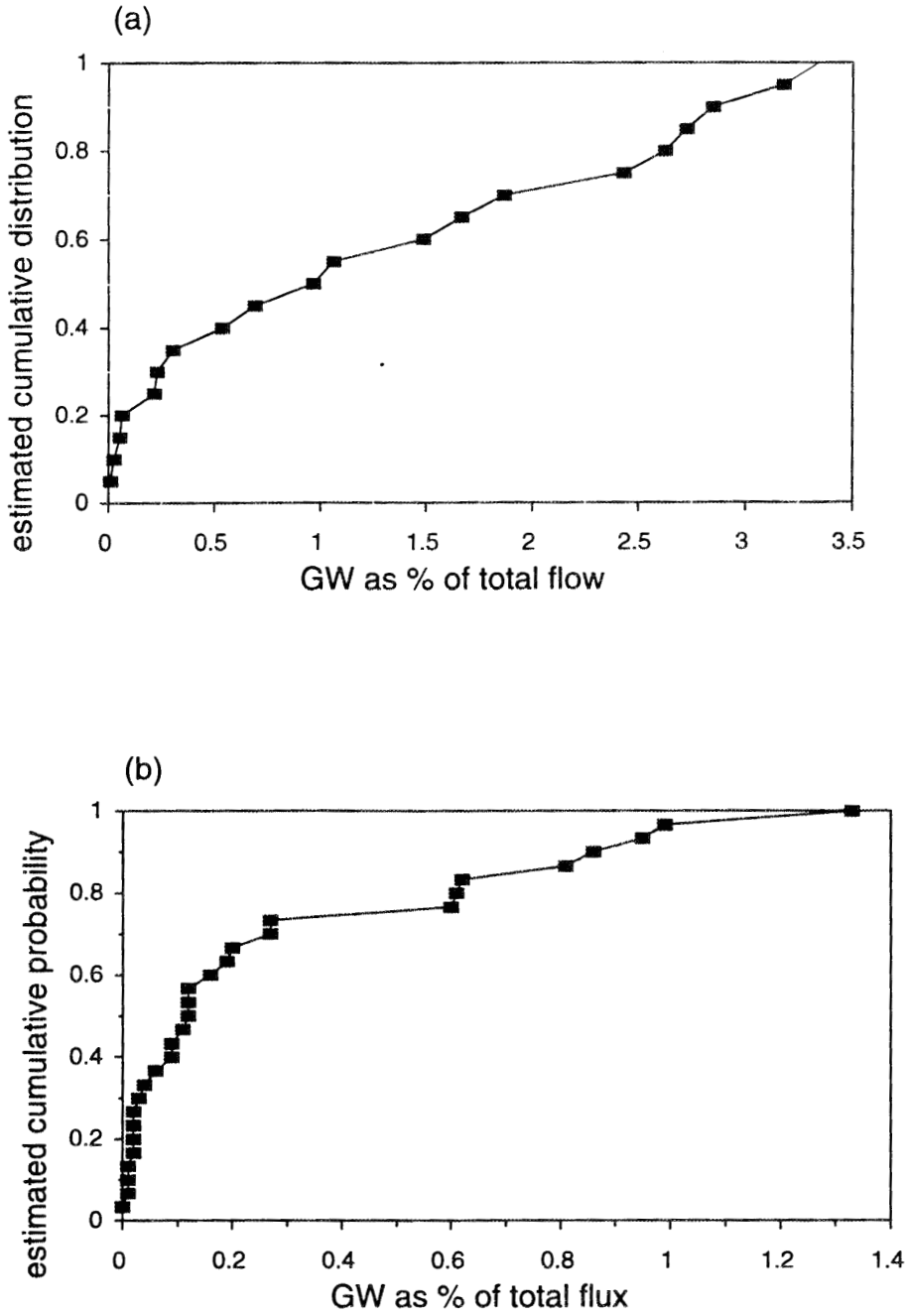

Fig. 11. Estimated cumulative distribution of groundwater flux (as percentage of total flux) for (a) layer cross section with no clay lenses and remediation designs and (b) cross section with clay lenses and without remediation designs.

the results presented here are good only for the initial screening of influential model parameters. In other words, the estimated distributions should be considered preliminary here. Nonetheless, both Fig. 11 suggested that less than 3% of the fluxes to surface water was contributed by groundwater, which agreed fairly well with data inferred from field observations (Solomon et al. 1992).

5. SUMMARY AND CONCLUSIONS

Two-dimensional hillslope cross-section models of a waste disposal site at ORNL were developed to study variably saturated flow processes and to identify important model parameters for further studies of the site. The conceptual model that the hillslope numerical model was based on did not address local heterogeneities; therefore, field data from a proposed disposal site were also used to study the effect of these heterogeneities on small watershed subsurface flow processes. Local heterogeneities, as suggested by the present study, may alter local flow patterns and affect recharge to groundwater zones and discharge to surface waters. Local features such as clay lenses, bedding planes, and geological strikes will need to be addressed carefully when basin or watershed scale models are to be used to obtain off-site water movement.

Uncertainty of model parameters largely arises from the lack of field data needed for modeling studies and is usually analyzed using sensitivity analysis techniques such as Monte Carlo simulations. A Latin-hypercube simulation technique was used in the present study to reduce computational requirements that are usually intense in uncertainty analyses and risk assessment. Among the model parameters treated as randomly distributed variables, hydraulic conductivity was shown to be the most influential parameter to all the target variables. Estimated distribution functions of flux were also obtained, but the results should be considered as preliminary because the underlying distributions of the model parameters had not been adequately characterized.

Results from the present study also indicated that neither of the two engineering designs, capping and French drains, was by itself effective in isolating downslope waste trenches. Both increase of unsaturated area downslope of the drain and disappearance of stormflow zone perched water tables beneath a cap, however, suggested that combinations of the two engineering designs will be more effective than either of them alone. Nevertheless, the numerical models can be used to evaluate various engineering designs and have provided a set of useful tools for further studies of disposal sites at ORNL. The framework for uncertainty analysis can also be adapted to management and decision-making cycles and, with its abilities to prioritize model parameters and to estimate probabilities of target variables, should prove helpful in cutting disposal operation costs.

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