Review of permeability in buried-valley aquifers: Centimeter to kilometer scales

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Abstract Aquifer systems are considered in which measurements of log-permeability (Y) at a 1E-2 m support scale are unimodally distributed as taken within the 1E0 to 1E1 m scale of individual sand and gravel (*sg*) lithofacies, are weakly multimodal at the 1E1 to 1E2 m scale of assemblages of these facies, and are strongly multimodal at the 1E3 m scale of complexes of *sg* facies assemblages juxtaposed with mud and diamicton (*md*) facies assemblages. Contaminant plumes resulting from decades-old disposal have grown to the 1E3 m scale with a high probability of sampling both facies assemblages in the complex. The relevant aspects of the complicated residence time distribution (varying orders of magnitude between the time of travel in preferential pathways through *sg* facies assemblages and the longer time of travel if in part through *md* facies assemblages) of mass at this scale is explained by the heterogeneity in the pattern of facies assemblages in the complex; in-facies permeability structure is not important. However, recent spills and tracer tests create smaller plumes at the 1E1 to 1E2 m scale. Here the spatial structure of in-facies permeability and the spatial structure of facies within the *sg* assemblage is relevant. A hierarchical random space function model gives the global spatial structure of Y as a linear function of the mean, variance, the two point auto and cross-covariance of Y_i for each *i* facies, as weighted by the auto and cross-transition probabilities representing the proportions, the modality, mean and variance in facies lengths, and the juxtapositioning pattern of the facies. This is illustrated with data from an outcrop analog study.
Key words heterogeneity; geostatistics; permeability; scaling; glacial aquifers; contamination

INTRODUCTION

Summarized here are the results of characterizations of permeability and associated sedimentary units across a range of scales summarized conceptually in Fig. 1. The goal of this ongoing project is to statistically characterize the relevant spatial attributes (proportions, geometry and pattern) of the sedimentary units, and the spatial structure of permeability within the units. The sedimentary units exist within a hierarchical system with actually a greater number of hierarchical levels than depicted. The spatial attributes of the sedimentary units are being characterized with the transition probability at each of the hierarchical levels. Log permeability (Y) is being characterized as a continuous random variable within each of the units.

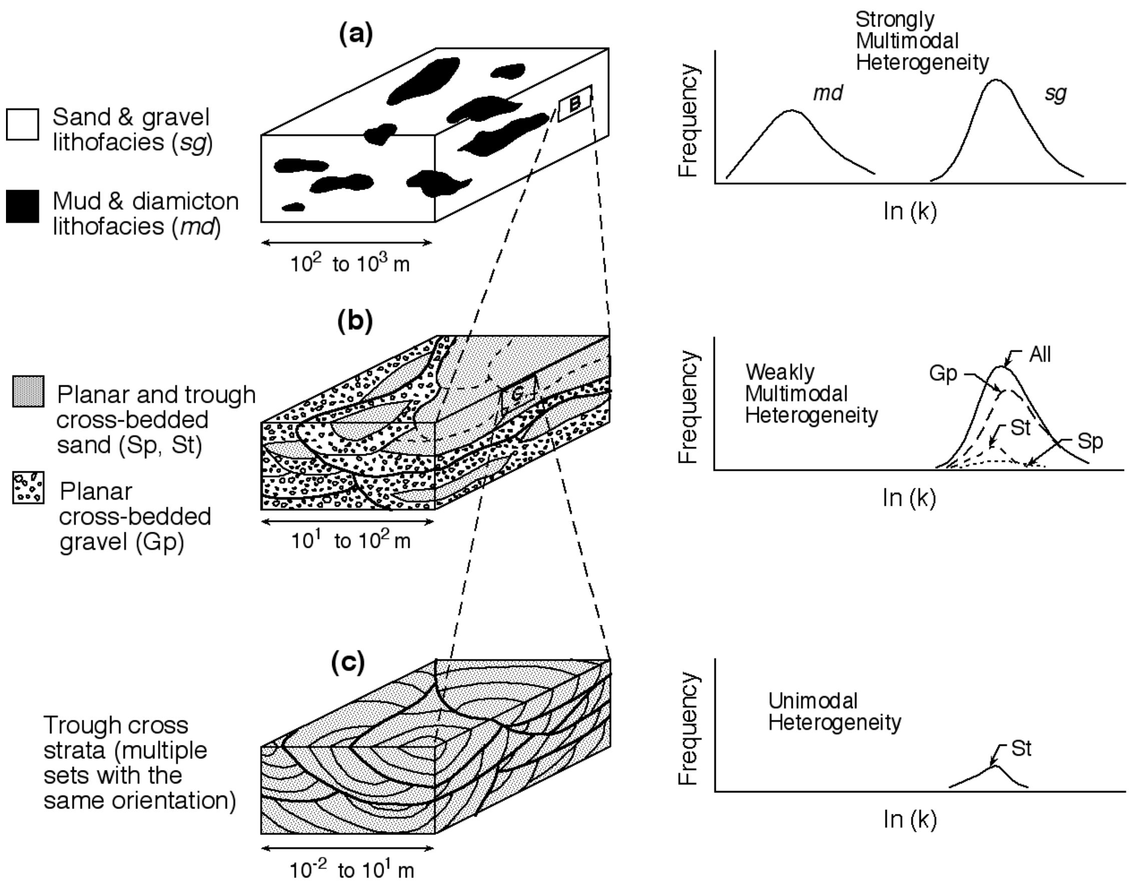


Fig. 1 Hierarchical organization of lithofacies across scales (a)-(c), and corresponding permeability modes (from Ritzi *et al.*, 2002).

The conceptual model in Fig. 1 is derived from our studies of buried-valley aquifer systems in the North American mid-continent. The general ideas presented here may have application in aquifers derived from other depositional process as well. The buried-valley aquifers we have studied occur within the extent of Pleistocene glaciation. Formally pro-glacial valleys, they directed drainage away from ice margins and were in-filled during periods of aggradation (Figs 2 and 3).

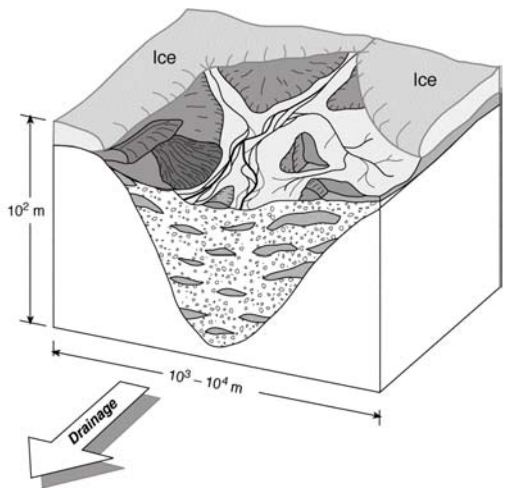


Fig. 2 Depositional environments in the creation of buried-valley aquifers (from Ritzi *et al.*, 2000).

Fig. 3 Province in which buried-valley aquifers occur in North America (from Ritzi *et al.*, 2000).

A variety of depositional processes (e.g. fluvial, lacustrine, glacial) created complex mixtures of two main lithofacies: 1) a sand and gravel facies, *sg*, which predominates, and 2) a mud and diamicton facies, *md*. At the 100 m to km scale, Fig. 1a, the deposits exhibit a strongly bimodal distribution of permeability corresponding to the two larger lithofacies categories. As the scale decreases to the 10 to 100 m scale , permeability becomes weakly multimodal as in Fig. 1b, the modes corresponding to lithofacies which occur at the cm to 10 m scale and within which permeability appears unimodal, as in Fig. 1c.

The conceptual model in Fig. 1 is based in part on data collected from the Miami-Valley aquifer system as shown in Fig. 4. Photographs are given in Ritzi *et al.* (2002). In sand and gravel facies the distributions of air-permeameter measurements (Figs 4b-d) have a central tendency that corresponds closely to pumping test measurements (Fig. 4a), with more variance because of the "hydraulic averaging" of individual occurrences of relatively higher and lower permeability facies, inherent in estimates derived from pumping tests (Fig. 5). The data do not support the existence of a measurement scaling effect.

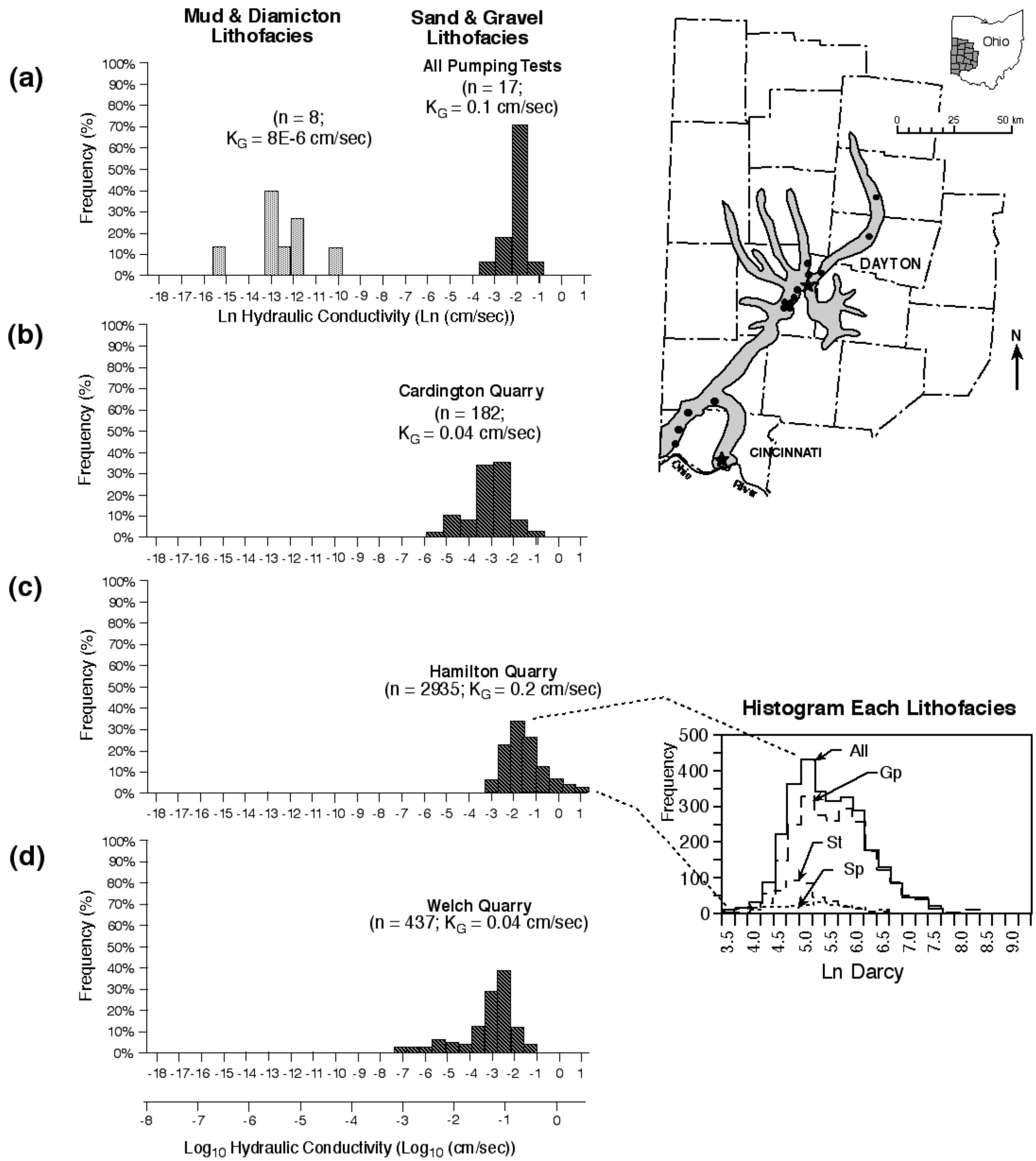


Fig. 4 Defining modes for permeability. From Ritzi *et al.* (2002) as adapted from Titzel (1997).

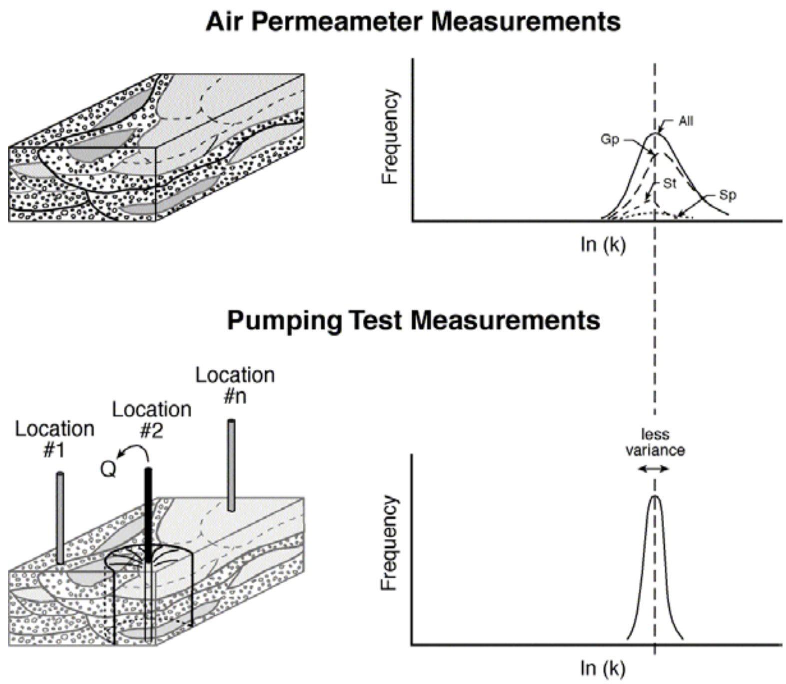


Fig. 5 Comparing measurements from small and large support scales. From Ritzi *et al.* (2002).

At each relevant scale we develop transition probability models (Carle & Fogg, 1996) which represent the volumetric proportions, geometry (mean length and variance in length in each direction) and pattern of the units, as described by Ritzi (2000). Some of the relevant results from that paper are summarized here. For a given facies, the sill of the autotransition probability represents its proportion in the assemblage, the slope (lag=0) intercept represents the mean length and embeddedness, and shape and range represent the variance in length. Figure 6a shows the autotransition probability for a system with two facies, each in large numbers, in equal proportion, and with equal mean lengths in whatever is the direction represented. It can be shown analytically that when facies length is a constant the probability of internal transitions dies off linearly to zero at where lag distance equals facies length. As lag distance further increases the probability of autotransitions that bridge over the other facies type increases linearly, reaching a probability of 1 at double the facies length. The cycle repeats at larger lags giving a perfectly periodic function in curve *a*. As the variation of facies lengths is made to increase, the probability of internal autotransitions at lags equal to the mean length increases, and the probability of bridging transitions at double the mean length decreases, and thus the periodicity is dampened out. Curves *b-e* correspond to coefficient of variation in facies length, *cv*, equal to 0.20, 0.75, 0.93, and 1.32 respectively. Curve *f* is from a bimodal distribution of facies lengths with *cv* equal to 1.32. We see that as the coefficient of variation for the facies increases toward unity the effective range of the autotransition probability or indicator variogram increases, while the structure evolves from a periodic linear structure, to a somewhat periodic structure close to the spherical model, to an aperiodic structure close to the exponential model.

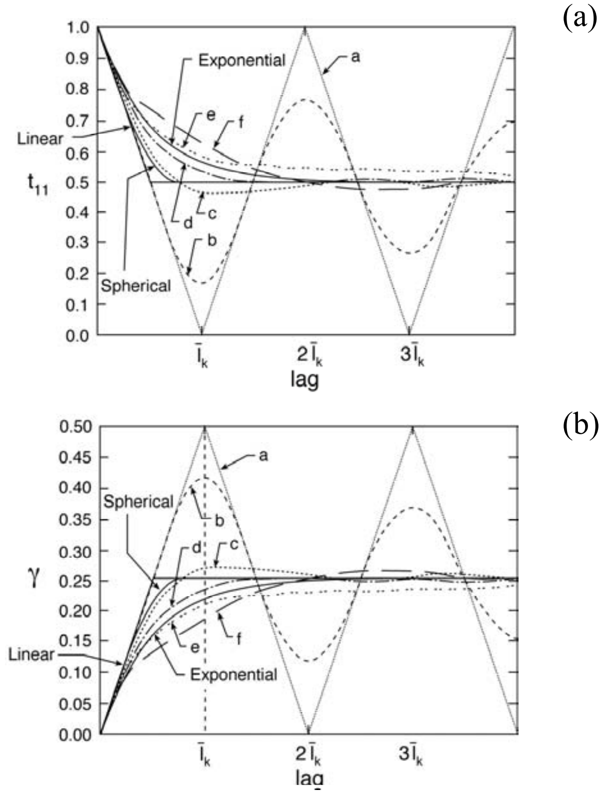


Fig. 6 Analysis of (a) autotransition probabilities and (b) indicator semivariograms. From Ritzi (2000).

DEFINING THE RELEVANT QUESTIONS

Importantly, the real plumes occurring in buried-valley aquifers that we are familiar with are either old and large or new and small. Older plumes are those originating from disposal decades ago. These usually are from dumps filling old gravel pits, thus local sources, which created plumes that have grown to the kilometer scale. Older plumes have sampled the strongly multimodal heterogeneity as depicted in Fig. 1a. New plumes originating from recent spills or tracer tests have a high probability of only sampling heterogeneity within the *sg* facies, as depicted in Fig. 1b.

Old large plumes

The predominant control on the spatial moments for mass in old large plumes is the strongly multimodal aspects of heterogeneity, as represented in the transition probability models for facies *sg* and *md*. Ritzi *et al.* (2000) developed and compared models in a number of buried-valley locations: the White River aquifer in Indiana and the Miami Valley aquifer in Ohio. Despite the general complexity of glacial and glacio-fluvial settings, similarities among the major depositional controls create optimism for finding similar models in separate aquifers. The depositional areas were tectonically quiescent, influenced by a similar climatic regime, and had topography that laterally constrained the extent of facies assemblages.

The method and results of Ritzi *et al.* (2000) are briefly summarized here. A binary indicator data base was created from categorizing and coding lithologic data according to inferred permeability, as below in Fig. 7.

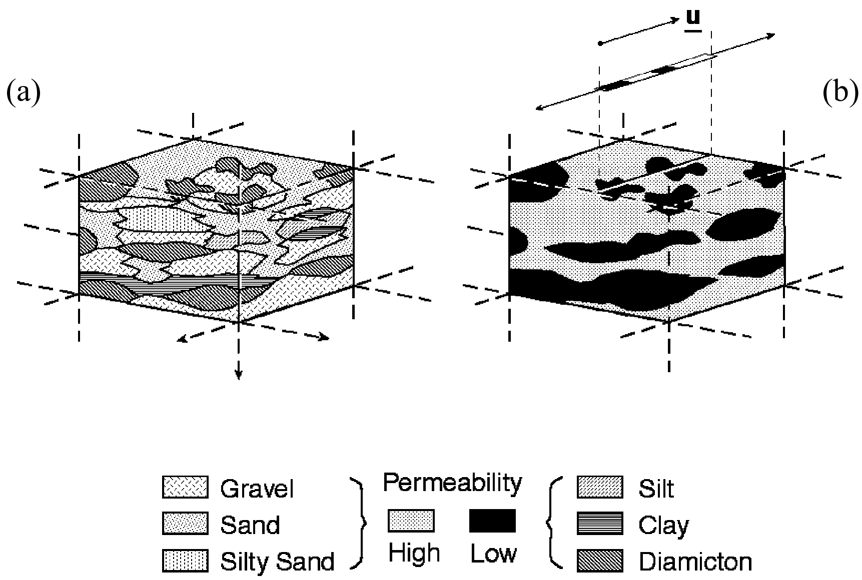
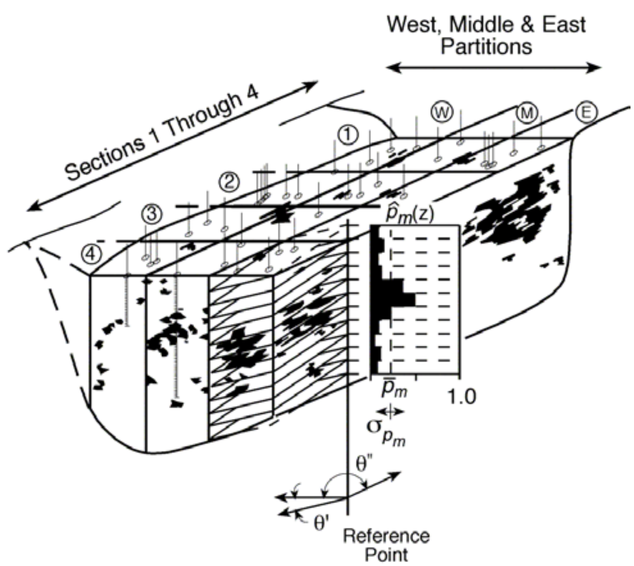


Fig. 7 Combining (a) lithofacies to form (b) permeability facies. Modified from Ritzi (2000) and Johnson & Dreiss (1989).

Figure 8 conveys an iterative, exploratory analysis used in which we sought statistical populations in which the proportions of mud and diamicton (*md*) and sand



and gravel (*sg*) are stationary.

Fig. 8 Method for defining data populations. From Ritzi *et al.* (2000).

The results gave rise to a general model for heterogeneity in valley-fill sediments along the proglacial sluiceway in both aquifers. The proportion of *md* facies is approximately 15%. The mean thickness of *md* facies is 3.5 m and on the order of 10 m for *sg* facies. The coefficient of variation in thickness for either facies is on the order of 1, with thickness ranging over orders of magnitude. Correspondingly the vertical autotransition probabilities are exponential, and they are relatively symmetric with effective range on the order of 10 m. The lateral facies lengths are indicated to vary over orders of magnitude and to be multimodally distributed, with mean lengths on the order of 10^2 m, effective range in correlation structure on the order of 10^3 m, and lateral anisotropy ratio less than 2. There is some variation in how the *md* facies are vertically embedded within the *sg* facies. The White River aquifer and areas in the Miami aquifer have facies proportions relatively stationary with elevation. In other areas of the Miami there are near-horizontal zones having relatively higher or lower proportions (see Ritzi *et al.*, 2000, Fig. 8, or Ritzi *et al.*, 2002, Fig. 11 (in colour)).

The question of what details to include in the general model may be best answered by considering how the model is to be used. Our interest is in using the model to represent facies assemblage heterogeneity at the scale of old large solvent plumes in ground water flow and transport models. In this case, differences will be meaningful if they cause significantly different transport statistics. To illustrate, six scenarios were created to reflect variations on the general model that are likely to exist (Table 1). In Monte Carlo simulations, realizations of facies distributions corresponding to each scenario were generated with sequential indicator simulation (Fig. 9).

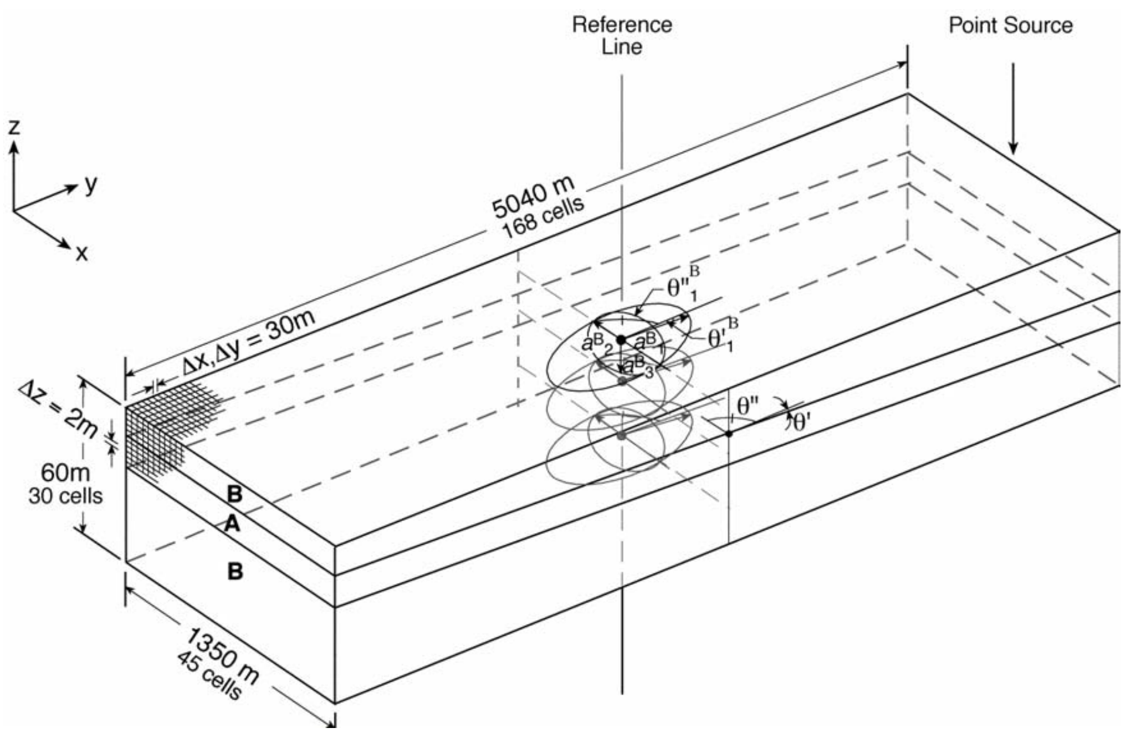


Fig. 9 Grid and parameters for indicator simulation. From Ritzi *et al.* (2000).

Table 1 Parameters used to create heterogeneity scenarios. Angles given are in degrees counterclockwise from the *y* coordinate axis. Y- yes, N - no.

Scenario	I	II	III	IV	V	VI
σ_{pmd}	low	high	high	high	low	low
dipping zones	N	N	Y	Y	N	N
anisotropy	N	N	N	N	Y	Y
Orientation of zones:						
θ'	0	0	1	1	0	0
θ''	--	--	0	90	--	--
Global proportion and zonal proportion of *md* facies (as volume fraction):						
p_{md}	0.15	0.15	0.15	0.15	0.15	0.15
p_{md}^{A}	0.15	0.33	0.33	0.33	0.15	0.15
p_{md}^{B}	0.15	0.05	0.05	0.05	0.15	0.15
Orientation of principal directions of correlation:						
θ'^{A}_{1}	0	0	1	1	0	0
θ''^{A}_{1}	0	0	0	90	0	90
θ'^{B}_{1}	0	0	1	1	0	0
θ''^{B}_{1}	0	0	0	90	0	90
Effective range of exponential variogram (meters):						
a^{A}_{1}	10^3	10^3	10^3	10^3	10^3	10^3
a^{A}_{2}	10^3	10^3	10^3	10^3	5×10^2	5×10^2
a^{A}_{3}	10^1	10^1	10^1	10^1	10^1	10^1
a^{B}_{1}	10^3	10^3	10^3	10^3	10^3	10^3
a^{B}_{2}	10^3	10^3	10^3	10^3	5×10^2	5×10^2
a^{B}_{3}	10^1	10^1	10^1	10^1	10^1	10^1
Conditioning data:						
	N	N	N	N	Y	Y
# Realizations:						
	30	30	30	30	10	10

As with *Desbarats* (1990), most residence time distributions are characterized by distinct parts to the curves: a steep section characterizes the arrival of "fast" particles which have traveled along preferential channels; later sections with a gradual rise characterize drawn-out arrivals of "slow" particles which have traveled at least partly in *md* facies; subhorizontal sections indicate an almost total absence of particle arrivals; subsequent steeply rising sections characterize the arrival of clusters of slow particles. A time sequence shows the position of particle groups for one realization in Scenario I in Ritzi *et al.* (2000, Fig. 11, or Ritzi *et al.*, 2002, Fig. 12 (in colour)).

The variants on the general model that were found to occur within and between the aquifers give rise to similar statistics on macrodispersion (Table 2) with, importantly, a high probability that slow groups of mass will occur. Thus, the general model appears to convey the information pertinent to macrodispersion in both aquifers in this context.

Table 2 Results of Monte Carlo simulations. With p_{md} specified as 0.15.

Scenario	I	II	III	IV	V	VI
Probability (as %) a slow group will occur:	80	100	80	100	93	100
Probability (as %)mass in the slow group will exceed:						
1% of total	40	73	37	63	10	70
10% of total	13	20	3	13	0	7
$\langle\sigma_x\rangle$ (m)	36	51	32	39	26	35
$\langle\sigma_z\rangle$ (m)	4	5	6	4	6	5
Parameters as in Scenario I, changing p_{md}:						
p_{md}		0.05	0.15	0.28		
Probability (as %) a slow group will occur:		50	80	100		
Probability (as %) mass in the slow group will exceed:						
1% of total		20	40	80		
10% of total		7	13	42		
$\langle\sigma_x\rangle$ (m)		15	36	89		
$\langle\sigma_z\rangle$ (m)		2	4	6		

Conclusions and future work on heterogeneity relevant to old large plumes

For the old large plumes we are familiar with, the fast group of mass has already arrived at down-gradient receptor points and is under some remedial action. The high probability for slow groups of mass to arrive later suggests that a long term perspective is required on the arrival of contamination and on the corresponding length of time that will be required for remediation. Research is needed on the question of what intrinsic biodegradation is to be expected within facies *md*. Representing weakly multimodal heterogeneity that exists within facies *sg* is not important in these cases. Thus, as a practical matter, the hierarchical scaling relationship for permeability that we have developed need not be applied across all scales depicted in Fig. 1. General models arise only from many well-studied examples. We are studying data rich areas in more buried-valley aquifers to the west including the Mahomet aquifer (Illinois) and the Sundre, New Rockford, and Spiritwood aquifers (Saskatchewan and North Dakota), and to the east including the Woburn aquifer (Massachusetts).

FUTURE WORK RELATED TO NEW SMALL PLUMES

Future sources of groundwater contamination, such as from accidental spills or leakage from tanks and new landfills, are likely to be known or detected rapidly and generate a relatively rapid response while the plume is still small. Buried-valley aquifers are predominantly composed of the *sg* facies. Thus, there is a high probability that future source areas and resulting plumes will exist within the *sg* facies. The predominant control on the spatial moments for mass in new small plumes is expected to be the weakly multimodal aspects of heterogeneity, motivating the study of the relation between sedimentary architecture and permeability at and below the scale of Fig. 1b. Here the hierarchical scaling relationship is important across a number of levels. In ongoing work we are characterizing the proportions, geometry and patterns of a hierarchy of depositional structures. This hierarchy includes laminea, groups of laminea (beds or sets), groups of beds (cosets or mesoforms), and mesoform assemblages (macroforms). The models for covariance and macrodispersion for bimodal media (Rubin, 1995) have been expanded for a greater number of modes and a greater number of hierarchical levels. The Scheibe numerical aquifer (Scheibe & Freyberg, 1995) provides an opportunity to study the hierarchical scaling relationship of second order moments on [Y(x),Y(x')], in an exhaustively sampled, three dimensional representation of a lateral accretion complex, and thus an opportunity to test our model. The results of this work Ritzi *et al*. (in review) will be the focus of the oral presentation at the conference.

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