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THREE-DIMENSIONAL CHARACTERIZATION OF HYDRAULIC PROPERTIES OF A COARSE GLACIAL OUTWASH DEPOSIT

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ABSTRACT

Glacial outwash deposits form important aquifers throughout the northern United States and Canada. They provide large groundwater yields because of their generally high hydraulic conductivity. However, their high conductivity also allows them to rapidly transmit contaminants. The threat of contamination to water supply wells has stirred interest in better understanding the heterogeneity within these aquifers as a way to predict contaminant movement. Heterogeneity within geologic materials is often conceptualized as one or more high conductivity lenses or layers within a matrix of lower conductivity material. When a contaminant is released in an aquifer of this type, it flows preferentially within these lenses. Identification of these preferential flow paths and the geologic processes that control their distribution is critical to predicting contaminant movement and mitigating the impact of contaminants on water resources and, thus, protecting public drinking water supplies. The heterogeneity of a gravelly outwash deposit located in southern Wisconsin was examined by detailed mapping and numerical modeling. The mapping was conducted on a scale typical of point-source contaminant release (a scale of 1 to 10's of meters). Most hydrogeologic field studies at this scale attempt to infer geologic heterogeneity from measurement of aquifer properties and limited borehole sampling.

In this study individual sedimentary bodies were mapped as they exist in the deposit. A numerical model based on the three-dimensional distribution of the mapped heterogeneities was constructed to simulate groundwater flow through the deposit. The model was then linked to a particle tracking code to demonstrate the effect of the mapped units on contaminant movement. Most of the site is a matrix of high conductivity and gravel with rare discontinuous zones of even more conductive, relatively well-sorted gravel and layers of fine-grained, lower conductivity sand. These two sediment types constitute the high and low conductivity end members of the facies at the site. Because they are relatively rare, these units would intuitively have little impact on contaminant movement. However, areas of the site in which preferential contaminant movement is indicated by the model are closely associated with these two facies. The coarser grained facies affect contaminant movement because of their high conductivity. The fine-grained facies acts as a stratigraphic marker that mantles the basal erosional boundaries of channel scours. These channels are commonly filled with laterally continuous combinations of coarse-grained facies. The relative hydraulic conductivity of the course- grained facies and the directional trend of the channel scours (delineated by the fine-grained facies) are largely responsible for the preferential concentrations of contaminants indicated by the model.

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INTRODUCTION

Studies of aquifer heterogeneity often lack discrete spatial data on the distribution and hydrogeologic characteristics of the aquifer. These data are critical for defining the distribution of the velocity field within an aquifer that controls contaminant movement. Mathematical and statistical techniques can be employed to predict contaminant movement at various scales in heterogeneous aquifers, however, all of these methods require realistic geologic information to construct models of heterogeneity.

A considerable gap exists between the ability of the hydrogeologist to construct models of heterogeneity and the availability of field data on which to base and compare these simulations. The gap exists because detailed geologic information is usually not available for a specific site without enormous expenditures of time and money. One way to approximate the distribution of hydrogeologic heterogeneity is by analogy to site-specific examples that have a particular arrangement of sediment with distinct properties. These similar geologic materials are described by sedimentologists as geologic facies. In many cases, the processes that influence the characteristics and arrangement of these facies can be inferred from commonly available information such as published maps, reports, and boring or water well records. These sources of information may allow interpretation of general trends in grain size distribution and the nature of facies present. Coupling these sources of information on the likely distribution of geologic materials with a representative suite of detailed site examples can provide a scaled representation of heterogeneity for input or calibration for modeling.

This study is one of three designed to characterize the hydrogeologic properties of three major types of sediment associated with glaciation. Sandy basal till was examined by Rayne (1993) and Rayne et al. (1994). In this case, the grain size distribution of the sediment is uniform, producing a narrow range of hydraulic conductivity and an isotropic medium with respect to hydraulic conductivity. A second study (Anderson, In progress) examines the extremely variable sediments of the supraglacial environment. These sediments are very anisotropic and vary greatly over short distances vertically and horizontally.

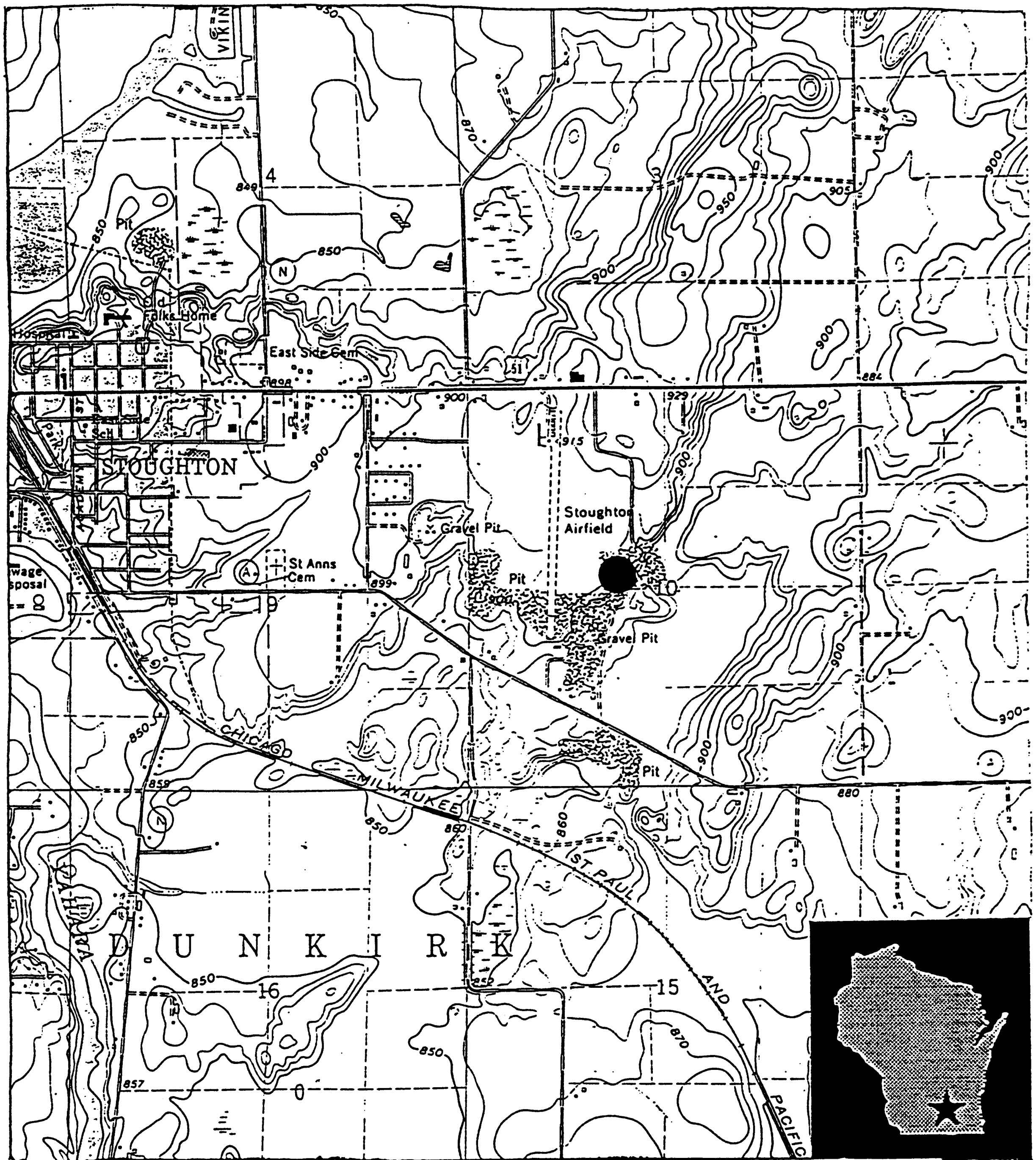
An example of the three-dimensional distribution of sediments within a glaciofluvial deposit with variability on the scale of 1 to 10s of meters is presented here. An outwash deposit in south-central Wisconsin was mapped in outcrop as it was incrementally exposed during commercial gravel quarrying. The site was also mapped with ground-penetrating radar (GPR) prior to excavation (Aiken, 1993). Numerous grain size analyses and oriented laboratory permeability measurements were used to estimate the hydrogeologic properties of the mapped units (facies), resulting in a three-dimensional map of the hydraulic conductivity of the outwash deposit.

Because the deposit was above the water table, the effect of these facies on contaminant movement could not be measured in the field. Instead, the outwash deposit was evaluated using a numerical flow model linked with a particle tracking code by assuming that the aquifer was saturated.

Although no two outwash deposits are identical, a similar distribution of facies can be expected in other coarse outwash deposited in a similar position with respect to the ice margin. Thus, the model is not predictive, but it is useful in demonstrating which facies combinations are likely to have the most influence on contaminant movement in similar deposits.

The study site (Figure 1) is located behind the Milton recessional moraine, 2 km east of Stoughton, Wisconsin. The area is underlain by Ordovician dolomite covered by late-Wisconsin glacial sediments deposited by the Green Bay Lobe. The dolomite surface slopes toward the west into a pre-glacial valley. The postglacial topography roughly mimics the surface of the bedrock so that the drainage was from the ice margin east of the site toward the topographically lower outwash and lacustrine and plain to the west. Boring logs and water well records for the site indicate about 20 m of sand and gravel that becomes coarser upward through the deposit.

The field mapping concentrated primarily on the upper 7 m of the outwash deposit, which consists of cobbles, gravel, and sand. To the northeast, this deposit interfingers laterally into layered sand and gravel and silty diamicton (till). Finer outwash is present to the south and west. Paleocurrent measurements made at the site indicate that the meltwater flow direction was generally toward the southwest (Aiken, 1993).



SCALE 1:24000

1 ½ 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 .5 0 1 KILOMETER

CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Figure 1. Location of study site east of Stoughton, south-central Wisconsin.

METHODS AND PROCEDURES

GEOLOGIC MAPPING

The area shown in Figure 2 was mapped during July and August 1991. Each of the curved lines represent the position of the mapped face at the end of a day of the quarrying operation. The pit face was mapped by taking photographs of the deposit approximately twice daily. These photographs were compiled into photomosaic cross-sections that were used as the primary map data. The mapped units were determined by field observation of bounding surfaces, sedimentary structures, and grain size analyses. From these observations, 11 major units, or lithofacies, were described. These are shown in Figure 3. The descriptions of the lithofacies are based on the nomenclature of Miall (1978) and others with some modifications that more accurately represent the lithologies observed at the site.

HYDROGEOLOGIC DATA USED FOR MODEL INPUT

Estimates of hydraulic conductivity based on grain size using the method of Hazen (Freeze and Cherry, 1979), were used to approximate relative contrasts in hydrogeologic properties of the lithofacies. Laboratory permeabilities were also determined for samples with grains smaller than gravel size (Aiken, 1993). The estimates of hydraulic conductivity based on grain size provide an adequate match to the laboratory permeability data.

Based on similarities in hydraulic conductivity, the lithofacies were grouped into hydrogeologic "facies" for use in the model. The term "facies" is used here to denote groups of lithofacies rather than in the formal sedimentological sense of the term as a single distinct geologic entity. For example, lithofacies St and Sh were grouped into facies St/Sh, and lithofacies Gt and Gp were grouped into facies Gt/Gs (Figure 3). Each facies was assigned a single (geometric mean) hydraulic conductivity value.

NUMERICAL MODEL DISCRETIZATION

Because the deposit is unsaturated, the assigned hydraulic conductivity (K) values were used to construct a computer simulation of groundwater flow to demonstrate the effect facies with different hydraulic conductivities had on contaminant movement. A fence diagram constructed from the cross-sections mapped in the field provided the initial three- dimensional model of the site (Aiken, 1993). To meet the needs of the three-dimensional numerical model of the site a three-dimensional grid was superimposed on the fence diagram. A digitizing scheme was employed to transform the irregularly spaced data set from the fence diagram into a uniformly spaced, three-dimensional numeric data set for use in the computer flow

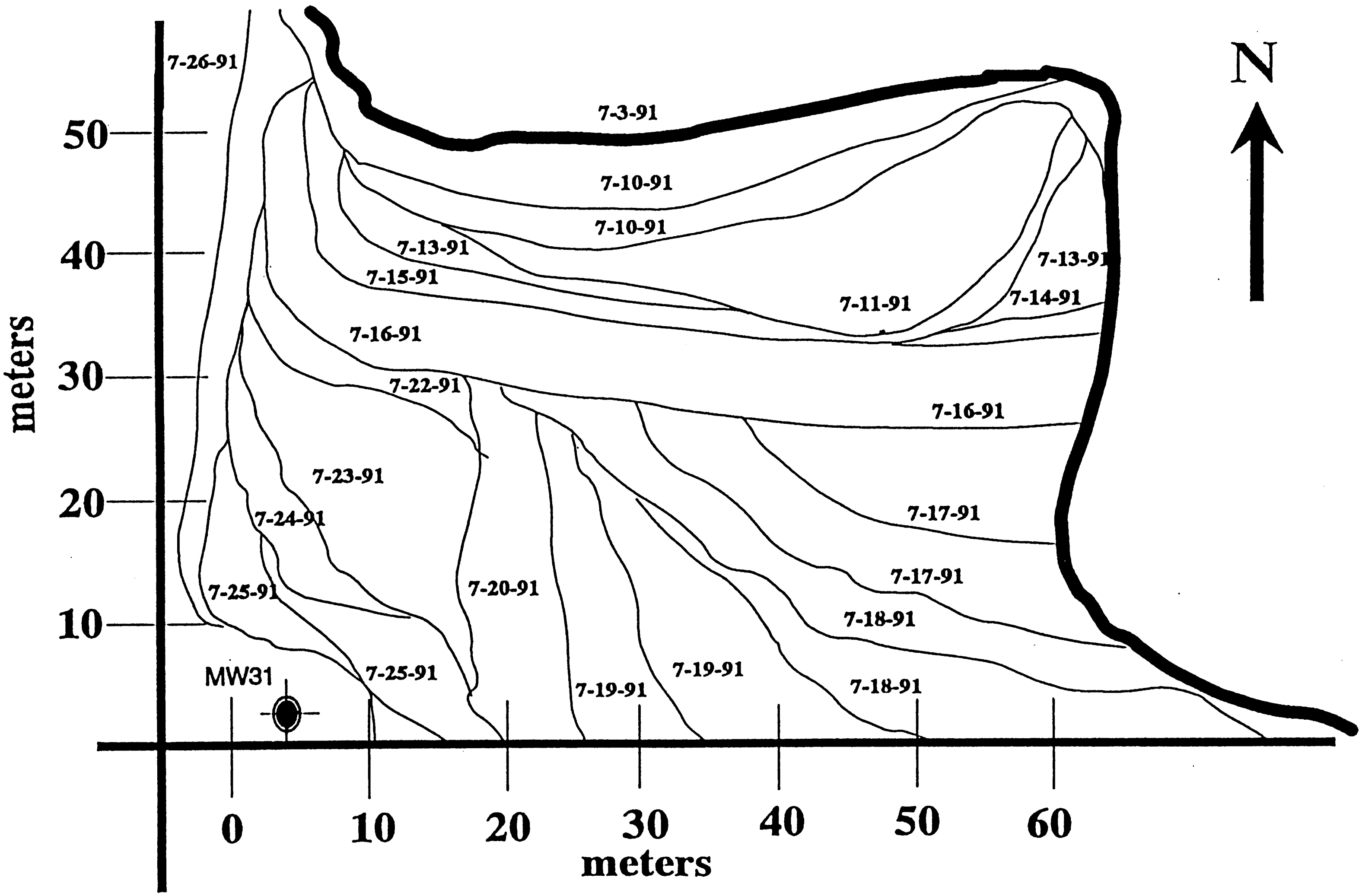


Figure 2. Map of excavated area showing the daily progression and position of the pit face.

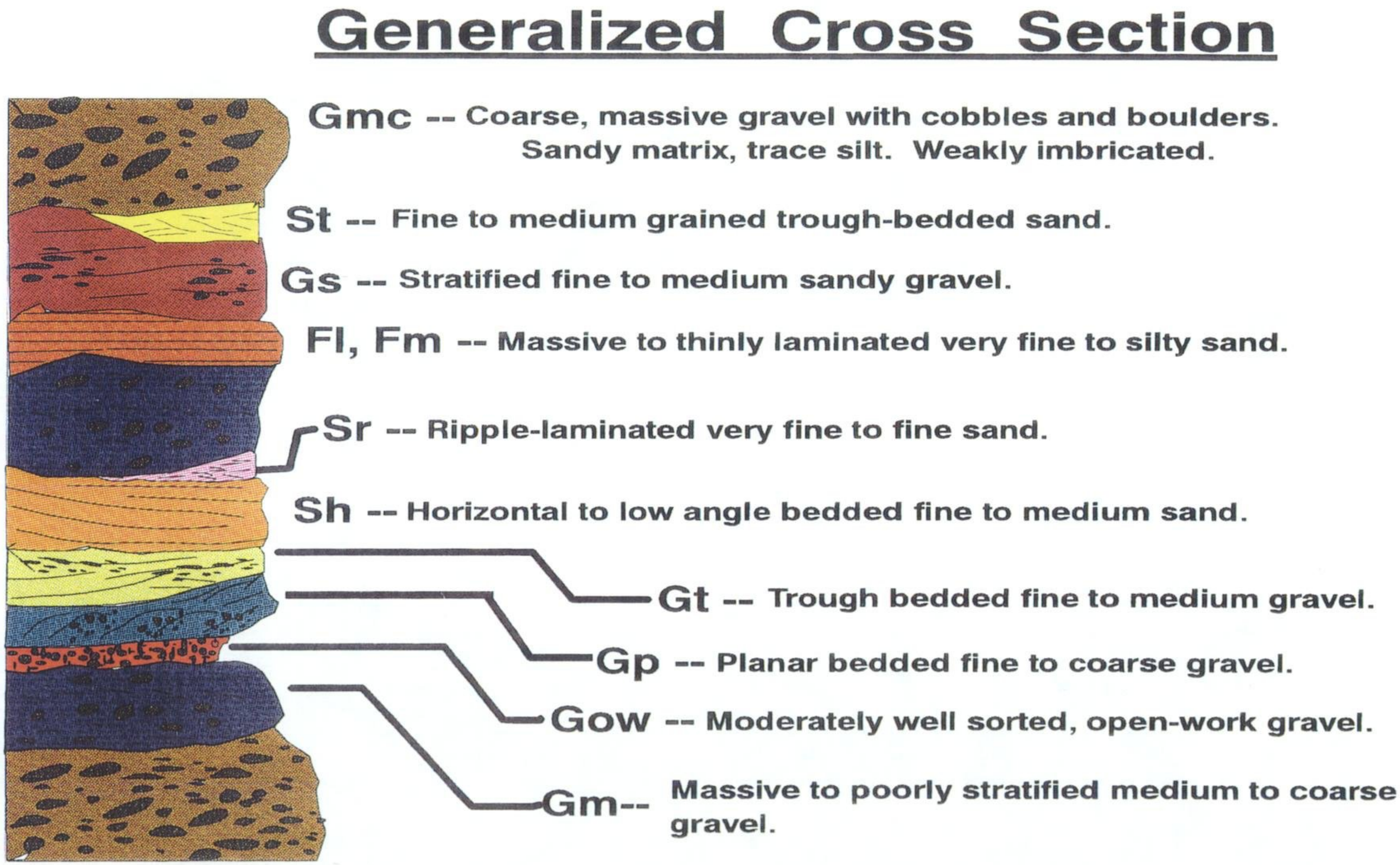


Figure 3. Generalized vertical section describing the types of distinct sedimentary units (lithofacies) observed during the excavation. The shorthand nomenclature (based on Miall, 1978) includes the dominant clast size in upper case and indicates other distinctive features in lower case.

model (Aiken, 1993). This was done by dividing the fence diagram horizontally into 1-foot thick increments, each representing a slice through the fence diagram of the site. Each 1-foot thick slice comprised a layer of the flow model; for example, the K values from the facies between elevation 904 and 903 feet above msl or 275.6 and 275.3 m above msl) comprised layer 1 of the model. The distribution of each facies was recorded on the coordinate grid sheet using a horizontal grid spacing of 6.6 feet (2 m). Because the mapped thickness of the gravel pit did not conform to a uniform cube of data required by the model, some of the mapped information from the southeast portion of the site was truncated and the upper parts of the northwest corner (where the land elevation is below 904 feet msl) were extrapolated from surrounding facies.

The 10 horizontal grid sheets representing successive 1 foot slices through the site were input directly into ModelCad (Geraghty and Miller, 1989), a pre-processing code, that translates these data into the input package files used by MODFLOW.

The three-dimensional distribution of hydraulic conductivity units used in the model is shown in Figure 4. The colors represent the relative hydraulic conductivity of each of the facies. The largest values are indicated by red and the lower values are shown as violet and black.

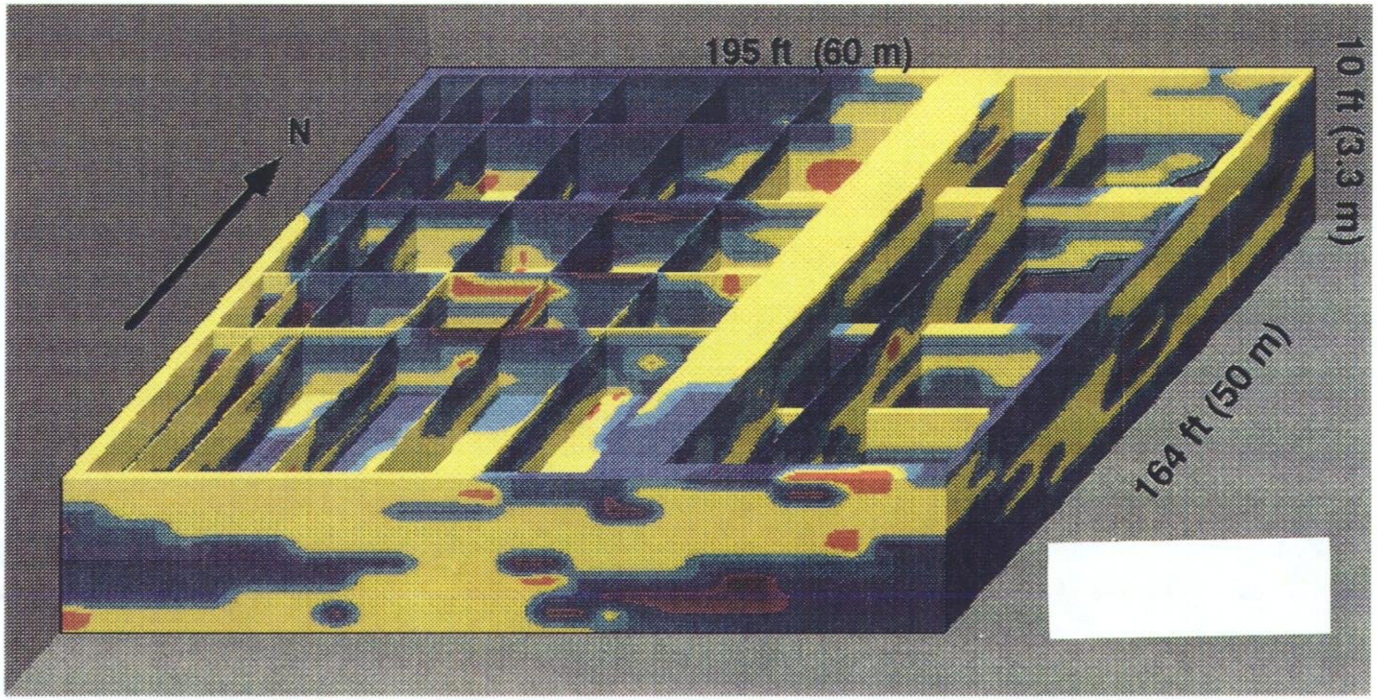
MODEL CONSTRUCTION AND METHOD

The model code used is the modular three-dimensional, finite-difference groundwater flow model developed by the U.S. Geological Survey, commonly known as MODFLOW (MacDonald and Harbaugh, 1988). The model domain consists of 30 columns, 25 rows, and 10 layers. The rows and columns are each 6.56 feet (2 m) on a side, representing a modeled area of 197 x 164 ft (60 x 50 m). The layers are each 1 foot (0.30 m) thick and grid spacing is uniform. The hydraulic conductivity was input in feet/day for each facies as one of the eight mean values obtained from the grain size estimates.

The model was run twice, each with a different flow configuration. The boundary conditions for the first model run were set to a specified head of 905.5 feet (276.1 m) on the north edge of the model and at 904 feet (275.6 m) on the southern edge of the model. For the second model run the head was specified at 905.5 on the eastern edge and 904 on the western boundary. Because the problem domain is not equidimensional, this resulted in a gradient of 0.009 for Model Run 1 and 0.0075 for Model Run 2. The remaining model edges were no-flow boundaries.

The model assumes steady-state, unconfined conditions. Although the overall medium is heterogeneous and anisotropic with respect to the flow field, three-dimensional flow was approximated in the model by assuming that hydraulic conductivity in each facies (and at each node) was homogenous and isotropic. The governing equation for steady-state flow of a fluid of constant density in three

Stoughton Gravel Pit - Distribution of Hydraulic Conductivity Values



Hydraulic Conductivity Values:		Facies Units:
K > 500 to 3500 ft/day	(150 to 1070 m/day)	Gow
K= 290 to 500 ft/day	(90 to 150 m/day)	Gmc
K= 250 to 290 ft/day	(80 to 90 m/day)	Gm
K= 240 to 250 ft/day	(70 to 80 m/day)	Ga/Gp
K= 140 to 240 ft/day	(40 to 80 m/day)	Gt
K= 80 to 140 ft/day	(25 to 40 m/day)	St/Sh
K= 1 to 80 ft/day	(0.30 to 25 m/day)	Fm/Fl

Figure 4. Block diagram of site showing distribution of hydraulic conductivity of lithfacies units.

dimensions assuming a homogenous, isotropic saturated porous medium reduces to:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial_2 h}{\partial Z^2} + \frac{\partial^2 h}{\partial z^2} = 0 \qquad (1)$$

The finite-difference approximation of the governing equation was solved using the Strongly Implicit Procedure package in MODFLOW, with an error tolerance of 0.001.

PARTICLE TRACKING SIMULATIONS

After running MODFLOW, the model was linked with PATH3D (Zheng, 1991). This code tracks infinitely small particles using the head values from MODFLOW. The model output was read into a three-dimensional graphics program to present the particle concentration maps. Particle tracking simulations consisted of two runs, both using a global porosity value of 0.20.

In the first run, four particles were randomly placed in each cell of the entry face so that 1200 particles were released from the north model boundary. In the second run, 1230 particles were released from the eastern model boundary. These particles were released so that five randomly spaced particles were placed within each cell of the up-gradient side of the model. Most of the particles released arrived at the exit face after 500 days. Those that did not exit after 500 days were usually trapped at the water table or no-flow boundaries.

RESULTS

The dominant map unit at the site is massive, cobbly gravel (Gmc) that tends to occur as laterally extensive tabular sheets. Lateral transitions with other lithofacies are gradational, with little evidence of bounding erosional surfaces. Vertical transitions to sandier lithofacies tend to be erosional and either convex-upward where the sandier facies was incised into the Gmc, or concave-downward where the contact was formed depositionally as a cobble-gravel sheet overran an existing sand bar.

MODEL RESULTS

The resulting hydraulic head distributions show that flow is dominantly horizontal and the equipotential lines are very close to vertical throughout the model. Head distributions in each of the model layers showed very little indication of the trends in heterogeneity seen in the field (Aiken, 1993).

Because no field measured head or flux values are available within the modeled area, no calibration or sensitivity analyses were performed. This makes the model inappropriate for predictive purposes, but acceptable for the stated purpose of using the model as a tool to demonstrate the possible effects of the facies distribution on contaminant movement.

PARTICLE TRACKING RESULTS - MODEL RUN 1

Figure 5 is a three-dimensional visualization of the distribution of hydraulic conductivities used as model input data. The lower edge of Figure 5A is the southern "exit" face of the model. The red color indicates areas of high conductivity and the darker colors indicates areas of lower conductivity. A particle concentration map corresponding to this exit face is shown in Figure 5B.

Model Run 1 consisted of 1200 particles released from the north model boundary. The particles that reached the exit face show several distinct concentration areas where more than 4 particles per cell (ppc), and as many as 20 ppc, reached the exit face after 500 days. The areas of highest particle concentration are shown in red in Figure 5B, with decreasing concentrations shown in yellow and blue.

The cells within these areas contained more than 4 ppc. Values higher than 4 ppc indicate cells where more particles exited the model at that cell than were introduced at the entry face directly up-gradient from that cell's position on the exit face. These areas of high concentration are referred to in future discussion as "zones".

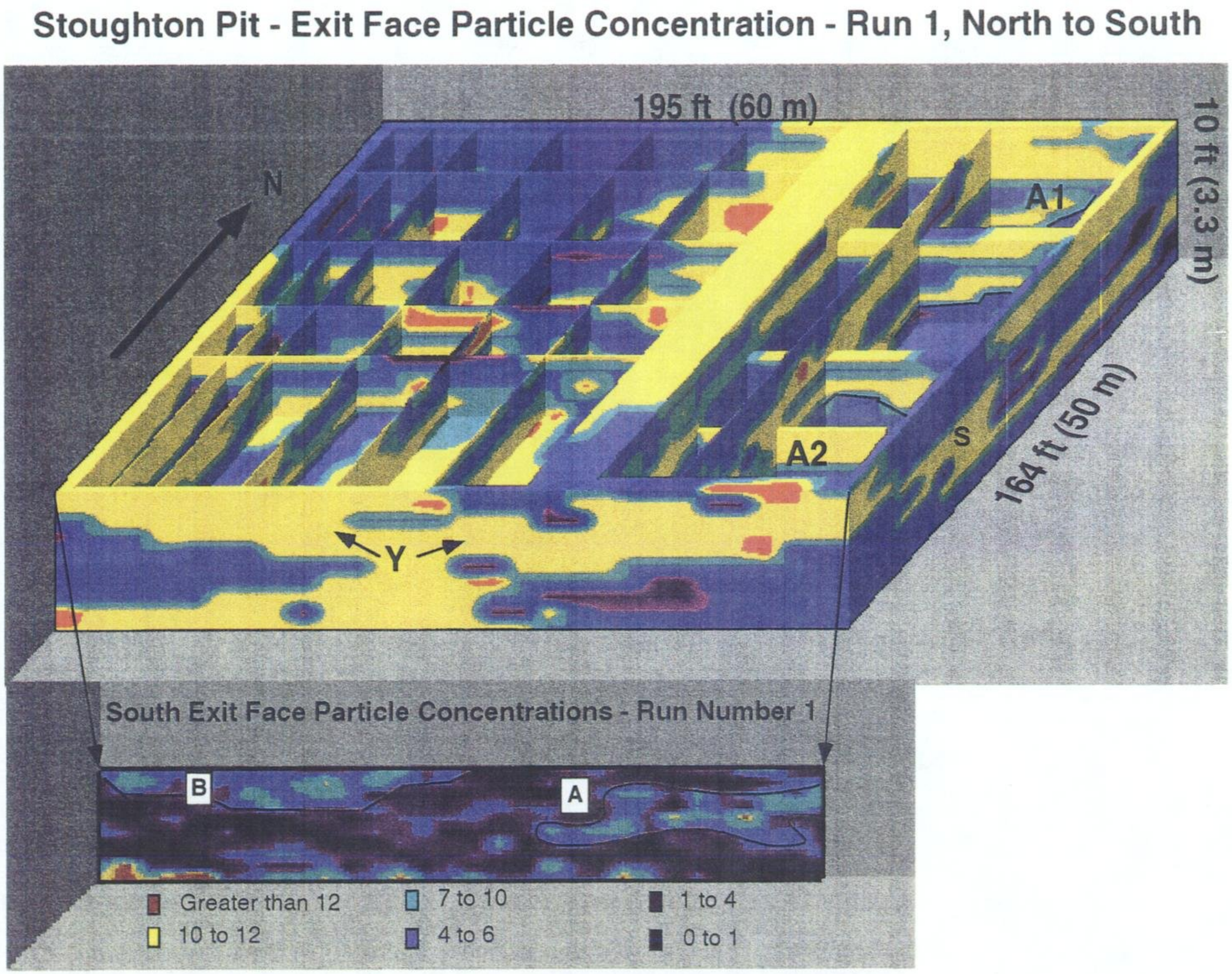


Figure 5. Block diagram of site showing input hydraulic conductivity of model run 1. Simulated flow was from north to south. Figure 5A shows the distribution of hydraulic conductivity; Figure 5B shows particle concentrations at exit face for this model run.

Because of the complex interfingering of the facies, correlations between zones of high particle concentrations and the facies that might contribute to them are somewhat subtle. However, some connection between facies and particle concentrations are evident.

Three distinct areas of high particle concentration are shown in Figure 5B. The most obvious is the high concentration zone shown in red in the lower left corner of the figure below location B. This high concentration zone lies along the edge of the particle concentration map. The location of this zone coincides with a Gow shown in red on the exit face in Figure 5A. There is a clear association between Gow and this zone, however, this zone is immediately adjacent to the model boundary. The relationship of facies farther along the flow path that might contribute to the high concentrations observed at the exit face are difficult to assess because they are likely influenced by channelling along the no-flow boundary. The difficulty arises because these particles were trapped along the model boundaries and were not exposed to lateral flow variations that would allow the particles to move off the boundary. Concentrations of particles that appear related to these boundary effects are considered to be an artifact of the model.

Two other zones, shown at locations A and B on the exit face in Figure 5B, are generally within the broad, yellow-colored high conductivity zone indicated by the letter Y shown on the south model face in the top of Figure 5A. These two higher concentration zones have particle concentrations that are higher than were released on the entry face of the model. In one of those zones, located on the right portion of the exit face (Figure 5A), facies Gow (red) and Gmc (yellow) correspond to Zone A on the particle concentration map (Figure 5B). Up-gradient from Zone A (Figure 5A), a series of channel shaped scours are partly highlighted by thin black lines between A1 and A2 on Figure 5B. This south-trending, channel-shaped scour is actually a combination of channels filled mostly with Gmc (shown in yellow) and not a single channel.

Examples of other facies that are also associated with this trend are Fm/Fl (shown in Figure 5A in dark violet) located just below A1, Gs (light blue) and Gm (darker blue). Where the Fm/Fl facies is present, it is below facies Gs, Gmc, and Gm at the base of the channel-shaped scour. The channel complex is truncated near the exit face where an east-west trending zone of Gmc cuts across the axis of the channel. A cross section of this second channel is shown on the right model wall of Figure 5A at location S.

A second zone of high particle concentration is shown near the letter B (called "Zone B") toward the left side of the exit face in Figure 5B, which consists of four light blue (7 to 10 ppc) oblong shapes. This zone is located within an area of the exit face corresponding to facies Gmc (shown in yellow on Figure 5A).

Up-gradient from Zone B, lenses of Gow (shown in red) in the middle part of the upper diagram may have an effect on the concentrations within Zone B, but no clear directional trend, such as a channel that would cause obvious funneling of the particles toward Zone B, is evident.

Discontinuous lenses of facies St/Sh and Fm/F1 (shown in violet and dark violet, respectively) flank the Gmc and Gow facies up-gradient of the exit face at Zone B. It is possible that these discontinuous low conductivity facies act as boundaries that keep the particles confined within a channel-shaped trend. The primary influence on the concentration shown in Zone B of Figure 5B is either facies Gmc or Gow. A summary of the facies observed is shown in Table 1.

Table 1. Summary of facies observed in association with zones of high particle concentration.†

		Facies Associations Up-Gradient from Exit Face		
Location	Facies at Exit Face	Vertical Facies Transitions	Lateral Facies Transitions	Geometry
Zone A	Gow, Gmc	\Fm/Fl,Gm → Gs,Gm → Gmc	Gmc, Gow	Multiple, superimposed channel scours
Zone B	Gmc	Gm → Gow → Gmc	St/Sh, Fm/Fl	Tabular, sheet-like bodies
Zone C	GmC, Gow, Fm/Fl	\Fm/Fm → Gmc → Gow → Gmc	Variable, any	Large channel scour and fill

† \ = scoured base; → = facies transition.

The dark areas on the particle concentration map (Figure 5B) are areas where no or few particles exited the model. These particles were either diverted to the high concentration areas, trapped in fine grained facies or trapped along the water table.

PARTICLE TRACKING RESULTS - MODEL RUN 2

A total of 1176 particles of 1230 released reached the exit face in the second model run, which simulated contaminants moving from the east end of the modeled area to the west face (Figure 6). This figure is oriented at 180° from Figure 5A and B. The two particle concentration zones, A and B, are shown with white arrows on the right side of Figure 6A.

Stoughton Pit-West Exit Face Particle Concentrations

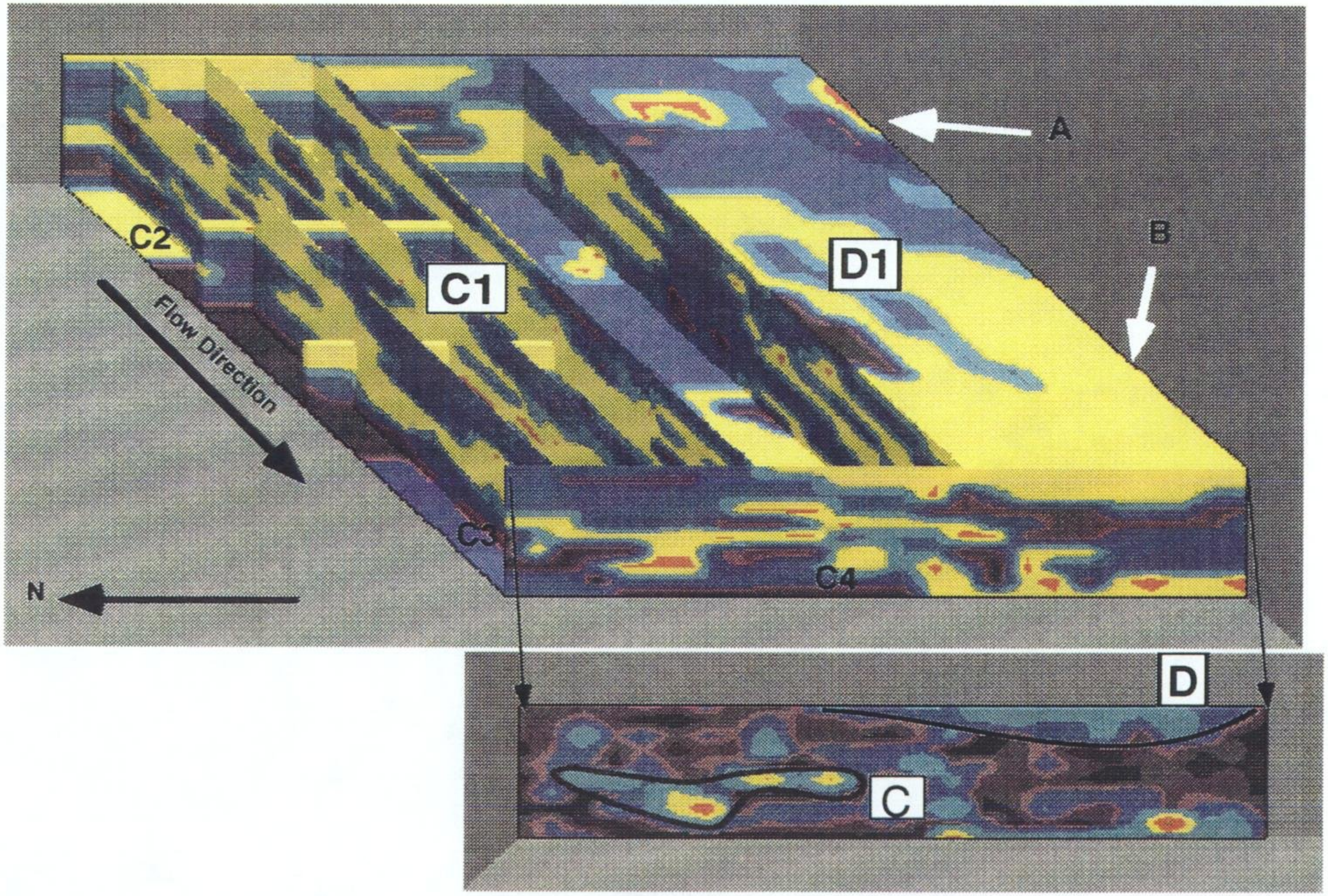


Figure 6. Block diagram of site showing input hydraulic conductivity of model run 2. Simulated flow was from east to west. Figure 6A shows the distribution of hydraulic conductivity; Figure 6B shows particle concentrations at exit face for this model run.

A high concentration zone is evident near location C, as well as a small area in the lower right of Figure 6B. The zone at letter A is roughly channel-shaped and coincides with Gow within a Gmc unit that is bounded by Fm/Fl at the exit face. The facies at the exit face extend up-gradient from the exit face in roughly the same association. Overall, there is a trend of Gmc (yellow) that extends the length of the model. At location C1, a discontinuous trend of Gow (red) lies within the Gmc facies. Underlying both of these facies is the finer-grained Fm (dark violet) that is a relatively continuous unit through the northern part of the site, extending west from C2 to C3. The presence of the high concentration zone at C is due to the tabular body of Gmc with embedded Gow; however the fine-grained facies Fm/Fl controls the shape of Zone C. This is because this facies fills in the base of a channel scour.

This channel scour overlain with the facies Fm/Fl was observed in the field as a prominent unconformable surface and was a robust reflector on several of the radar profiles discussed by Aiken (1993). The facies associations observed at C are summarized in Table 1.

In the lower right of Figure 6B just above location D, is another high concentration zone directly associated with Gow at the exit face in Figure 6A. The up-gradient association for this zone is unclear and the concentration may be produced by boundary effects.

Because of the complex interfingering of the facies, correlations between zones of high particle concentration and the facies that might contribute to them are only obvious in a few places. These zones tend to have three important characteristics in common. The first is that they contain a relatively high conductivity (coarse-grained) facies, such as Gow or Gmc. The second is that they are laterally continuous. Particles tend to be drawn toward the axis of these facies over the length of the flow path. Finally, high concentrations occur where coarse facies are constrained in their shape by fine-grained facies such as Fm/Fl. The fine grained facies sometimes are channel boundaries such as those that underlie the facies near location C1 in Figure 6a. These low conductivity (fine-grained) facies evidently act as boundaries that keep the particles confined within a channel-shaped trend.

SUMMARY AND CONCLUSIONS

Results of both model runs display distinct zones in which particles are concentrated, as well as areas where particles are conspicuously absent. In most cases, the facies relationships that might explain the particle "channeling" are subtle, but observations of the three zones (A, B, and C, Figures 5 and 6) suggest that three principal vertical facies relationships exist up-gradient of the high concentration zones that appear to influence the distribution of particles within the model.

In the "Zone A" type facies relationship (Figure 5), fine-grained facies (St/Sh or Fm/Fl) is at the base. Several interconnected channels are scoured into this part of the deposit, are filled with sand and gravel (Gm or Gs), and overlain by Gmc. The "Zone B" type facies relationship (Figure 5) appears to occur where tabular bodies of more permeable Gow are present surrounded by Gmc.

High particle concentrations of the "Zone C" type (Figure 6) appear where a single large channel is scoured into fine-grained sediment (Fm/Fl) and filled with high conductivity Gow or Gmc facies.

In general, the most obvious relationships are that high particle concentration zones are associated with high conductivity facies at the exit face. The up-gradient facies relationships are in some cases are less obvious, but also appear to have an important role in determining the location of the elevated particle concentrations. High conductivity facies with a distinct anisotropy, such as Gmc or Gow bounded by Fm/Fl, form preferential pathways that result in zones of high particle concentration. These directional trends can be distinct channels (eg. associated with Zone C in Figure 6A), combinations of channels, or tabular bodies.

The channel scours at this site are subtle when observed in the field because they often show little contrast in grain size. Facies Fm/Fl, because it is commonly found on these boundaries, is a good indicator of channel scour in these sediments. It is a sedimentary unit that can be detected in subsurface investigations such as drilling or radar surveys.

The large-scale trend of channel elements like Zone C have been observed in modern environments. These scour features with fine-grained fill are similar to the "bar-edge sand wedge facies" observed at the Scott outwash fan by Boothroyd and Ashley (1975). The presence and nature of Gow units at many sites have been discussed by Smith (1985).

This project successfully linked a detailed three-dimensional, highly deterministic, field data set to a computer flow model. The model output indicates that combinations of facies can influence the path followed by a particle, or by extension, a contaminant plume. This is important information for hydrogeologists because it provides an example of the actual shapes and dimensions of these preferential pathways. Although this example is specific to a particular outwash deposit, it provides a set of parameters that can be applied to other site investigations or well-head protection projects in other areas with outwash aquifers.

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