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The Influence of Streambed Heterogeneity on Hyporheic Exchange in Gravelly Rivers

YaoQuan Zhou
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THE INFLUENCE OF STREAMBED HETEROGENEITY ON HYPORHEIC EXCHANGE IN GRAVELLY RIVERS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science

By

YAOQUAN ZHOU
B.S., Beijing University of Chemical Technology (Beijing), 2010

2012
Wright State University
I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Yaoquan Zhou ENTITLED The influence of streambed heterogeneity on hyporheic exchange in gravelly rivers BE ACCEPTED IN PARTIAL FUFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science.

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ABSTRACT

Zhou, Yaoquan. M.S., Department of Earth and Environmental Sciences, Wright State University, 2012. The influence of streambed heterogeneity on hyporheic exchange in gravelly rivers

Hyporheic exchange can be influenced by channel meanders, by streambed topography, and by the heterogeneity within subsurface sediments. Fluvial systems with streambed sediments composed of sandy gravel can be heterogeneous and contain open-framework gravel strata sets that comprise roughly one-third of the sedimentary deposit by volume. The open-framework gravel strata sets have an average lateral length scale on the order of 10 m, average thickness on the order of a decimeter, and an average dip on the order of 10 degrees downstream. The hydraulic conductivity of open-framework gravel strata sets is on the order of $10^{-1}$ m/s, and for the larger volume of sandy gravel it is on the order of $10^{-3}$ m/s. Connected open-framework gravel strata sets form tortuous higher-permeability pathways throughout the sub-streambed sediment. The results of modeling show that the heterogeneity within the sub-streambed sediment influences the location and magnitude of the interfacial flow (flow across the streambed) more than the effect of meanders, and more than the effect of streambed topography. The heterogeneity gives rise to regions of positive and negative interfacial flow (flow over areas on the order of 50 m by 50 m) scattered across the streambed surface, which are not present in an equivalent but homogeneous system. The heterogeneity also gives rise to interfacial fluxes that are more than an order of magnitude higher than would occur in an equivalent but homogeneous...
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Thanks to my parents for being understanding during my study in the US. Thanks to all those who helped me during my time as a graduate student.
I. INTRODUCTION

The hyporheic zone is the area within fluvial systems where groundwater and surface water interact (Figure 1). The interaction between groundwater and surface water plays an important role in water resources and the aquatic ecosystem (Thibodeaux and Boyle, 1987; Alley et al., 2002). The hyporheic zone is where energy and solutes exchange between aquatic and riparian systems. It provides a spawning ground and refuge for certain species of fish, and moderates the river water temperature. It further is a buffer zone for the attenuation and release of nutrients and contaminants, and a domain for the cycling of carbon.

The hydrodynamic forces driving hyporheic exchange are the spatial gradients in pressure, elevation, and velocity head. Figure 1 illustrates that these differences in head are influenced at different scales by different scales of fluvial forms. The interfacial flux (flow across the streambed surface within the river channel) can vary from positive to negative by orders of magnitude, with a complex pattern reflecting these different scales of influence.

Meanders create a large-scale driving force on hyporheic exchange. The interfacial flux will be positive (i.e., into the subsurface) on the upstream side and negative on the downstream side of point bars at the inside bend of the meanders. The streambed topography reflecting smaller-scale fluvial forms such as ripples and dunes creates differences in the driving forces over scales smaller than bars, and adds complexity to the subsurface flow paths and consequent interfacial flux patterns, as shown in Figures 1 and 2.
Figure 1. Larger-scale drivers of hyporheic exchange including meanders and bars (aqua blue and purple arrows) and smaller-scale bedform drivers including ripples and dunes (blue pathlines). From Stonedahl et al. (2010).
Figure 2. Predicted head (magenta), observed streambed topography (blue), and simulated hyporheic exchange flow paths (black) for a two-dimensional case (from Stonedahl et al., 2010).
Figure 3. Distribution of interfacial flux (from Stonedahl et al., 2010). The case in (a) includes meanders, (b) includes meanders and ripples and dunes but with only the gravitational head driving force, and (c) adds the velocity head driving force.
Stonedahl et al. (2010) modeled these scales of influences; their results are shown in Figure 3. The scales of influence are progressively added from Figure 3a to 3c. Figure 3a shows the interfacial flux as influenced by meanders alone. Figure 3b shows the additional influence of streambed topography, as it affects gravity head. Figure 3c shows the additional influence of velocity head differences caused by increases in stream velocity on the lee side of ripples, dunes, and bars. Stonedahl et al. (2010) concluded that all scales influence the interfacial flux, and that the velocity head differences have the dominant influence.

Heterogeneity within the streambed sediments has also been shown to strongly influence the hydrodynamics of hyporheic exchange (Conant, 2004; Niswonger, 2005; Fleckenstein et al., 2006; Krause et al., 2007; Nyquist et al., 2008; Sawyer and Cardinas, 2009). Sawyer and Cardinas (2009) showed that the heterogeneity can produce long hyporheic exchange paths and modify the average exchange depth.

My interest is in investigating the influence of heterogeneity in fluvial channel belts with streambeds dominated by sandy-gravel (Klingbeil, 1998; Kleinedam et al., 1999; Heinz et al. 2003; Lunt and Bridge, 2004). In sandy-gravel fluvial systems, networks of interconnected, clast-supported, large-diameter pore spaces in open-framework gravel strata sets (Figure 4) provide conduits for rapid groundwater transport (Klingbeil, 1998; Kleinedam et al., 1999; Lunt, 2002; Bridge, 2003; Heinz et al. 2003; Lunt and Bridge, 2004; Lunt et al., 2004). Open-framework gravel strata sets comprise 25%-30% of the deposit, are decimeters thick, and meters to tens of meters in lateral extent. They dip downstream on the order of 10 degrees (Lunt and Bridge, 2007). Their porosity is on the
Figure 4. Dissected unit bar showing alternations of large-scale inclined sandy gravel (white arrow) and open-framework gravel (black arrow) strata. Shovel is 1.3 m long. (from Lunt, 2002)
order of 25% and their hydraulic conductivity is on the order of 0.1 m/s (Klingbeil, 1998; Kleinedam et al., 1999; Klingbeil et al., 1999; Heinz et al., 2003). They are known to create connected pathways for preferential flow (Lunt and Bridge, 2004; Guin et al., 2010).

Up to 75% of these sedimentary deposits are composed of sandy gravel and sand, which have similar hydraulic conductivities that are on the order of 0.0005 m/s (Klingbeil, 1998; Kleinedam et al., 1999; Klingbeil et al., 1999; Heinz et al., 2003). Because they have similar hydraulic conductivities, the sand and sandy gravel are not differentiated in this study. They are referred to collectively as sandy gravel hereafter.

The goal of this study was to better understand how heterogeneity in sandy-gravel channel belts with open-framework gravel strata influences the interfacial flux. The objective was to create a three-dimensional model for the sandy-gravel channel belt system. The Stonedahl et al. (2010) model was modified so that streambed heterogeneity was represented. Flow was simulated and the interfacial flux was quantified. By comparing the results to a homogeneous model, the influence of heterogeneity was ascertained.
II. METHODOLOGY

A three-dimensional model of hyporheic exchange requires the following elements: (1) a model for surface water flow and the channel boundaries that contain it, and (2) a model for subsurface fluid flow and the heterogeneity of the sediments through which it flows. The Stonedahl et al. (2010) model elements were used, with the subsurface fluid flow model modified to represent heterogeneity, and with other modifications discussed below. Here, these elements of the Stonedahl et al. (2010) model are reviewed and the details of the modifications are discussed.

The Stonedahl et al. (2010) surface water model incorporated channel boundaries and bedform topography, shown in Figure 5, that were mapped by laser profiling a laboratory flume experiment. The equations for open-channel flow were solved in three dimensions with an analytical approach involving conformal mapping (Stonedahl et al., 2010). The head distribution over the streambed boundary was used as a boundary condition in a finite-difference solution for groundwater flow. The finite-difference solution gave the interfacial flux across the streambed boundary. As with other recent work on the hydrodynamics of hyporheic exchange by Cardenas (2008) and Saywer and Cardenas (2009), the surface water flow and groundwater flow equations are decoupled in the Stonedahl et al. (2010) model. The coupled models in the literature (e.g. Frei et al., 2009) have not represented three-dimensional surface water flow and the velocity head as influenced by bedforms, and that velocity head was shown to be important by Stonedahl et al. (2010). Solving fully coupled three-dimensional surface and groundwater flow
Figure 5. Map view of the channel bed topography (left), shown for the first meander of the Stonedahl et al. (2010) model (right).
equations with complex boundary conditions remains as a very challenging problem for future research, and is beyond the scope of this study.

Modifying the finite-difference solution of Stonedahl et al. (2010) for groundwater flow required changing the grid to adequately include heterogeneity representing high-permeability open-framework gravel stratasets occurring within sandy gravel. Note that in nature the dimensions of bedform topography and stratasets scale together with the channel width (Bridge, 2003). The overall dimensions of the model were re-normalized to reflect the scale of channel widths and bedform topography in gravel-dominated systems as described by Lunt et al. (2004), and the finite-difference grid was made finer to adequately resolve the size and connectivity of dipping stratasets. To keep the number of grid cells less than 5 million, and thus keep the problem computationally tractable, only the first meander (Figure 5) was included in the simulation. The grid was composed of 200 rows, 400 columns and 60 layers, with a uniform cell size of 2 m by 2m by 0.05 m. This gives an overall domain size of 400 m by 800 m by 3 m (Figure 6). The Stonedahl et al. (2010) solution for the head distribution in the top grid layer, including head on the streambed boundary, was interpolated from their 169 column by 96 row grid to 400 column by 200 row grid by kriging.

The model heterogeneity was simulated in two steps. The first step was to represent heterogeneity at the scale of open-framework gravel stratasets and surrounding strata. Indicator simulation with a Markov Chain model and quenching (Carle, 1999) were used to represent the structure of open-framework gravel stratasets as they exist within other types of lower-permeability strata. The Markov Chain model represents the mean and
Figure 6. Three-dimensional realization of the distribution of sediment types in the heterogeneous model shown with front right octant removed. A cross section view is enlarged.
variance in length of open-framework gravel strata in direction $i$ using a transition probability structure having a transition rate of $-1/\bar{\ell}_i$, where $\bar{\ell}_i$ is the mean length. The coordinate axes of the Markov Chain model are oriented relative to the axes of the simulation domain to achieve a dip of $10^\circ$ in the down-gradient direction. The quenching step helped ensure that a specified proportion of 28% was honored. The simulation in Figure 6 was created using mean lengths of 5 m in the dip direction, 2 m along strike, and 0.2 m in the vertical direction. Details of the method are given in Carle (1999) and the input files and program are included in Appendix B.

The second step was to represent heterogeneity at the scale of grid cells within open-framework gravel sets or surrounding strata. The heterogeneity among cells within a cluster of open-framework gravel cells was represented by randomly assigning hydraulic conductivity to each cell. These hydraulic conductivity values were drawn from a lognormal distribution defined by an appropriate geometric mean and variance. The heterogeneity among cells within the background was represented by randomly assigning hydraulic conductivity to each cell from a different lognormal distribution, one having a lower geometric mean. The model is intended to represent general hydraulic attributes common to gravelly channel-belt deposits, and not to any single site. In this vein, the hydraulic conductivity distributions used to populate the cells of the model were generalized from those quantified in the literature. Measurements were made on a number of exposures of channel-belt sediments around central Europe by Klingbeil et al. (1999), Kleinedam et al. (1999), and Heinz et al. (2003). As summarized in Klingbeil (1998), the geometric mean, $\bar{K}_G$, for horizontal hydraulic conductivity of open-
framework gravel measurements from among these studies is of the order of 0.1 m/s. The \( \bar{K}_h \) of horizontal hydraulic conductivity for measurements in the other sediment types is of the order of 0.0005 m/s. The vertical hydraulic conductivity measurements are generally one tenth of the corresponding horizontal measurement.

The variance among these measurements is large, and reflects the variation between different sites as well as the variation at a given site. The coefficient of variation (CV, the variance divided by the squared mean) for a given site is indicated to be at least as large as unity. It is assumed that random variation with a lognormal distribution and a coefficient of variation of unity represents the variation of permeability within the two region types defined by the indicator simulation. Two natural-log normal distributions were used to represent the permeability distributions for each of the two stratal regions (open-framework gravel and sandy gravel).

For the open-framework gravel region, a normal random number generator was used to generate \( \ln(\bar{K}) \) values with a mean of -2.3025 and variation of 1.0, which gave \( K \) values with a geometric mean of 0.1 m/s and coefficient of variance of 1.0. The same procedure was followed for sandy gravel, generating \( \ln(\bar{K}) \) values with a mean of -7.6009 and variance of 1.0, which gave \( K \) values with a geometric mean of 0.0005 m/s and coefficient of variation of 1.0. The combined distributions are shown in Figure 7. Further detail is given in Appendix A. The program and input files are given in Appendix B.

A search algorithm was used to determine how the open-framework gravel is connected in the model for heterogeneity. This algorithm determined that 94.34% of open-framework gravel cells are connected in a single cluster that spans between any pair
of opposing domain boundaries, creating a percolating cluster. Figure 8a shows the top grid layer and identifies open-framework gravel cells that are part of this percolating cluster. The two-dimensional view does not convey the complex three-dimensional connectivity of the cluster, but does show that connected and percolating open-framework cells are abundantly distributed on the streambed. Figure 8b shows the corresponding hydraulic conductivity distribution on the top layer. Figure 8c shows an expanded view of the first 100 columns at row 100, and shows that the open-framework gravel cells have higher hydraulic conductivity values. The program and input files are given in Appendix B.

For comparison, I also created a homogeneous model with a hydraulic conductivity of 0.002211 m/s which is the geometric mean hydraulic conductivity in the heterogeneous model. The finite difference code (Harbaugh and McDonald, 1996) and boundary conditions used by Stonedahl et al. (2010) were again used to solve for groundwater head and velocity. The program and input files are given in Appendix B.
Figure 7. Distribution of hydraulic conductivity values (m/s) in the heterogeneous model showing a bimodal distribution. The higher-K mode has values from the open-framework gravel and the lower-K mode has values from the sandy gravel.
Figure 8. (a) Percolating (black) and non-percolating (grey) open-framework gravel distribution at the top layer. Sandy gravel is the white portion. (Continued on next page)
Figure 8. Continued. (b) Hydraulic conductivity distribution at the top layer. (c) Expanded view of the first 100 columns at the row 100. Top bar shows percolating cells (red box) from (a). Bottom bar shows permeability (red box) from (b).
III. RESULTS AND DISCUSSION

Table 1 gives the global water budgets for the homogeneous model and the heterogeneous model. The inflow and outflow are about 3 m$^3$/s for the homogeneous model and about 30 m$^3$/s for the heterogeneous model. Thus, the volume rate of flow through the heterogeneous model is an order of magnitude higher than that of the homogeneous model. This observation is consistent with the fact that the heterogeneous model was shown to have higher-conductivity preferential pathways through open-framework gravel that connect the up- and down-gradient boundaries of the flow domain. With the flow in parallel along higher- and lower-conductivity pathways, the effective permeability is always above the geometric mean. Thus, the volume flow rate is expected to be higher in the heterogeneous system than in a homogeneous system that has conductivity equal to the geometric mean conductivity of the heterogeneous system.

The volume rate of flow across the surface water – groundwater interface, “interfacial flow” hereafter, is plotted in Figure 9. The interfacial flux plotted by Stonedahl et al. (2010) in Figure 3 was the interfacial flow (direct output from the code) divided by the cell-top surface area.

Figure 9a shows the interfacial flow in the homogeneous model. There are larger regions of positive and negative interfacial flow on the inside and outside, and upstream and downstream margins of the meander. These are about 400 m by 200 m in area, about half the length and width of the meander. Away from the channel margins, there are smaller regions of positive and negative flow, about 100 m by 100 m in area, reflecting the influence of the bedform topography and the related influence of velocity head. The
Table 1. Water budgets for the homogeneous and heterogeneous models

<table>
<thead>
<tr>
<th>Water Budget</th>
<th>Homogeneous Model</th>
<th>Heterogeneous Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow In (m$^3$/s)</td>
<td>3.3305</td>
<td>30.8124</td>
</tr>
<tr>
<td>Flow Out (m$^3$/s)</td>
<td>3.3306</td>
<td>30.8121</td>
</tr>
<tr>
<td>Percentage Discrepancy</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Hydraulic Conductivity (m/s)</td>
<td>0.002211</td>
<td>0.002211 (Geometric mean)</td>
</tr>
</tbody>
</table>
Figure 9. Interfacial flow across the streambed for (a) homogeneous model and (b) heterogeneous model. Positive flow is into the aquifer and negative flow is leaving the aquifer. Blue arrow shows channel flow direction.
greatest interfacial flow rates in the homogeneous model have magnitudes less than $1 \times 10^{-3}$ m$^3$/s. This result and the one from Stonedahl et al. (2010) shown in Figure 3c both reflect the influence of the bedform topography in the middle of the channel, but the meander-scale influence is more pronounced in my result.

Figure 9b shows the interfacial flow in the heterogeneous model. The regions of positive or negative flow are on the order of 50 m by 50 m and are scattered throughout the channel. The meander-scale influence is not readily apparent (perhaps there is a bit more positive interfacial flow on the downstream, outside margin of the meander). The greatest interfacial flow rates in the heterogeneous model have magnitudes above $1 \times 10^{-2}$ m$^3$/s. By comparing 8b to 8a, it is apparent that the dominant patterns of interfacial flow are smaller in 8b, and thus the heterogeneity-scale influence is more predominant than is the influence of meander or bedform scale and velocity head.

Figure 10 allows the interfacial flow to be compared between the homogeneous model and the heterogeneous model, and between sandy gravel and open-framework gravel in the heterogeneous model. The interfacial flow rates are given for columns 200 to 300 in row 100 (middle row) of the grid. The ordinate scaling emphasizes the extreme values. For these 100 cells, high values of interfacial flow occur through cells that are open-framework gravel.

Figure 11 provides additional information for the cells in rows 99-101 of the grid, including hydraulic conductivity, whether or not the open-framework gravel cells percolate, and the streambed topography. The relevant information includes the horizontal hydraulic conductivity in the top active layer of the grid (layer 2) and the
vertical conductance between that layer and the prescribed-head layer above it (layer 1). Because layer 1 is a prescribed head layer and does not have active nodes or equations to solve, it is the presence of connected open-framework gravels in layer 2, connected with layer 1, which mostly contributes to higher interfacial flow.

The results reflect a complex flow system. The greatest (magnitude) interfacial flow rates are occurring where there are connected open-framework gravel cells and thus the vertical conductance is high, but high flow rates do not occur exclusively there.

In Figure 11, the results for columns 250 to 300 are for cells nearer to the channel margin upstream of a point bar. The meander-scale influence is to create positive interfacial flow. Indeed, in both the homogeneous (Figure 11e) and the heterogeneous (Figure 11d) model results, the interfacial flow can be seen to be predominantly positive, but more variable in the heterogeneous model. Columns 350 to 370 are more associated with the downstream side of a point bar. In the homogeneous model result, the interfacial flow is predominantly negative, whereas this is not evident in the heterogeneous model result.
Figure 10. Interfacial flow rates for column 200-300 in row 100 of the grid.
Figure 11. (Caption on next page)
Figure 11. Continued. Combining information from the middle rows (rows 99-101) of the model grid. Results are shown as 100 column groups. In each group, the following information is presented: (a) Distribution of connected (black) and unconnected open-framework gravel (grey) in top active layer. (b) Horizontal conductivity distribution in top active layer. (c) Vertical conductance distribution in top active layer. (d) Interfacial flow (in top active layer) in the heterogeneous model. (e) Interfacial flow (in top active layer) in the homogeneous model. (f) Bed topography.
IV. CONCLUSIONS

Hyporheic exchange can be influenced by channel topology, by streambed topography, and by the heterogeneity within subsurface sediments.

Fluvial systems with stream bed sediments composed of sandy gravel can contain open-framework gravel strata sets that make up roughly one-third of the sedimentary deposit by volume. The open-framework gravel strata sets have an average lateral length on the order of 10 m, average thickness on the order of a decimeter, and an average dip on the order of 10 degrees downstream. The hydraulic conductivity of open-framework gravel strata sets is on the order of $10^{-1}$ m/s, and in the larger volume of sandy gravel it is on the order of $10^{-3}$ m/s. Open framework gravel strata sets can have interconnections that form a tortuous and connected higher-permeability pathway throughout the composite sub-streambed sediment.

Three-dimensional heterogeneity within the sub-streambed sediment reflecting the existence of open-framework gravel strata sets influences the location and magnitude of interfacial flow across the streambed. The influence is more than the influence of meanders, and more than the influence of streambed topography. The heterogeneity gives rise to regions of positive and negative interfacial flow that are on the order of 50 m by 50 m, ubiquitously scattered across the streambed surface, and that are not present in an equivalent but homogeneous system. The heterogeneity also gives rise to interfacial flow rates that are more than an order of magnitude higher than would occur in an equivalent but homogeneous system.
APPENDIX A

A random normal number generation algorithm (Deutsch et al., 1998) was used to generate the values for each natural-log normal distribution using the following procedure.

In generating values for horizontal $K$ in the open-framework gravel, the geometric mean $\bar{K}_G$ conductivity is expected to be 0.1 m/s with a variance of 1, where median $\ln (K) = \ln(\bar{K}_G)$, as true for a symmetric log-normal distribution (Walpole, 1998).

The relationship between the variance of $K$ and the variance of $\ln (K)$ is given by the identity (Walpole, 1998):

$$\sigma_K^2 = (\bar{K}_G)^2 \exp(\sigma_{\ln (K)}^2 - 1)$$

(3)

And therefore:

$$\sigma_{\ln (K)}^2 = \ln \left( \frac{\sigma_K^2}{(\bar{K}_G)^2} \right) + 1 = \ln(CV) + 1 = 1; \quad \text{if } CV = 1$$

(4)

The input parameters required for the random normal number generator are the $\ln (\bar{K}_G)$ and the $\sigma_{\ln (K)}^2$, which are -2.3025 and 1.0 respectively. This gives a symmetric and normal distribution centered on -2.3025. Approximately 99% of the values fall within +/- three standard deviations, and thus between -5.3 and 0.697. The values of $\ln(K)$ were then transformed back to $K$ values according to $K_i = \exp (\ln (K)_i)$. The $\bar{K}_G$ was almost exactly 0.1 and fell between 0.005 and 2.

The same logic applies directly to simulation of $K$ in each of the background cells. Here, the geometric mean $\bar{K}_G$ conductivity is expected to be 0.0005 m/s with a variance
of 1, where median ln (K) = ln(\(\bar{K}\)) = ln (\(\bar{K}_g\)), as true for a symmetric log-normal distribution (Walpole, 1998).

The random normal number generator required the ln (\(\bar{K}_g\)) and the \(\sigma_{ln(K)}^2\), which are -7.6009 and 1.0 respectively. This gives a symmetric and normal distribution centered on -7.6009. Approximately 99% of the values fall within +/- three standard deviations, and thus between -10.6009 and -4.6009. The values of ln (K) were then transformed back to K values according to \(K_i = \exp(\ln(K_i))\). The \(\bar{K}_g\) was almost exactly 0.0005 and fell between 0.000025 and 0.01.
APPENDIX B

INSTRUCTION FOR RUNNING CODES AND FILE TYPES

Please refer to the CDROM in the back of this thesis for digital copies of the program codes, input files, and sample output files used or generate during this study. Figure B gives a flow chart for an entire simulation.


The folder TSIM includes a FORTRAN code, an executable file for TSIM, a parameter file tsim28.par, and tsim.inc. Tsim.inc is an include file for the FORTRAN code, which is used to recompile the FORTRAN code. Mcmod28.bgr and mcmod28d.bgr must be included in the TSIM folder in order to run the executable file successfully. A run through TSIM.exe provides tsim28.bgr and tsim28.dbg. In order to see the type of sediment (open-framework gravel or sandy gravel) each x, y and z coordinate represents, one needs transfer tsim28.bgr to tsim28.ascii using the executable file bgr2ascii2.exe.

To visualize the OFG and SG distribution pattern, one needs to use the CHUNK program to create a .pdf figure. The CHUNK folder includes two FORTRAN codes, two corresponding executable files, a parameter file chunk28.par, and an include file for
the FORTRAN code, which is used when recompile the code chunk.f. The convertchunk.exe will convert tsim28.ascii to tsimchunk.bgr that is used as the input for chunk.exe. The executable file chunk.exe will convert tsimchunk.bgr to tsim28.ps. The tsim.28.ps should be opened as a PDF file and it provides the visualization of OFG and SG distribution.

To check OFG connectivity in the simulation, the Search.f code in Search Connectivity can be used. When the search.exe is running, it will ask what parameter file to be used. The parameter file can be created as in the example, tsc.par. In parameter file, the first line is the name of ascii file (output from TSIM) you want to search in. The second line is the name of output file in your choice. The third line is the dimension in x, y and z. The unit intervals in x, y and z are in the fourth line. The groups of connected OFG will be listed in the output (tsc.out in this example). In the output file, each “group” is a cluster of connected cells. The total number of groups is listed at the beginning. In each group, the columns two to four are the x, y and z coordinates of the connected cells in different clusters. The biggest group has connected cells that span across all the three coordinate directions.

The PERMEX folder contains an executable file permx.exe, a parameter file permx.par, and the tsim28.ascii from TSIM run. Note the tsim28.ascii here has a different heading (as presented in the sample) than that in the TSIM folder. When the PERMEX is running, it will ask you to put in the value of nx, ny and nz. They are 400, 200, and 60 in this case. Then it will ask you to choose the seed value specific <1> or random <0>. I put <1> here to generate specific seed numbers, in which IS1 is 5000, IS2 is 20000, IS3 is 10000. One of the output files from PERMEX named results20.out has
ln(K) values for each x, y and z coordinates. It needs to be reordered along x, y and z, and the ln(K) values need to be converted to K. Due to a large amount of data, this data processing is done with SURFER. Then, the reordered and converted K values are saved in another file named permx.out (single column with heading) which is the input for MKMODFLOW. In the heading of permx.out, the first line has a value of 3, which represents three coordinates. The second line has numbers that represent the total cells in each coordinate.

One of the ln(K) values in results20.out is “-Infinity”. One needs to match the category type of this node and give it a mean K value of the corresponding category type (be it OFG or SG). In the sample case, I found the “-Infinity” node belongs to type 2, SG. Thus, I gave it a mean K value of 0.0005m/s, with a ln(K) value of -7.6.

The MKMODFLOW folder has two separate folders corresponding to two case studies, heterogeneous and homogeneous. The heterogeneous folder includes an executable file, a parameter file, the permx.out file from PERMEX and a Head.dat file. The homogeneous folder also includes an executable file, a parameter file, a permx.out file and a Head.dat file. In the homogeneous permx.out file, all the K values are the same, which equal to the geometric mean K value calculated from the heterogeneous case study. The Head.dat contains the starting head arrays, which are extracted from the Stonedahl at al. (2010) model’s first meander head distribution. These head values are expanded by using kriging to fit the size of this model.

The output files of MKMODFLOW are the input for MODFLOW96. The name and output control files need to be changed as that in this example.
The `tsim1.bcf` file (in both the heterogeneous and homogeneous cases) needs to be modified before any `MOFFLOW96` run. The VCONT constant ratio needs to be changed from 1 to 0.1 for each layer so that the vertical K values are one tenth of the corresponding horizontal measurement.

The `MODFLOW96` folder contains the modified `FORTRAN` code and its executable file. The name of “name file” needs to be typed in, when running `MODFLOW96`.

An open-framework gravel distribution plot was created by sorting the output data from `TSIM` run according to x, y coordinates and the corresponding categories. A hydraulic conductivity distribution plot was created by sorting the output data from `PERMX` run according to x, y coordinates and the corresponding conductivities. A velocity distribution plot was created by sorting the output data from `MODFLOW` run according to x, y coordinates and the corresponding velocity values. All of the plots are created as New Classed Post Map in Surfer.
Figure B. Flow chart of the methodology.
Appendix C

Figure C shows a conceptual diagram of reality, and a conceptual representation of the MODFLOW model. River stage, river flow and streambed topography are not represented directly in the MODFLOW model. They are only represented through the prescribed head boundary condition in layer 1. All nodes in layer 1 are prescribed head nodes. Thus, the finite-difference equations are not solved in layer 1, and the layer 1 horizontal conductivity is not used.

The sediment at the interface is represented by 1-2 VCONT (vertical conductance), the layer 2 horizontal conductivities, and the 2-3 VCONT. Interfacial flow is reported for layer 1 in the MODFLOW output, but controlled by the 1-2 VCONT, the layer 2 horizontal conductivities, and the 2-3 VCONT.

Thus, 1-2 VCONT and layer 2 horizontal conductivities are at the streambed interface.

![Figure C. Conceptual diagram of reality and MODFLOW model](image)

Figure C. Conceptual diagram of reality and MODFLOW model
Appendix D

The file titled `mdflow files susa` includes all the input and output files of Stonedahl model, and a MODFLOW 2000 manual. In the `SAFL6all_4_mf.ba6` file, the first 169 columns through 96 rows of the starting head array are interpolated to 400 columns and 200 rows using kriging in Surfer. This interpolated head array is used as the starting head values in MODFLOW simulation. The Stonedahl model head values and interpolated head values are both saved in `Krig head.xlsx`. The interpolated surfer file is saved as `Head.grd`.

The elevation data is interpolated in the same way from the `SAFL6all_4_mf.dis` file. The surfer file `Elevation.grd` is created while interpolating data using kriging. The elevation of the model (i.e. streambed topography) can be plotted using the New 3D Surface tool in Surfer 10 version. Here, streambed topography is saved as `Elevation figure.png`.

Figure 7, 8, and 10 are created by first sorting the data according to x, y, and z coordinates, and then using Surfer to create New Classed Post Plots. These data and Surfer files can be found in MODFLOW folder in APPENDIX B.
REFERENCES


