A New Approach in Geostatistical Modeling to Capture Stratification of Macroporosity in the Biscayne Aquifer using Borehole Imagery for Improved Groundwater Flow Prediction

Abstract

Accurate characterization of porosity and pore space geometry are important in developing models that predict the response of the Biscayne aquifer to Everglades restoration projects. Optical borehole images (OBI) and variogram-based geostatistical methods have been applied to develop 3D models of the rock and its pore space for use in computation of groundwater flows and estimation of hydraulic conductivity of the Biscayne aquifer. The variogram-based approach successfully captured the gross macroporosity of the rock and its spatial distribution. However, it failed to reproduce the vertical cyclic changes in 0.4 x 0.4 m square by 17 m tall simulations of the carbonate rock mass surrounding a borehole. Variogram analysis of the data suggested a nearly isotropic macroporosity network at OBI variogram sample separation distances (geostatistical "lags") less than the nominal borehole diameter of 0.2 m. Biases in the structure of the data set led to a situation in which the horizontal correlation was strongest at lags greater than the nominal borehole diameter. This is due to the continuity of macroporous bedding-plane vugs, which are visible in the OBI data and detected by the caliper log, across the borehole.

Variogram analysis of caliper-corrected OBI data provides a two-point statistic that is limited in its ability to capture the geometric shapes of pore spaces and their spatial distributions. Multiple-point statistics, an emerging geostatistical approach, uses observation-based "training images", which are datasets that provide the statistical information needed to characterize the pore space more fully. Multiple-point statistics techniques simulate matches to multiple observations simultaneously and thereby reproduce more realistic patterns. These methods require that the observation data to be used as a training image be gridded in 3-D space however, and this poses computational challenges for utilization of the caliper-corrected OBI data. Multiple-point statistical simulations will use digital OBI and caliper data obtained from Biscayne aquifer boreholes at the L-31N (L-30) Seepage Management Pilot Project in Miami-Dade County and could lead to more realistic simulation models for the macropore network and subsequently for groundwater flow present at this critical Everglades restoration project. Success should help stakeholders to better predict changes in groundwater flow at seepage management sites and elsewhere in the Greater Everglades hydrologic system.

1 Introduction

Groundwater underflow from the Everglades to urban water supply and drainage systems represents a potential source of water for the Everglades ecosystem. One possible means of controlling this seepage is the construction of subsurface barriers such as slurry walls.

In an upcoming large scale experiment, a slurry wall will be constructed north of the Miccosukee casino along levee L-30 (Figures 1 and 2). In addition, this particular slurry wall will incorporate a "window" that will allow hydraulic control of seepage (Figure 3).

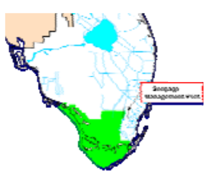

Figure 1. Location of L-31N (L-30) Seepage Management Pilot Project in south Florida. Details of the project site are shown in Figure 2.

Figure 2. Location of L-31N (L-30) Seepage Management Pilot Project. Details of the borehole site are shown in Figure 8.

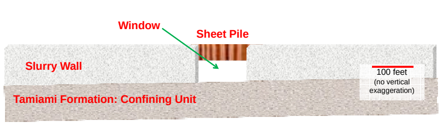

Figure 3. Seepage Management Pilot Project schematic.

1.1 Modeling Biscayne Aquifer Flow

The Biscayne aquifer is perhaps the world's most prolific aquifer and its extreme transmissivities result from a network of touching-vug macropores. Centimeter-scale touching-vugs can create stratiform (where controlled by bioturbation), areally extensive, groundwater flow pathways. Less commonly observed are bedding-plane and cavernous vugs, vertical solution pipes, and solution-enlarged fractures. The hydrodynamics of this aquifer are likely to be non-Darcian and therefore outside the realm of traditional groundwater flow models, which are based on the assumption of a constant hydraulic conductivity and linearity of Darcy's Law.

One alternative to traditional models is direct modeling of the flow in the pore space. This type of modeling requires a three dimensional rendering of the pore space, though these data are not typically available from field studies. In this work, we create statistical representations of the rock by extracting data from digital optical borehole images (OBI).

1.2 Previous Work

Previous efforts to utilize borehole imagery data from the Biscayne aquifer were limited to single borehole datasets. The caliper (borehole diameter) log was combined with the OBI to re-create the 3-D structure of the data.

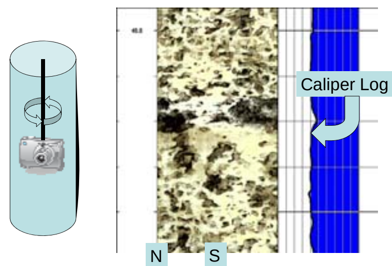

Figure 4. Schematic of Optical Borehole Image log data collection, results presented as a 2-D image, and caliper (borehole diameter) log.

The resolution of the OBI data can be quite high; in Figure 5, approximately 6 million points at 2 mm resolution define a 22 m borehole. The water table, well casing, bedding plane vugs, and the macroporosity related to bioturbation are all clearly visible.

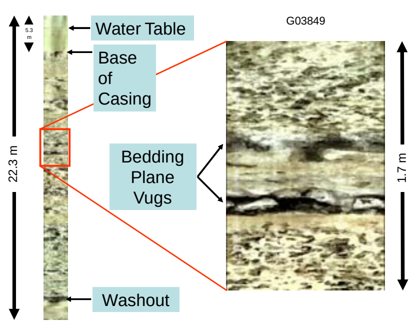

Figure 5. Optical Borehole Image log data.

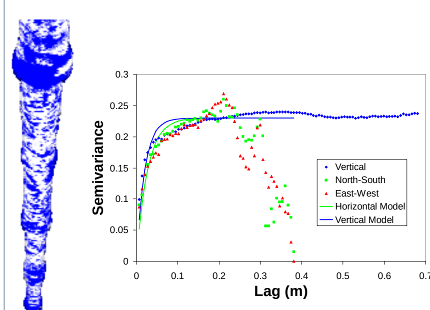

Figure 6. 3-D borehole re-constructed from OBI and caliper data (pore space blue) and derived 3-D variograms with models. Horizontal variograms show a bias beyond the nominal borehole diameter of 0.2 m. Otherwise, all variograms are similar and an isotropic rock simulation is justified.

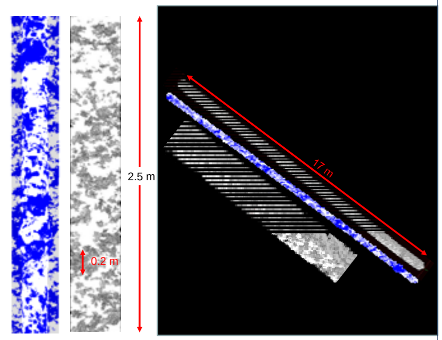

Figure 7. Close-up and whole borehole comparisons of observed and simulated rock. The overall character of the rock is captured but the bedding plane vugs are not reproduced.

2 Pilot Project Borehole Data

The data examined in this preliminary multiborehole assessment were obtained from the boreholes shown in Figure 8.

Figure 8. Close-up of window region along L-30.

3 Geostatistical Simulations

There are two major types of geostatistical simulation methods. The newest methods are multiple-point statistics algorithms developed over the last ten years. Two of these methods are single normal equation simulation and categorical filter-based simulation. More traditional methods are variogram-based two-point algorithms for spatial structure determination and simulation. Below, we experiment with each of these methods in the context of multiborehole-based Biscayne aquifer rock simulation. To conduct these simulations, we used the Stanford Geostatistical Modeling System (SGeMS, Remy et al, 2009) This provides a flexible graphical user interface for data analysis and interpretation.

3.1 Single Normal Equation Simulation

Single Normal Equation Simulation (SNESIM in SGeMS) is a multiple-point simulation method that emulates the behavior of a training image by storing data on image proportions in a search tree structure. Simulations are drawn from these proportions.

Despite the apparent potential of this method for certain types of training images, the results we obtained using the sparse training images that are available from the borehole data failed to provide adequate simulations of the rock thus far (Figure 9). The simulations fail to demonstrate the expected continuity of the bedding plane vugs and cannot be considered an adequate model of the subsurface. These simulations are complex with many variables and are memory-intensive. It is possible that improved simulations can be achieved with additional effort and enhanced computing resources.

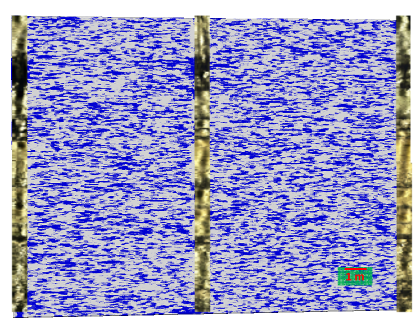

Figure 9. SNESIM Simulation of the 3-borehole domain. Original OBI data shown. Horizontal connectivity is inadequate.

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3.2 Categorical Filter-based Simulation

Categorical Filter-based simulation (FILTER-CATE in SGeMS) uses patterns found in small filtered images to construct larger patterns on the simulation grid, like a jigsaw puzzle. This method is less demanding than SNESIM for computer memory and computation time.

Simulations based on an isotropic search template and conditioning to the OBI data show a structure of the porous medium (Figure 10) that looks like copies of the original borehole data but lacks the expected horizontal continuity.

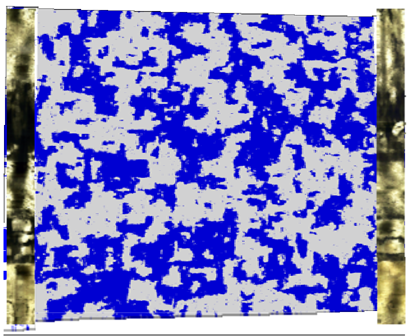

Figure 10. FILTER-CATE simulation using default isotropic search template on one-quarter of full 3-borehole domain. Original OBI data shown.

Simulations using an anisotropic search template show promise in simulating high observed horizontal continuity (Figure 11) but could not be pushed far enough to be satisfactory. Results for the full 3-borehole domain are similar (Figure 12).

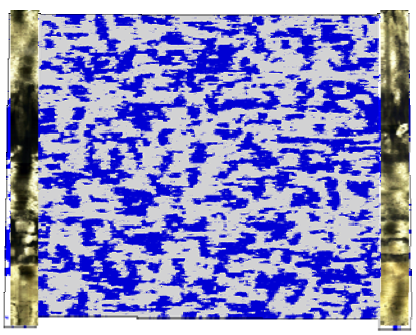

Figure 11. FILTER-CATE Simulation using anisotropic search template on one-quarter of full 3-borehole domain. Original OBI data shown.

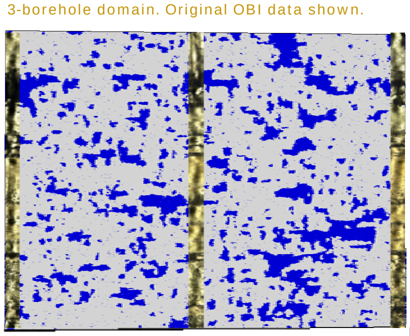

Figure 12. FILTER-CATE Simulation using anisotropic search template on full domain. Original OBI data shown.

3.3 Traditional Variogram-based Simulations

Given the difficulties in producing satisfying simulations with multipoint algorithms, traditional 2-point variogram-based simulations were also explored. Variogram-based simulations remain popular because they are more widely understood and more easily conditioned to observations than multipoint geostatistical algorithms.

3.3.1 Experimental Variograms and Fits

Experimental variograms are computed from the binary (pore/solid) borehole image data. Separate horizontal and vertical variograms were computed at two different scales (referred to as fine and coarse). The fine and coarse variograms generally confirm each other where they overlap and the fine variograms provide additional insight into the nature of the short range spatial structure—in particular the possible existence of short range randomness ("nugget" effect).

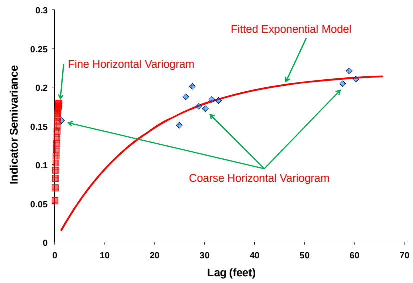

Figure 13. Horizontal variogram with fitted exponential model without nugget. Note data gaps due to borehole separation.

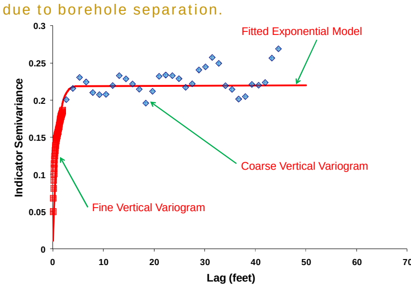

Figure 14. Vertical variogram with fitted exponential model without nugget. Note sinusoidal "hole effect" due to cyclic nature of stratigraphy.

The exponential model was created with the aim of eliminating the nugget effect and insuring a long horizontal correlation length; however, as the fine variogram in Figure 13 demonstrates, the single, short lag, coarse variogram point is accurate and should not be ignored in fitting a variogram model. This equates to the importance of fine-scale porosity in the Biscayne Aquifer.

An alternative model with a substantial nugget effect is shown in Figures 15 and 16.

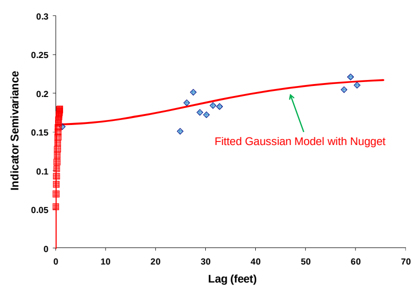

Figure 15. Horizontal variogram with fitted Gaussian model and nugget.

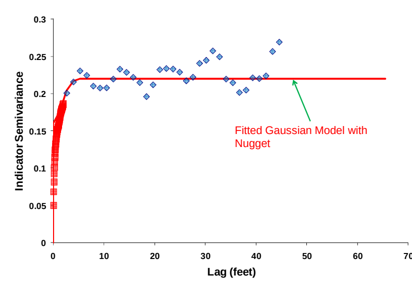

Figure 16. Vertical variogram with fitted Gaussian model and nugget.

3.3.2 Variogram-based Sequential Indicator Simulations

Sequential Indicator Simulation (SISIM in SGeMS) is a variogram-based two-point simulation that utilizes the variograms discussed above.

Without a nugget effect, good horizontal connectivity can be obtained in simulations but there is no fine-scale porosity in the rock (Figure 17).

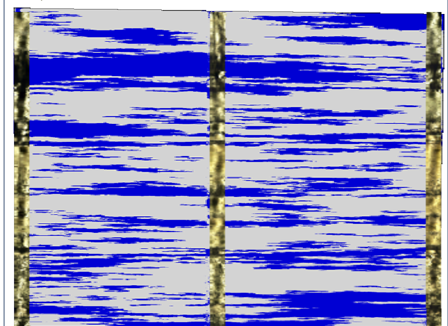

Figure 17. SISIM simulation run from exponential variogram models. Original OBI data shown.

Including a nugget leads to a pervasive fine-scale porosity and good horizontal correlation of bedding plane vugs (Figure 18).

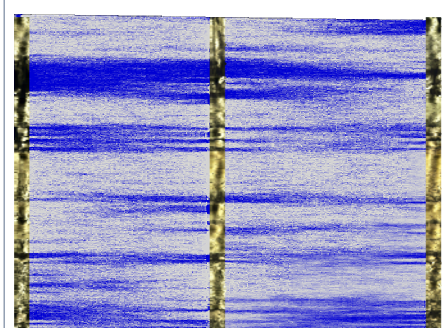

Figure 18. SISIM simulation run from Gaussian variogram models with nugget. Original OBI data shown.

4 Conclusions

Multiple-point statistical methods for creating simulations of the Biscayne Aquifer based on OBI data appear to be limited due to the sparseness of the training images and high computational memory requirements. Improvements in these methods seem likely in the future.

Two-point, variogram-based methods were able to reproduce the known horizontal connectivity of bedding plane vugs across the 18 m distance between the selected boreholes. However, exponential models without a nugget failed to reproduce adequate fine-scale porosity. Including a nugget led to considerable fine-scale porosity, but with a completely random character.

5 Further Research

Exploitation of the hole effect observed in the vertical experimental varoiograms could lead to simulations displaying better fidelity to observed cyclostratigraphy.

The particular boreholes studied here are eccentric leading to uneven illumination, which presents difficulties in thresholding the OBI data into pore and solid space. Application of the techniques of Cunningham, et al. (2004) would serve to improve the geostatistical input data.

Ultimately, 3-D rock simulation to generate domains suitable for Lattice Boltzmann fluid flow modeling will be required.

6 References

Cunningham, KJ, Carlson, JI., Hurley, N F, 2004, New method for quantification of vuggy porosity from digital optical boreholes images as applied to the karstic Pleistocene limestone of the Biscayne aquifer, southeastern Florida, Journal of Applied Geophysics, 55:77-90

Cunningham, K.J., M.C. Sukop, H. Huang, P.F. Alvarez, H. A. Curran, J.F. Dixon, and R.A. Renken, 2009. Prominence of ichnologically-influenced macroporosity in the karst Biscayne aquifer: stratiform "super-K" zones, Geological Society of America Bulletin 121:1-2, 164-235. doi: 10.1130/B26392.1

Remy, N, A Boucher and J Wu, 2009, Applied Geostatistics with SGeMS: A User's Guide, Cambridge University Press, 288 p

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