Hierarchical geostatistics of porosity derived from neutron logs at the Boise Hydrogeophysical Research Site, Idaho, USA

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Abstract The Boise Hydrogeophysical Research Site (BHRS) is a research wellfield designed to support hydrological and geophysical testing with the goal of developing methods to map three dimensional distributions of permeability in shallow alluvial aquifers by combining (sparse, hard) hydrological and (abundant, soft) geophysical data. The BHRS is located in a shallow, unconfined aquifer consisting of coarse, unconsolidated braided-stream deposits (~18 m thick) near Boise, Idaho, USA. Thirteen wells in the central area (~20 m diameter) of the BHRS are arranged to capture information to determine the geostatistical structure and dimensions of hydrological and geophysical parameters. Modelling of porosity values derived from neutron well logs indicates that porosity exhibits non-stationary nested periodic structure site wide (~80 m diameter) for the aquifer as a whole (first hierarchical level), but exhibits stationary geostatistical structure for three of the five sedimentary units (second hierarchical level) that can be traced in the central area of the BHRS. One of the five units is a channel sand with uncertain geostatistics because of limited data. Of the remaining four cobble-dominated units, three exhibit stationary anisotropic transition structure with similar nuggets; two of these units have similar porosity, correlation lengths, and sills, and are the same geologic facies. The fourth cobble-dominated unit is non-stationary with an anisotropic periodic structure; sandier lenses in this unit may represent a third hierarchical level for spatial correlation.

BOISE HYDROGEOPHYSICAL RESEARCH SITE

The Boise Hydrogeophysical Research Site (BHRS) is being developed as a three dimensional (3-D) control volume in a natural heterogeneous aquifer to support research on developing methods for combining non-invasive geophysical techniques with hydrological measurements to map variations in permeability in shallow alluvial aquifers. This paper briefly introduces the BHRS and discusses the 3-D spatial distribution of porosity, a fundamental hydrological and geophysical parameter for which abundant data currently are available from well logs at the BHRS. The BHRS is located on a gravel bar adjacent to the Boise River (Fig. 1) about 15 km east of downtown Boise. Cores from 18 wells installed in 1997 and 1998 indicate that the alluvial (braided-stream) deposits are ~18 m thick at the BHRS and are underlain by a very thin layer of basalt and a clay that is >3 m thick (Barrash & Knoll, 1998). Ground penetrating radar profiles across the site (Peretti et al., 1999) show a sequence of laterally variable deposits separated by subhorizontal bounding surfaces.
The wellfield at the BHRS consists of 13 wells in a central area (~20 m diameter) and five boundary wells located 10–35 m from the central area (Fig. 1). The 13 central area wells are in two concentric rings at offset radial angles around a central well; this design supports a wide variety of single-well, cross-well, and multiple-well hydrological and geophysical tests for thorough 3-D characterization (Barrash et al., 1999; Clement et al., 1999). The exact locations of the central area wells were selected using a Monte Carlo process to find the optimal well arrangement with similar numbers and azimuthal distributions of well pairs at 1 m lags through expected horizontal ranges of spatial correlation of hydrological and geophysical parameters (Barrash & Knoll, 1998).

**POROSITY LOGS AND STRATIGRAPHY**

Porosity values were derived from neutron well logs in the 18 wells at the BHRS. The porosity data set consists of 4699 measurements at 6 cm intervals in the saturated portion of the cobble-and-sand deposits. Porosity logs may be interpreted for lithologic units where lower porosity intervals are cobble-dominated units and higher porosity intervals are sand or relatively sand-rich portions of cobble-dominated units. The
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(stratigraphic interpretation of units is (Fig. 2): Unit 1, the lower low-porosity cobble-dominated unit overlying a very thin (<1 m thick) portion of a basalt flow and a tight red clay (>3 m thick); Unit 2, the lower variable-porosity cobble-dominated unit; Unit 3, the upper low-porosity cobble-dominated unit; Unit 4, the upper variable-porosity cobble-dominated unit; and Unit 5, channel sand (thickens toward the Boise River and pinches out in the centre of the wellfield).

**HIERARCHICAL APPROACH TO GEOSTATISTICAL ANALYSIS AT BHRS**

We have adopted a hierarchical approach to analysing the geostatistics of the porosity data at the BHRS; this approach is similar to architectural elements in sedimentary systems (Miall, 1985) where units with recognizable boundaries occur at successive size scales (i.e. assemblages of facies, facies, subfacies). In this paper, assemblages of facies (e.g. the alluvial aquifer as a whole at the BHRS) are the highest hierarchical level (level 1), facies are the next highest hierarchical level (level 2), and subunits within facies are level 3. In the following geostatistical analysis, experimental variograms have been generated with 95% jack-knife confidence intervals (Shafer & Varljen, 1990; Davis et al., 1997); the inverses of these confidence intervals were used as weights in the non-linear least-squares routine for fitting the experimental variograms with model structures. Further detail is given in Barrash et al. (1999) and Barrash & Clemo (in review).

**HIERARCHICAL LEVEL 1: ALLUVIAL AQUIFER AT THE BHRS**

Level 1 geostatistical analysis includes all saturated alluvial deposits sitewide. The horizontal (omnidirectional) variogram is fit best with a nested periodic model.

Fig. 2 Cross-sections of interpreted stratigraphy in the alluvial aquifer at the BHRS based on porosity logs. Units 1–4 are cobble-dominated units; Unit 5 is a channel sand. (a) Parallel canyon axis. (b) Cross canyon axis. Channel sand thickens toward the river and pinches out at the centre of the wellfield.)
(Barrash et al., 1999); this model is also an excellent fit to the vertical variogram although short-range periodicity does not appear to be required (Fig. 3). Also the sill of the vertical variogram (0.0034) is significantly greater than the sill for the horizontal variogram (0.0024). Both inconsistent sills and periodicity (although not uncommon in sedimentary deposits) are indications of non-stationarity.

HIERARCHICAL LEVEL 2: UNITS IN THE CENTRAL AREA OF THE BHRS

For level 2, the porosity structure is analysed for the stratigraphic units (Fig. 2) in the 13 central area wells only because of uncertainty in tracing these units to the outer wells. Although the sand channel facies (Unit 5) is the easiest to identify and trace, it pinches out in the middle of the central area and has too few data points to support a geostatistical analysis based on porosity log data alone. For Units 1, 2 and 3, exponential models are fitted to vertical variograms (Fig. 4) although spherical or Gaussian models are comparable fits. Horizontal variograms for Units 1, 2 and 3 exhibit pure nugget effects indicating that the horizontal range is ≤3 m (Fig. 5). Vertical and horizontal sills are similar and stable indicating stationary geostatistics. Also, Units 1 and 3 have quite similar ranges, sills, and porosity probability density functions, indicating that they are the same geological facies (Barrash & Clemo, in review). Unit 4 has a periodic vertical variogram (Fig. 4) and an indeterminate horizontal variogram (Fig. 5) indicating that this unit does not have stationary porosity geostatistics, probably because of relatively distinct higher-porosity lenses or subunits in this unit (Fig. 2).

HIERARCHICAL LEVEL 3: SUBUNITS IN UNIT 4

Efforts to determine criteria for discriminating level 3 units in Unit 4 and to supplement porosity log data with other geophysical data are areas of current activity.
Fig. 4 Vertical variograms for hierarchical level 2 units, central area of the BHRS. 
(a) Unit 1, fit with an exponential model. (b) Unit 3, fit with an exponential model. 
(c) Unit 2, fit with an exponential model. (d) Unit 4, fit with a periodic model. Note 
doubling in scale for the vertical axis.

Fig. 5 Horizontal variograms for hierarchical level 2 units, central area of the BHRS. 
(a) Unit 1, fit with a pure nugget model. (b) Unit 3, fit with a pure nugget model. 
(c) Unit 2, fit with a pure nugget model. (d) Unit 4, fit with a pure nugget model (solid 
line) and a linear model (dashed line). Note doubling in scale for the vertical axis.
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REFERENCES


