APPLICATION OF TRANSITION PROBABILITY GEOSTATISTICS IN A DETAILED STRATIGRAPHIC FRAMEWORK

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Heterogeneity of hydraulic properties at multiple scales in an alluvial aquifer is largely controlled by the distribution of facies. Therefore, we require quantified stratigraphic and sedimentologic models in order to incorporate this spatial variability of hydraulic properties into groundwater flow and contaminant transport simulations. Our approach uses sequence stratigraphic concepts, developed for the fluvial fan continental setting to (1) delineate large-scale stratigraphic units in the alluvial aquifer, (2) predict overall facies patterns in the aquifer, and (3) guide development of appropriate Markov chain models used in transition probability geostatistics. After geostatistical simulation, our results are used in groundwater models to estimate groundwater age distributions, evaluate remediation strategies, and model aquifer hydraulic tests in a heterogeneous setting. To illustrate and provide a “how-to” guide to this approach, I use examples from the Kings River fluvial fan, located southeast of Fresno, California (Figure 1).

Initially, we assessed and developed the sequence stratigraphic concepts for the Kings River fluvial fan (Weissmann et al., 2002a). We use the term ‘fluvial fan’ to distinguish fans dominated by deposits of perennial streams from those dominated by debris flow or sheet flood processes. Depositional patterns on the fluvial fan formed in response to Pleistocene glacial cyclicity in the Sierra Nevada (Figure 2). These glacial cycles produced at least four unconformity-bounded sequences within the alluvial basin fill (Figure 3). In this context, we identified three deposit types – open fan (consisting of coarse-grained channel deposits held within finer-grained floodplain deposits), incised valley fill (dominated by very coarse-grained channel fill deposits), and pre-glacial Pliocene deposits (similar to open-fan deposits, however numerous paleosols are present in this unit) – that are held within the sequences. Relatively mature paleosols bound each of these sequences, thus we could define the large-scale sequence geometries through correlation of these paleosols (Figure 4).

We use this stratigraphic framework to develop Markov chain models specific to each deposit type. We take the following steps to develop and apply the Markov chain models of spatial variability (Weissmann and Fogg, 1999):
1. Classify core, geophysical well log, and drillers' lithologic log data into hydrofacies categories;
2. Measure vertical transition probability from core or geophysical well log data within each stratigraphic unit or deposit type and visually match a Markov chain model to these measured results.
3. Estimate lateral Markov chain models for each deposit type based on:
   a. estimated facies mean lengths from geologic mapping, geophysical surveys, conceptual models, and/or outcrop analogs (Figure 5);
   b. estimated embedded transition probabilities for facies juxtaposition tendencies from application of Walther's Law, geologic mapping, conceptual geological models, and/or outcrop analogs (Figure 4).
4. Simulate each sequence separately using conditioning data from that sequence, then combine all individual sequence realizations into a final realization (Figure 6).

Stratigraphically-based geostatistical simulation using this approach has several advantages over non-stratigraphic approaches. First, the sequence boundaries are marked by unconformities, therefore facies that exist on one side of the unconformity do not correlate to facies on the other side of the unconformity. Thus, correlation across the unconformity (in both model development and simulation) is avoided using this approach. Second, geostatistical simulation assumes stationarity (e.g., statistical homogeneity across the modeled region). By dividing the section into these stratigraphic units, different statistics (e.g., the Markov chain model) of different units are honored. For example, the coarse-grained dominated incised valley fill deposits have a much higher proportion of sand and gravel than the open-fan deposits. By deterministically modeling the distribution of these large-scale units, we separate their simulation and honor this difference in facies proportions and geometries. Finally, facies distributions can be predicted based on position within a sequence, thus allowing use of the sequence stratigraphic conceptual model in a quantitative way. This approach allows geologists to quantify their conceptual geologic interpretations and formulate realizations of the subsurface heterogeneity that appear to reasonably reflect the complex stratigraphic character of alluvial aquifers.

Upon compilation of multiple realizations for the study site, we readily incorporate the facies distributions into groundwater models by assigning hydraulic properties (e.g., hydraulic conductivity, storativity, dispersivity, etc) to each facies type. To date, we have used these realizations of the Kings River fluvial fan to investigate the distribution of groundwater ages to a well (Weissmann et al., 2002b), the influence of incised valley fill deposits on overall
hydrodynamics of the regional flow system (Weissmann et al., 2004), the migration of nitrates through the vadose zone (Harter et al., 2005), and susceptibility of aquifers to contamination (watch for Zhang et al., in the near future).

Figure 1. Satellite image and location map of the Kings River fluvial fan. From Weissmann et al. (2004).

Figure 2. Sequence stratigraphic cycles on the Kings River fluvial fan are developed from changes in sediment supply to discharge ratios due to cycles of outwash from glaciers in the Sierra Nevada. Darker shading indicates active areas of the alluvial fan.
A) incision into the fan during the transition from glacial to interglacial climates.
B) Interglacial climate morphology.
C) Morphology at the beginning of significant glacial outwash.
D) morphology during periods of significant glacial outwash. Figure from Weissmann, et al. (2002a).
Figure 3. Cross sections through the upper Kings River Alluvial Fan. Section A-A’ is parallel to depositional dip, and section B-B’ is parallel to depositional strike. From Weissmann, et al. (2002a)

Figure 4. Modeled sequence bounding surfaces through the study site (from Weissmann et al. (2004).

Figure 5: Soil map of the Kings River fluvial fan showing the generalized distribution of facies on the fan surface. C-horizon textures were used to develop this facies map (see Weissmann et al., 1999, 2002a, for further discussion). The facies distribution on this map were used to measure lateral transition probabilities. These were slightly modified to account for preservation potential and incorporated into the lateral Markov chain models for open-fan deposits (Weissmann et al., 1999). Map from Weissmann et al. (2005).
Figure 6. Compiled realization for the Kings River fluvial fan study area (From Weissmann et al., 2004).

References Cited


