

## **Conditional geostatistical modelling of an alluvial aquifer system characterized by poor-quality shallow groundwater**

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**Abstract** A conditional geostatistical model is being developed for the eventual simulation of non-point source salt transport in an aquifer system characterized by poor-quality shallow groundwater, located in the central region of the western San Joaquin Valley, California. Deep groundwater pumping has been suggested as a viable method to decrease the amount of land subject to salinization due to the very shallow water table. We will focus on the risk of early, localized deep aquifer salinization as a result of increased groundwater pumping. Appropriate geostatistical characterization of the most permeable hydrostratigraphic structures within the complex alluvial deposits comprising the semi-confined aquifer and the Corcoran Clay aquitard is therefore key to the risk analysis. We apply the transition probability/Markov approach for stochastic representation of the highly permeable channel sediments within the alluvial sequence. The model will be appropriate for a conservative risk assessment of early salt arrival times, where only transport through the channel deposits is considered while transport and diffusion processes in the less permeable, finer textured sediments are neglected.

### **INTRODUCTION**

The marine-derived sediments in the shallow semi-confined aquifer of the western San Joaquin Valley are an abundant natural source of salinity and selenium. Widespread agricultural irrigation on poorly draining soils has mobilized high concentrations of salinity ( $>1250 \text{ mg l}^{-1}$ ) and selenium ( $>2 \text{ } \mu\text{g l}^{-1}$ ) in the shallow part ( $<50 \text{ m}$ ) of the semi-confined aquifer. Extremely shallow saline groundwater encroaching on the root zone has impacted crops on several thousand  $\text{km}^2$  of land (USDI, 1990). Large networks of agricultural drains were effective in lowering the water table, but the disposal of drainage water high in salinity and selenium into wetlands was detrimental to water fowl, resulting in drain closure. Alternatives to drainage have been sought for lowering the water table in these areas (USDI, 1990).

Three alternatives: groundwater pumping, improved irrigation efficiency, and land retirement, were evaluated in an extensive regional groundwater flow modelling effort for a  $1400 \text{ km}^2$  subarea of this region (Belitz & Phillips, 1995). Increasing groundwater pumping was found to be an effective way to decrease the area vulnerable to near-surface contamination. However, increasing pumping in the lower semi-confined aquifer, or in the confined aquifer, results in the downward migration of the poor-quality groundwater at an estimated average rate of  $0.15\text{--}0.3 \text{ m}$  per year, depending on

surface water supplies and applied groundwater management strategies. On average, it would take between 200 and 600 years for high concentrations of salinity to reach production wells located in the lower semi-confined and confined aquifers. The ultimate objective of our work is to characterize the risk of accelerated (early) well contamination due to the existence of highly conductive flow paths connecting the shallow saline part of the aquifer system with the deeper production portions of the aquifer system. In this paper we present a geostatistical characterization of the aquifer-system hydrostratigraphy using a transition probability/Markov chain approach.

## HYDROGEOLOGICAL FRAMEWORK

The surface geomorphology of the central part of the western San Joaquin Valley consists of a series of coalescing alluvial fans of marine origin which emanate from the Coast Ranges and spread out northeastwards towards the southeast–northwest aligned valley trough. A traditional conceptual model of the subsurface hydrogeology across the valley is displayed in Fig. 1. The Coast Range alluvium in the apical and mid-fan regions are dominated by coarse-grained channel deposits while fine-textured overbank and flood basin deposits dominate the more distal regions. The aquifer system is generally thought to consist of a semi-confined aquifer overlying a deep confined aquifer. The semi-confined aquifer is composed of the Coast Range alluvium, flood-basin deposits, and Sierran sand. The confining layer is an areally extensive Pleistocene lake bed known as the Corcoran Clay Member of the Tulare Formation.

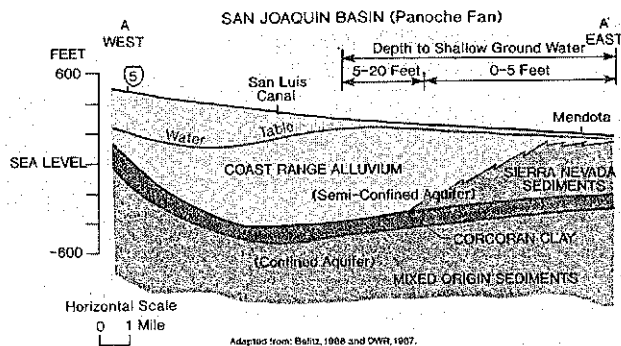


Fig. 1 Hydrogeological cross-section of the western San Joaquin Valley (USDI, 1990).

To capture phenomena that are potentially critical to fast salt transport we resolve the hydrogeological architecture at scales of several tens of metres in the horizontal and at scales of decimetres to metres in the vertical direction. This resolution is orders of magnitude smaller than the resolution scale of earlier regional studies, where horizontal discretization has typically been on the order of kilometres. We conceptualize the subsurface as consisting of alternating sequences of fine- and coarse-textured hydrofacies. The fine-textured hydrofacies consist of clay, shale, silt, and cemented fine sand from the debris flow, flood plain, and overbank deposits, and from

interbedded lacustrine sediments. The coarse-textured hydrofacies consist of unconsolidated sand or gravel deposits, possibly with thin interbedded clay and silt layers, from the alluvial and fluvial channel deposits. The hydraulic conductivity of the coarse-textured hydrofacies is several orders of magnitude larger than that of the fine-textured hydrofacies. Consequently, the vertical transport of these salts will be controlled by the abundance and degree of interconnectedness of the coarse-textured hydrofacies.

Will the flow paths formed by the interconnected coarse-textured hydrofacies contribute to rapid transport of poor-quality groundwater from the upper semi-confined aquifer to wells located in the lower semi-confined aquifer or the confined aquifer? To address this issue, we seek to utilize abundant well log information and limited hydraulic testing (Laudon & Belitz, 1989) within a geostatistical framework well suited to provide the basis for stochastic simulations of groundwater flow and salt transport in such a complex structured alluvial aquifer system.

## GEOSTATISTICAL CHARACTERIZATION

Since the hydrogeology of the semi-confined aquifer, the Corcoran Clay aquitard, and the confined aquifer are significantly different from each other, the geostatistical characterization and risk analysis is divided into two modelling problems. The first is concerned with the vertical migration of the poor-quality groundwater from the upper to the lower regions of the semi-confined aquifer. The second is concerned with the potential for leakage from the semi-confined aquifer into the confined aquifer through the Corcoran Clay.

Here, we demonstrate our approach specifically to address the first modelling problem. For this, we present a characterization of the spatial variability of the fine- and coarse-textured hydrofacies underlying two hydrogeologically different townships located in the study area: township T14S-R13E is located in the mid- to upper-fan area and is characterized by an abundance of coarse-grained channel deposits; T15S-R14E is located in the mid- to lower-fan area and is characterized by a predominance of fine-textured deposits. Both townships have an area of 92 km<sup>2</sup> (6 × 6 square miles). The transition probability/Markov chain approach (Carle & Fogg, 1997) is used as the geostatistical methodology for characterizing the spatial variability of these fine- and coarse-textured hydrofacies.

**Transition probability/Markov approach (TPMOD)** The transition probability/Markov approach was chosen because it allows for the inclusion of both measured geological data and conceptual model information (Carle & Fogg, 1996). It is ideally suited for the simulation of alluvial fan deposits (Weissmann *et al.*, 1999). The application of TPMOD is based on the measurement or estimation of the transition probabilities of the hydrofacies along the principal vertical and lateral dip and strike directions. The transition probability,  $t_{jk}$ , is the conditional probability that a hydrofacies of category  $k$  occurs at the spatial location  $\mathbf{x} + \mathbf{h}$  given that a hydrofacies of category  $j$  occurs at location  $\mathbf{x}$ :

$$t_{jk}(\mathbf{h}) = P\{k \text{ occurs at } \mathbf{x} + \mathbf{h} \mid j \text{ occurs at } \mathbf{x}\} \quad (1)$$

where  $\mathbf{h}$  is the lag distance between the two spatial points. In our two-category classification,  $j$  and  $k$  refer to the fine-textured or coarse-textured hydrofacies ( $2^2$  combinations). Once determined, the transition probabilities,  $t_{jk}(h_\Phi)$ , in principal directions  $\Phi$  are fitted to a one-dimensional, first order continuous lag Markov chain (equivalent to fitting variograms in conventional geostatistics), which is of a matrix exponential form:

$$\mathbf{T}(h_\Phi) = \exp(\mathbf{R}_\Phi h_\Phi) \quad (2)$$

$\mathbf{T}(h_\Phi)$  is the matrix of transition probabilities of lag  $h_\Phi$  in the direction  $\Phi$  and  $\mathbf{R}_\Phi$  is a transition rate matrix, where the transition rate,  $r_{jk,\Phi}$ , equals the slope of the transition probability as the lag  $h_\Phi$  approaches zero. The diagonal transition rates are related to the mean length of the hydrofacies of category  $j$  in the direction  $\Phi$ ,  $L_{j,\Phi}$ , by:

$$r_{jj,\Phi} = -\frac{1}{L_{j,\Phi}} \quad (3)$$

The mean length of the hydrofacies provides a statistical measure of its average longitudinal extent in the principal direction in which it is observed. Transition rates must satisfy basic laws of probability: the proportions of all facies must add to 1, and the probability that a transition occurs from *any* category to category  $k$  at a given lag distance must be equal to the proportion (marginal probability) of  $k$  (Carle & Fogg, 1997). Only  $k-1$  hydrofacies categories need to be considered for fitting transition probabilities to one-dimensional Markov chain models. The  $k$ th hydrofacies becomes a "background" facies whose properties can be derived by enforcing these probability rules.

**Categorization of hydrofacies** The spatial locations and vertical thickness of the fine- and coarse-textured hydrofacies were interpreted using downhole descriptions of sediments documented in drilling well logs. These logs provide a description (e.g. texture, colour, hardness, etc.) of the sediment, observed during drilling, at different depth intervals down the borehole. The vertical resolution of these logs is approximately 0.3 m. Driller's descriptions "gravel", "gravelly (...)", "sand", "clayey sand", "loamy sand" were classified as coarse-textured hydrofacies.

Figure 2 illustrates the vertical sequences of well logs in T15S-R14E after the depth intervals in each borehole were classified as being either a fine- or coarse-textured hydrofacies. A comparison of Figs 1 and 2 reveals the complicated heterogeneity that exists in the aquifer system even for just two hydrofacies categories. For the characterization of the semi-confined aquifer, we used well log descriptions from the surface to approximately the top of the Corcoran Clay (150–210 m or 500–700 feet below ground surface).

**Vertical spatial variability** The abundance of data in the vertical direction enabled us to compute the theoretical Markov chain model directly from the vertical transition probabilities obtained from well logs. Separate models were fitted for data in township T14S-R13E and T15S-R14E by evaluating equation (2) using an eigensystem analysis (Fig. 3). The model sills in the diagonal plots for T15S-R14E indicate that approximately 20% of the volume consists of the coarse hydrofacies and

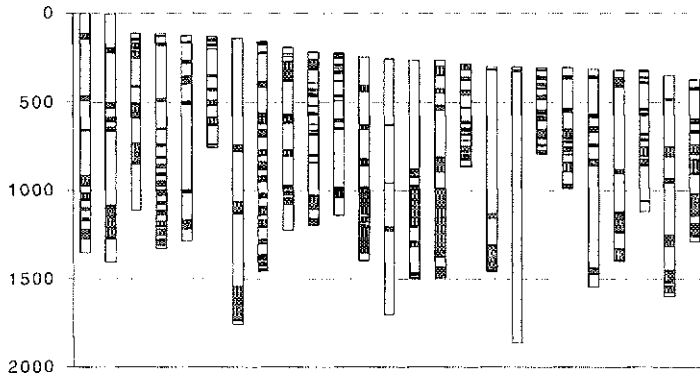


Fig. 2 Cross-section of well logs for township T15S-R14E. The vertical axis is depth in feet from an arbitrary universal datum. Black: coarse-textured, white: fine-textured.

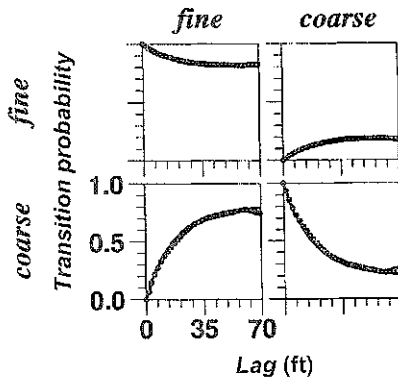


Fig. 3 Measured (dotted) vertical transition probabilities,  $t_{ij}(h)$ , for township T15S-R14E and fitted one-dimensional Markov chain model (solid) using TPMOD.

80% is fine-textured. The analyses for T14S-R13E yields estimates of 41% coarse and 59% fine material (not shown). The mean lengths of the fine and coarse hydrofacies in the vertical direction for T15S-R14E are approximately 26 and 6.3 m, respectively. The mean lengths of the fine and coarse hydrofacies in T14S-R13E are 6.4 and 4.6 m, respectively. The large percentage volume of observed coarse material in T14S-R13E reflects its location in the mid- to upper-fan area.

**Lateral spatial variability** Computing the transition probabilities of the hydrofacies in the principal lateral directions from the drilling log descriptions is problematic because the mean lengths of the hydrofacies in these directions are often observed to be smaller than the distance between boreholes. Consequently, a conceptual model of the semi-confined aquifer hydrogeology is used to infer the mean lengths of the two hydrofacies in the principal lateral directions (Weissmann *et al.*, 1999). Based on the alluvial fan geomorphology, soil maps, and the computed proportions of each texture, geologically plausible mean lengths of the coarse-textured hydrofacies in the northwest–southeast and southwest–northeast directions were chosen as 760 and 4570 m, respectively, for both T14S-R13E and T15S-R14E. The

mean lengths of the fine-textured hydrofacies are computed from the ratio of the proportions and from consideration of marginal probabilities.

## CONDITIONAL SIMULATION

Fitted one-dimensional continuous lag Markov chain models are combined into a three-dimensional Markov chain model, one representing the semi-confined aquifer heterogeneity in T14S-R13E (upper fan area) and one representing T15S-R14E (mid to distal fan area). These are used to generate conditional simulations of the hydrofacies distribution underlying each township-range on a  $201 \times 201 \times 41$  node grid with a discretization of  $150 \times 150 \times 3$  m. TPMOD generates each realization using a sequential indicator simulation (Deutsch & Journel, 1992) in conjunction with a simulated quenching algorithm (Carle & Fogg, 1997). In Fig. 4, we present realizations of the simulated three-dimensional semi-confined aquifers for T14S-R13E and T15S-R14E. Inspection of Fig. 4 shows that extensive vertical connections exist in the upper fan area while the probability for vertical interconnection is much lower in the mid to distal fan areas, which are most plagued by the salinity problem. The conditional realizations provide the basis for numerical stochastic analysis of the fast transport behaviour of salts in these complex alluvial environments.

Using similar information, we can also characterize the spatial variability of the Corcoran Clay layer heterogeneity and then investigate the potential for degradation of the groundwater in the confined aquifer from leakage of poorer-quality groundwater from above. These models will be used to implement a risk analysis of groundwater degradation in both the lower semi-confined aquifer and the confined aquifer for management alternatives similar to those evaluated by Belitz & Phillips (1995). Ongoing work includes flow and transport simulation, sensitivity analysis with respect to mean length and proportions, and extension of the hydrofacies model to three categories. With three and more hydrofacies, the transition probability/Markov chain approach allows us to analyse and incorporate juxtapositional properties into the simulation.

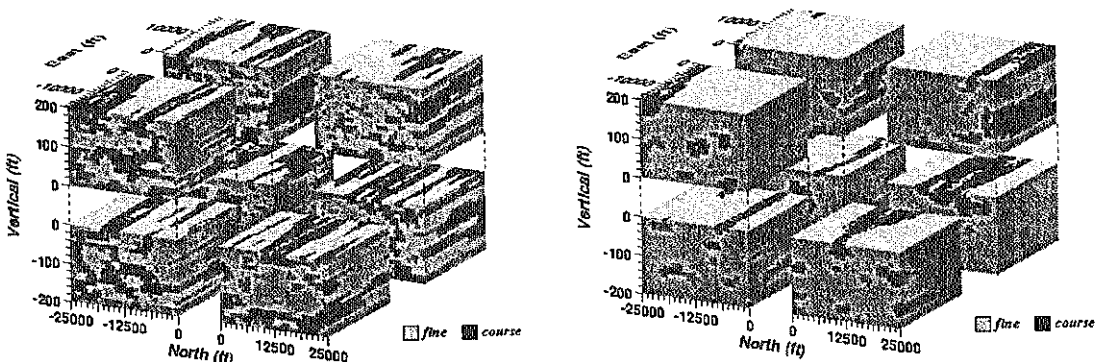


Fig. 4 Conditional simulation for T14S-R13E (left) and for T15S-R14E (right).

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