Space-local spectral texture segmentation applied to characterizing the heterogeneity of hydraulic conductivity

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[1] Spatial variability of hydraulic conductivity exerts a predominant control on groundwater flow by influencing advective pathways, hydrodynamic dispersion, and density-dependent instabilities. Space-local spectral texture segmentation aids in the macroscale characterization of the spatial heterogeneity of natural porous media via an outcrop analogue approach. Detailed photographic data sets were obtained for a 45 m $\times$ 3 m vertical section of glacial-fluvial sand and gravel deposit in the Fanshawe Delta area (Ontario, Canada). High-resolution texture maps of the sedimentary exposure are generated using a texture segmentation routine based on the space-local S transform with the photographic data sets used as input. Geostatistical analyses of the texture maps reveal similarity between the spatial correlation structures of spectral texture and hydraulic conductivity as determined from constant-head permeameter testing of sediment cores. Conditioned on the permeameter measurements, texture maps can be used to provide local continuous estimates of the hydraulic conductivity field at a spatial resolution equal to the sediment core dimensions. *INDEX TERMS:* 1829 Hydrology: Groundwater hydrology; 1894 Hydrology: Instruments and techniques; *KEYWORDS:* texture segmentation, hydraulic conductivity, heterogeneity, S transform

1. Introduction

[2] Spatial variability of hydraulic conductivity or intrinsic permeability exerts a predominant control on groundwater flow. Single order-of-magnitude contrasts in hydraulic conductivity may subtly influence the fluid potential and greatly influence the flow field, producing preferential paths for advective transport [*Gillham and Cherry*, 1982; *Yeh et al.*, 1995]. Heterogeneity of the porous media controls the macrodispersive component of the mechanical dispersion of solutes due to local-scale variations in groundwater velocity [*Gelhar and Axness*, 1983; *Frind et al.*, 1987]. In the case of variable density flow, heterogeneities are a controlling factor in the generation of plume instabilities [*Schincariol et al.*, 1997]. Accordingly, the character of the spatial distribution of hydraulic conductivity is a key input parameter for studies of contaminant transport, risk management for waste disposal, petroleum reservoir engineering, and general groundwater flow modeling.

[3] Large-scale descriptions of lithofacies and hydrofacies have proven inadequate for accurate predictions of groundwater flow and contaminant transport and dispersion [*Sudicky et al.*, 1983; *Anderson*, 1989; *Poeter and Gaylord*, 1990]. *Koltermann and Gorelick* [1996] reviewed several techniques being developed to address the need for representations of hydraulic property fields with increased spatial resolution. Generally, these representations of hydraulic property fields may take deterministic or stochastic forms. In the case of deterministic techniques, a single estimation of the hydraulic property field is developed through a combination of intense direct sampling and/or sophisticated interpolation and extrapolation techniques. Stochastic techniques, however, employ the spatial statistics of the hydraulic property (typically estimated via direct sampling) to generate any number of equally probable hydraulic property fields, all of which honor the observed spatial statistics. These multiple field generations are often used to investigate fluid flow problems in a Monte Carlo fashion. Minimum requirements for both deterministic and stochastic field estimation are a priori knowledge of the probability distribution of the hydraulic property and its spatial correlation structure. To this end, much focus of recent research has shifted toward attempts to incorporate remote sensing and data fusion into hydraulic property estimation in a groundwater context [e.g., *Hyndman and Gorelick*, 1996; *Cassiani and Medina*, 1997; *Hubbard et al.*, 1999].

[4] This paper investigates the applicability of a space-local spectral texture segmentation routine for characterizing the spatial distribution of hydraulic conductivity via an outcrop analogue approach. Texture may be defined as the combination of the magnitude and frequency of tonal change in an image; tone refers to the magnitude of the image variable and combinations of similar textures result in patterns [*Drury*, 1993]. Image may be generalized to refer to any two-dimensional representation of a scalar variable such as elevation, temperature or traditional photographic intensity. If the variable responsible for tonal change is grain size or grain size distribution, then sedimentary materials may be physically characterized or segmented (into patterns) by image texture. Furthermore, local empirical relationships between grain size distribution and hydraulic conductivity are well documented and often take the form of the Kozeny-Carman equation [*Mavko et al.*, 1998]. Thus the ability to

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