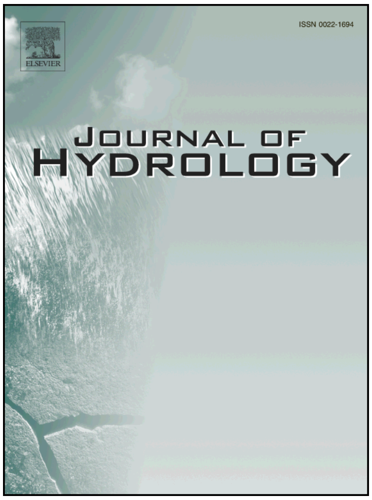

Spatial analysis of groundwater levels using Fuzzy Logic and geostatistical tools

P.G. Theodoridou, E.A. Varouchakis, G.P. Karatzas

PII: S0022-1694(17)30691-1
DOI: https://doi.org/10.1016/j.jhydrol.2017.10.027
Reference: HYDROL 22307

To appear in: *Journal of Hydrology*

Please cite this article as: Theodoridou, P.G., Varouchakis, E.A., Karatzas, G.P., Spatial analysis of groundwater levels using Fuzzy Logic and geostatistical tools, *Journal of Hydrology* (2017), doi: https://doi.org/10.1016/j.jhydrol.2017.10.027

Spatial analysis of groundwater levels using Fuzzy Logic and geostatistical tools

P.G. Theodoridou[a], E.A. Varouchakis[a,*], G.P. Karatzas[a]

[a] *School of Environmental Engineering, Geoenvironmental Engineering Laboratory,*
Technical University of Crete, 73100 Chania, Crete, Greece

Abstract

The spatial variability evaluation of the water table of an aquifer provides useful information in water resources management plans. Geostatistical methods are often employed to map the free surface of an aquifer. In geostatistical analysis using Kriging techniques the selection of the optimal variogram is very important for the optimal method performance. This work compares three different criteria to assess the theoretical variogram that fits to the experimental one: the Least Squares Sum method, the Akaike Information Criterion and the Cressie's Indicator. Moreover, variable distance metrics such as the Euclidean, Minkowski, Manhattan, Canberra and Bray-Curtis are applied to calculate the distance between the observation and the prediction points, that affects both the variogram calculation and the Kriging estimator. A Fuzzy Logic System is then applied to define the appropriate neighbors for each estimation point used in the Kriging algorithm. The two criteria used during the Fuzzy Logic process are the distance between observation and estimation points and the groundwater level value at each observation point. The proposed techniques are applied to a data set of 250 hydraulic head measurements distributed over an alluvial aquifer. The analysis showed that the Power-law variogram model and Manhattan distance metric within ordinary kriging provide the best results when the comprehensive geostatistical analysis process is applied. On the other hand, the fuzzy logic approach leads to a Gaussian variogram model and significantly improves the estimation performance. The two different variogram models can be explained in terms of a fractional Brownian motion approach and of aquifer behavior at local scale. Finally, maps of hydraulic head spatial variability and of predictions uncertainty are constructed for the area with the two different approaches comparing their advantages and drawbacks.

Keywords: Kriging, Fuzzy Logic, spatial variability, fitting criteria, distance metrics, fractional Brownian motion

---

1. Introduction

During the last decades geostatistics has been successfully established in environmental research (Journel & Huijbregts, 1978; Isaaks & Srivastava, 1989; Christakos, 1991; Deutsch & Journel, 1992; Cressie, 1993; Goovaerts, 1997; Kitanidis, 1997; Christakos, 2000; Elogne et al., 2008; Varouchakis & Hristopulos, 2013a). Geostatistics comprise a set of statistical techniques to analyze spatially and/or temporally dependent variables. The most well-known method to interpolate spatially autocorrelated variables such as groundwater level is the Kriging method and specifically the Ordinary Kriging (OK) technique (Aboufirassi & Marino, 1983; Ahmadi & Sedghamiz, 2007; Varouchakis & Hristopulos, 2013a,b). OK leads to optimal results in terms of estimation accuracy when the true variogram is known and the available data follow a multivariate normal distribution. Then, it can be applied to estimate the groundwater level spatial variability. In case of deviations from normality, data transformation/normalization e.g. Box-Cox transformation is applied. Therefore, outliers are suppressed, while more stable variograms are produced (Clark & Harper, 2000; Gringarten & Deutsch, 2001).

In geostatistical analysis using Kriging methods, the prediction of a value at unsampled locations is a weighted average of the neighboring data, where the weights are based on the spatial dependence function and the distance between observations and estimation points (Little et al., 1997). The distance metric is important because it affects both the variogram calculation and the Kriging method. However, most studies that involve Kriging focus on estimation and mapping processes (Christakos, 1984; Schlather, 1999) and not on the use of alternative distance metrics. The separation distance between observations and prediction points is usually defined using the Euclidean distance. The spatial scale of the sampling domains, inhomogeneity, heterogeneity and the different spatial distribution of environmental processes are some reasons to consider non-Euclidean distance metrics in geostatistical analysis (Curriero, 2006). Thus, the applica-

---

[*] Corresponding author
Email addresses: `giotatheod@gmail.com` (P.G. Theodoridou), `varuhaki@mred.tuc.gr` (E.A. Varouchakis), `karatzas@mred.tuc.gr` (G.P. Karatzas)

Preprint submitted to Journal of Hydrology *October 11, 2017*