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Patterns of temporal scaling of groundwater level fluctuation

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SUMMARY

We studied the fractal scaling behavior of groundwater level fluctuation for various types of aquifers in Puerto Rico using the methods of (1) detrended fluctuation analysis (DFA) to examine the monofractality and (2) wavelet transform maximum modulus (WTMM) to analyze the multifractality. The DFA results show that fractals exist in groundwater fluctuations of all the aquifers with scaling patterns that are anti-persistent ($1 < \beta < 1.5$; 1.32 ± 0.12, 18 wells) or persistent ($\beta > 1.5$; 1.62 ± 0.07, 4 wells). The multifractal analysis confirmed the need to characterize these highly complex processes with multifractality, which originated from the stochastic distribution of the irregularly-shaped fluctuations. The singularity spectra of the fluctuation processes in each well were site specific. We found a general elevational effect with smaller fractal scaling coefficients in the shallower wells, except for the Northern Karst Aquifer Upper System. High spatial variability of fractal scaling of groundwater level fluctuations in the karst aquifer is due to the coupled effects of anthropogenic perturbations, precipitation, elevation and particularly the high heterogeneous hydrogeological conditions.

1. Introduction

Fractal analysis is a method developed in recent decades to study the irregular features that are not characterized by conventional geometry (Mandelbrot, 1983). The concept has been extended to and applied in many disciplines such as physiology, geophysics, hydrology, and social sciences, as well as the study of nonlinear or stochastic processes. The fractal is defined as an object that reproduces itself invariant to scales, whereas it can be either deterministic fractal that has exactly the same geometry, or stochastic fractal that is statistically similar to the object in other scales. Homogeneous variability processes are characterized as monofractal, while complex nonlinear heterogeneous processes are described by multifractal structures (Stanley et al., 1999).

Groundwater levels reflect the potentiometric state of water recharge, storage and discharge of the aquifer (Law, 2001; Conlon et al., 2005). A metastable equilibrium state is easily upset by variations of the hydrogeological conditions such as precipitation, evaporation, transpiration, runoff, infiltration, soil moisture, and anthropogenic activities such as pumping, dams, irrigation, and other water management methods (Li and Zhang, 2007; Zhou et al., 2012). Consequently, groundwater levels fluctuate continuously to achieve potentiometric balance. The temporal fluctuations may exhibit periodic and seasonal cycling due to climatological conditions. The fluctuations are often not stationary and are not suitable to be simulated using ordinary linear and deterministic models. The non-stationary fluctuations of groundwater levels, which may be characterized as fractional Brownian motion (fBm; Hardstone et al., 2012), may not be completely random but, to a large degree, long-range correlated (Bak et al., 1987; Matsoukas et al., 2000; Veneziano and Langousis, 2010). The long-range correlation or self-affinity is also termed as fractals because the variations of groundwater levels, to some extent, follow a logarithmic linear power-law relationship with time windows, i.e. $F(l) \sim l^{\gamma}$ (fluctuations $F(l)$ vs. time windows l, γ is the scaling coefficient). The fractal scaling coefficients suggest both anti-persistent and persistent correlations, where anti-persistence means that variability in one direction is likely to be followed by variability in the opposite direction, and persistence means there is a trend of the fluctuations (Dingwell and Cusumano, 2010).

Studies on the persistent fractal scaling behavior of hydrology variables date back to the pioneering work of Hurst (1951) studying water levels and storage capacity in the Nile River. Researchers have reported on fractal scaling behavior for groundwater levels, where the power of the fractal correlations was proposed to

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decrease from persistent scaling in the short scale of about 10 days, to anti-persistent at a few months to a year, and to 1/f noise at larger time scale (Zhang and Schilling, 2004; Li and Zhang, 2007; Little and Bloomfield, 2010; Labat et al., 2011). Zhang and Schilling (2004) and Li and Zhang (2007) further suggested that aquifers tend to behave as a fractal filter where the temporal fractal correlation decreases from rainfall to stream flow, to groundwater, and to base flow due to damping effects of land surface, soil deposits and aquifers. Crossovers of the fractals were detected for groundwater level fluctuations, which indicate that the notion of monofractal may not be enough to describe these complex processes. Multifractal analysis is required to detect and quantity irregularities in the time series from point to point. In hydrology, fractal scaling analysis of groundwater level fluctuations is fundamental to more realistic hydrology modeling studies by considering the temporal scaling cascading issues, because every model is based on some spatial and temporal scales whereby the hydrogeology parameters may vary under different scales (Bergstrom and Graham, 1998). Fractal scaling analysis of the mechanistic properties of groundwater level fluctuations may also be useful in revealing intrinsic hydrogeological conditions and in evaluating extreme climatological events and anthropogenic perturbations (Liang and Zhang, 2013).

Aquifers are widely distributed throughout Puerto Rico with a concentration in the North Coast featuring karst limestone formations, which provides significant water resources to Puerto Rico. Research on groundwater level fluctuations of Puerto Rico's aquifers has significant scientific and engineering meaning. In this paper, we systematically investigate the temporal fractal scaling behavior of groundwater level fluctuations in wells associated with various types of aquifers in Puerto Rico. We use the well-developed methods of detrended fluctuation analysis (DFA) to study monofractality and wavelet transform maxima modulus (WTMM) to study multifractality. Our goal is to analyze the mono- and multi-fractality of groundwater level fluctuations, examine the origin of the fractality, and investigate the spatial patterns of the fractal scaling behaviors.

2. Methods

2.1. Site description

Puerto Rico (17°55′–18°33′N, 65°33′–67°17′W) is a relatively large island located in the Caribbean Sea covering a total area of 8710 km^2. The island is categorized into four areas based on geological formations: the North Coast, South Coast, Alluvial Valley, and Volcaniclastic-, Igneous-, and Sedimentary-Rock. The North Coast features karst limestone formations which can be found in the upper and lower systems as well as the confining units (Fig. 1). The geophysical properties of these aquifers are summarized from previous studies and presented in Table 1 (Lugo et al., 2001; Renken et al., 2002). Note that the area reported in Table 1 refers to the outcrop area, and may not reflect additional area extending beneath shallower formations. The total areas for the Confining Unit and the North Coast Lower Aquifer, which extend beneath the Aguada and Aymamon Limestone Formations, are larger than the reported outcrop area. The northern karst aquifers provide around 50% of the total groundwater production of Puerto Rico, where the total groundwater production accounts for 16% of the total water production in Puerto Rico by 2005 (Molina-Rivera and Gómez-Gómez, 2008). The karst aquifer is evolving stochastically as the combined effects of waterborne matter filling the openings and fractures encroaching through the flushing and dissolution of the limestone, which is likely to impact water storage and groundwater levels. Groundwater flow in karst aquifers is essentially stochastic due to the high heterogeneity in its pathways, unknown fractures and channels, and complex formation matrix (Ghasemizadeh et al., 2012; Yu et al., 2014). Water management activities also have considerable effects on groundwater levels such as pumping of many wells in the north karst aquifers. The closing of the pumping wells due to concerns of groundwater contamination and opening of new wells for water use or pollution remediation further complicate the hydro-potentiometric state of the water levels.

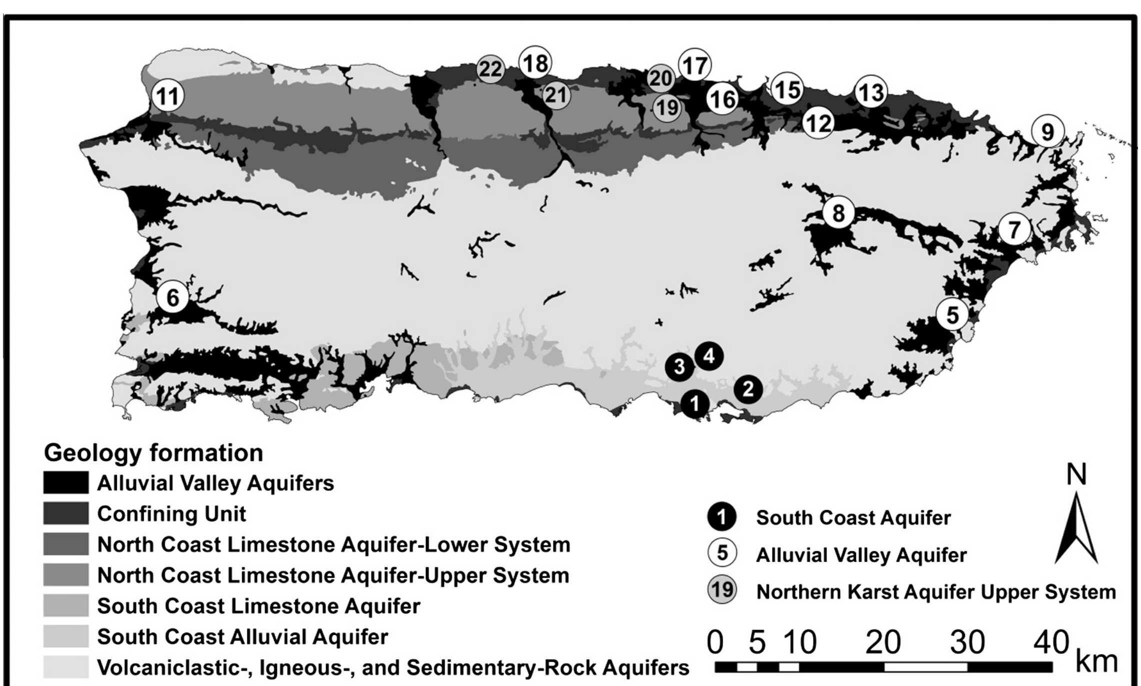

Fig. 1. Location of USGS groundwater monitoring sites (different black and white points denote wells in different types of aquifers; $n = 22$) in Puerto Rico. The geophysical properties of the study wells and associated aquifers are in Table 1 and Supplementary Material.