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Communicating uncertainty about groundwater scenarios using stochastic simulation of water table depths time series

Rodrigo Lilla Manzione[1], Edson Wendland[2]

[1] UNESP/Campus of Ourinhos, Av. Vitalina Marcusso 1500 CEP: 19910-206 Ourinhos (SP) Brazil
manzione@ourinhos.unesp.br
[2] USP/EESC/SHS, Av. Trabalhador Sãocarlence 400 CEP: 13560-970 São Carlos (SP) Brazil
ew@sc.usp.br

Abstract

Time series modeling provides an empirical stochastic method to model monitoring data from observation wells, without the complexity of physical mechanistic models. In the same direction, geostatiscal methods are used to make probabilistic statements about quantities of interest at non-measured locations. The aim of this work was to present water-table levels scenarios results of a combination of time series modeling and geostatistics to predict and discuss the communication via probability maps. The study case was held in a watershed located in an outcrop of the Guarani Aquifer System (GAS). The Onça Creek watershed has a monitoring scheme with 23 wells spatially distributed over the area. The water heads are measured with a semi-monthly frequency. First, the time series are inspected and modeled with a special type of Transfer-function noise model, the so called PIRFICT-model and then the model outputs are interpolated spatially using geostatistics. How communicate this results is discussed via the resulted maps that contain probabilistic measures about model uncertainty. Understand uncertainty and communicate it to practitioners, decision makers and stakeholders in a clear and simple form is a key element for efficient water resources planning.

Keywords: time series, geostatistics, groundwater, land use planning

1. Introduction

Uncertainty analysis and scenario evaluation can be taken into account during the planning processes of land use and natural resources appropriation. Scenarios evaluations are important results of modeling experiments involving natural resources. Monitoring water-table levels provide useful information for water management, giving the chance for water commissions and regulatory bodies predict the water availability in time and space. The parameters of hydrogeologic systems can vary greatly in space and time, but they are usually sparsely sampled. Our knowledge of system parameters is therefore partial at best and the most we can usually do is to quantify our uncertainty through stochastic, or related, models.

Considering that a scenario can be predicted in several levels of probability, the communication of these results should be considered a key element for efficient water resources planning.

The aim of this work is to present the results of a probabilistic experiment involving the combination of time series modelling and geostatistics in order to discuss how to communicate the risk of extreme levels in a watershed located in a outcrop area of the Guarani Aquifer System, one of the biggest groundwater reservoirs in the world.

2. Materials and methods

2. 1. Study area

The study area is an outcrop zone of the Guarani Aquifer System (GAS), in the municipality of Brotas, São Paulo State, Brazil. The Onça creek watershed is equipped with 23 wells installed in the watershed for groundwater level monitoring (Wendland *et al.*, 2007). Water levels were observed manually every 15 days, from April, 2004 until April, 2009, totalizing five years (1826 days) of continuous monitoring. These wells were selected purposively to cover the range of land uses and hydrogeological domains in the area, in a try to characterize the different responses of water levels in the watershed (Figure 1). The filter levels of the wells varied with soil depth. Series of precipitation and potential evapotranspiration data were available from CRHEA/USP (Center for Water Resources and Applied Ecology of the University of Sao Paulo), where climatologic data are collected continuously. These data were available from 1974 until 2009 (35 years) with a daily frequency. The watershed is located approximately 1.5 km away from the station.

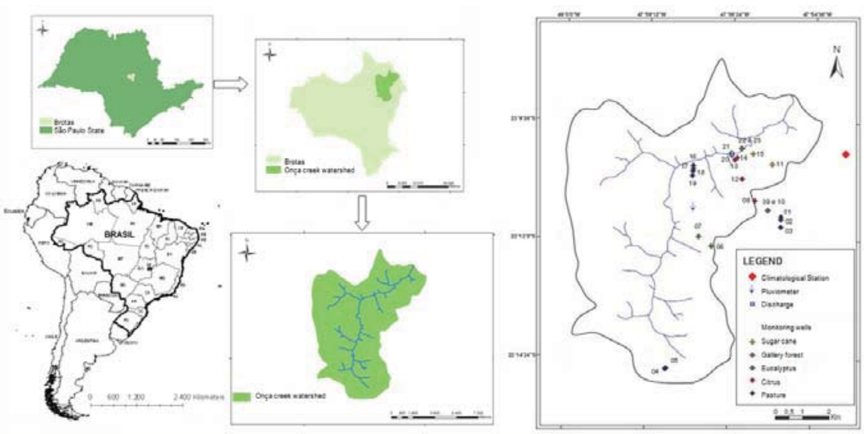

Figure 1: Map of the Brazilian territory and its provinces with a detail of Onça creek watershed in the municipality of Brotas, São Paulo State (left) and the monitoring scheme in the study area (right).

2. 2. Data analysis

The time series model used to establishes the dynamic relationship between water levels though its calculated IR function is the so called PIRFICT (Predefined

Impulse Response Function In Continuous Time) model, a special type of transfer function noise (TFN) model (Von Asmuth *et al.*, 2002). In time series analysis, many authors refer to transfer function-noise models to describe the dynamic relationship between climatological inputs and water-table depths (Hipel and McLeod, 1994; Van Geer and Zuur, 1997; Von Asmuth and Knotters 2004). The basic idea behind this TFN modelling is to split the observed series (output) into a number of components related to know causes (inputs) that influence the phenomena, an unknown noise component. TFN models are often applied to distinguish between the natural and the man-inducted components of groundwater series (Van Geer and Zuur, 1997).

The transfer function-noise models are calibrated to the set of time series observed in the various wells in the area. Next the time series model predictions are interpolated spatially. In this approach the spatial differences in water table dynamics are determined by the spatial variation in the system properties, while its temporal variation is driven by the dynamics of the input into the system (Knotters and Bierkens, 2001). To account for model uncertainty, the time series model are simulated over time, using 30 years long climatological data available from the area to reconstruct the water table series following the method proposed by Manzione *et al.* (2008) and Manzione *et al.* (2010) to predict extreme levels in the Brazilian Cerrados. The simulation procedure of the PIRFICT model generates 1000 realizations of long term time series of water table levels reconstructed by the signal of longer climatological series of precipitation and potential evapotranspiration in the Fourier space (e.g. 30 years). With this procedure is possible to avoid short-term disturbances in the time series, once it allows filtering out noises in these series, based on the response of the aquifer system to the input in the model (which is much more slow rather to climate circumstances). Then, probability density functions (PDF) are calculated for any date of interest in the agricultural calendar of the region to account for extreme levels. These levels are indicated by percentiles in the PDF's. The assessment of risk requires an understanding of extreme events, which are far from average by definition (Winter, 2004).

The values of the selected percentiles of the simulated water table levels are interpolated spatially using geostatistics techniques (Pebesma, 2004). These maps present the water table levels that will be exceeded with 95 and 5% chance for instance, in some specific date, sampled from the simulated series. The probability of exceedance with 95% chance (P 0.05) suggesting a scenario for deep levels and the probability of exceedance with 5% chance (P 0.95) suggesting a scenario for shallow levels, for instance. These limits are just examples and can be changed by the targets they have being used for.The selected date for this study was October 12, an interesting date in the agronomical calendar of the region, when the cultivations start, after the first rains of the spring season. In this date we are interested in extreme low levels in the watershed, since the water is need to start and maintain the crops in its first stages. The risk of dry wells can be evaluated from the 0.05 percentiles of the PDF. Here the spatial correlation structure of the estimated time series is characterized by a semivariogram and interpolated using a linear combination of the observed values in the ordinary kriging system:

$$\hat{z}(x_0) = \sum_{i=1}^{N} \lambda_i \cdot Z(x_i) \qquad (1)$$

where, N is the number of observed values $z(x_i)$ involved in the estimatives and λ_i are the kriging weights associated with each observed values $z(x_i)$. The results of spatial interpolation are evaluated using cross-validation (Pebesma, 2004).

3. Results and discussions

The results of the spatial interpolation of the 0.05 percentiles of the PDF calculated from the simulated time series models are presented at Figure 2.

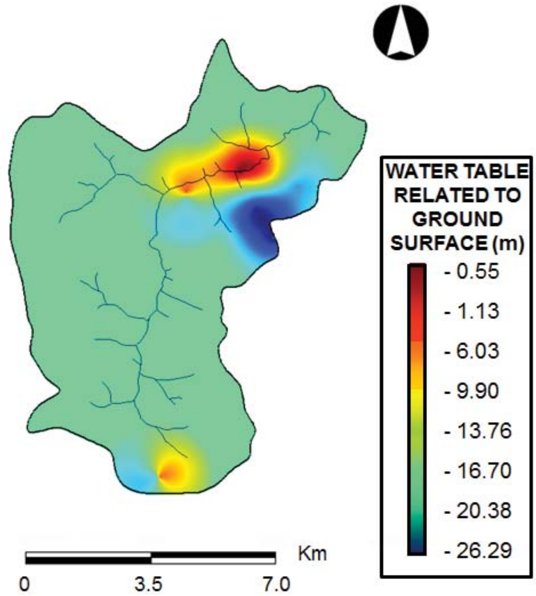

Figure 2: Water table levels that could be exceeded at 12 October with 95% probability.

The variation of the levels between the scenarios presented here for 12 October contains valuable information about groundwater dynamics in the basin. The areas in the eastern part of the watershed have lower levels compared with the other regions. Close to the river the levels are shallow. The lack of coverage of the monitoring network highly influences the performance of the kriging system, with high uncertainty of interpolation in the western part of the watershed.

From these maps, water boards and land use planers can start a discussion about strategies for the next cultivation season, based on the prevailing climatological condition and soil water balance. In wet years, the map of percentile 0.95 can be used, for instance, to selected areas with risks of shallow levels that can stop machinery and delay field operations (Manzione *et al.* 2010). In dry years, the map of percentile 0.05 can be used to select areas with risks of water shortage and dry wells (Manzione *et al.* 2008). It is important to mention that areas with shallow levels present more liability than areas with deep levels since the range of the variations is much smaller and, less uncertain. It is also an indicative that efforts should concentrate on that areas with large uncertainty if is desired to improve model results.

In this study, the map of 0.05 percentile established as a scenario of water shortage at October 12. Some would say that scenarios of extreme percentiles are unrealistic, since it would be impossible to imagine that in all pixels in this map the water table levels are reaching such extreme thresholds. But for water planning activities maps like that could reveal potential risk areas that deserve attention during land use regulation. Resilient systems can have a higher probability of success in this uncertain climate changing period and predicting extreme levels can incorporate resilience in this system via planning and management initiatives.

The visualization of the final results of a probabilistic experiment in the form of a map can enhance the comprehension by the general public. Manzione *et al.* (2010) considered maps more understandable for general public, rather than tables containing statistical intervals. Also, this kind of practice can motivate application of uncertainty analysis as routine in land use planning and evaluation of natural resources scenarios.

4. Conclusion

Communicate uncertainty to practitioners, decision makers and stakeholders in a clear and simple form is a key element for efficient water resources planning. Maps presenting probabilistic scenarios can be helpful in this task because it provides limits and thresholds about groundwater levels that can be incorporated into water resources management plans giving margin for efficient water planning.

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