WATER TABLE DEPTHS TRENDS IDENTIFICATION FROM CIMATOLOGICAL ANOMALIES OCURRED BETWEEN 2014 AND 2016 IN A CERRADO CONSERVATION AREA IN THE MÉDIO PARANAPANEMA HYDROGRAPHIC REGION/SP-BRAZIL

IDENTIFICAÇÃO DE TENDÊNCIAS EM NÍVEIS FREÁTICOS FRENTE ÀS ANOMALIAS CLIMÁTICAS OCORRIDAS ENTRE 2014 E 2016 EM ÁREA DE CONSERVAÇÃO DE CERRADO NA REGIÃO HIDROGRÁFICA DO MÉDIO PARANAPANEMA/SP

IDENTIFICACIÓN DE TENDENCIAS EN NIVELES FREÁTICOS FRENTE A LAS ANOMALÍAS CLIMÁTICAS OCURRIDAS ENTRE 2014 Y 2016 EN UNA ÁREA DE CONSERVACIÓN DE CERRADO EN LA REGIÓN HIDROGRÁFICA DEL MEDIO PARANAPANEMA/ SP – BRASIL

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Abstract

Allying temporal and spatial dimensions at phenomena analysis can bring answers that traditional geographical spatial data analysis alone would not revel. However, gathering scales that do not vary in the same way, such as space and time, is not routine in geosciences due to the complex structure of these data.The aim of this study was to investigate the behavior of groundwater resources against the climatic anomalies occurred in the State of São Paulo between 2013-2016 in a representative area of the Médio Paranapanema hydrographic region (UGRHI-17), in time and space. A monitoring network of water table depths and an automatic climatological station were installed in the Ecological Station of Santa Barbara, municipality of Águas de Santa Barbara (SP), Brazil, to collect groundwater and climatological data between September 2014 and August 2016 at 32 wells. Time series modelling showed that the climatic inputs influenced the behavior of the groundwater levels, indicating elevation trends in the studied period. On the other hand, the spatial analysis revealed differentiated patterns of elevation between EEcSB basins, mainly as a land use function.This information is important for groundwater management, water dependable activities planning and studies about the natural resources capacity of specific areas.
Keywords: time series, groundwater, monitoring, PIRFICT model.

Resumo

Aliar as dimensões temporais e espaciais na análise de fenômenos pode trazer respostas que a análise espacial de dados geográficos sozinha não revelaria. Entretanto, reunir escalas que não variam da mesma maneira, como o espaço e o tempo, não é rotina em geociências devido à complexa estrutura desses dados. O objetivo desse trabalho foi investigar o comportamento dos recursos hídricos subterrâneos frente às anomalias climáticas ocorridas no Estado de São Paulo entre 2013-2016 em área representativa daregião hidrográfica do Médio Paranapanema (UGRHI-17),no tempo e no espaço. Para isso, implantou-se na Estação Ecológica de Santa Barbara (EEcSB), Águas de Santa Barbara/SP, uma rede de monitoramento hidrometeorológica para coletar dados climatológicos e de níveis freáticos em 32 poços entre setembro de 2014 e agosto de 2016. A análise de séries temporais revelou que os estímulos climáticos influenciaram o comportamento

dos níveis freáticos, indicando tendências de elevação no período estudado. Já a análise espacial revelou padrões diferenciados de elevação entre bacias da EEcSB, principalmente em função do uso da terra. Essas informações são importantes para gestão dos recursos hídricos subterrâneos, planejamento de atividades que dependam da água e estudos sobre a capacidade de suporte de áreas quanto aos seus recursos naturais.
Palavras-chave: séries temporais, águas subterrâneas, monitoramento, modelo PIRFICT.

Resumen

Aliar las dimensiones temporales y espaciales en el análisis de fenómenos puede traer respuestas que el análisis espacial de datos geográficos por sí solas no revelaría. Sin embargo, reunir escalas que no varían de la misma manera, como el espacio y el tiempo, no es rutina en geociencias debido a la compleja estructura de esos datos.El objetivo de este trabajo fue investigar el comportamiento de los recursos hídricos subterráneos frente a las anomalías climáticas ocurridas en el Estado de São Paulo entre 2013-2016 en área representativa de la región Hidrográfica del Medio Paranapanema (UGRHI-17), en el tiempo y en el espacio.Se llevó a cabo en la Estación Ecológica de Santa Barbara (EEcSB), Águas de Santa Barbara (SP/Brasil) una red de monitoreo del agua subterránea y una estación meteorológica automática para recoger datos sobre el clima y los niveles de agua subterránea entre septiembre de 2014 y agosto de 2016. La modelización de series temporales se encontró que los estímulos climáticos influyeron en el comportamiento de los niveles de agua subterránea, lo que indica las tendencias de elevación durante el período de estudio. El análisis espacial reveló patrones diferenciados de elevación entre cuencas de la EEcSB, principalmente en función del uso de la tierra.Esta información es importante para la gestión de los recursos de aguas subterráneas, la planificación de actividades que dependen del agua y estudios sobre las áreas de la capacidad de carga de sus recursos naturales.
Palabras clave: series temporales, agua subterránea, monitorizaron, modelo PIRFICT.

1 Introduction

A common challenger in environmental studies is the methodological need for tools capable of describing and predicting complex, and typically high dimensional, processes. Cressie and Holan (2011) describe new approaches to modelling in this context, noting that among them the study of environmental time series is fundamental for the greater goal of sustainability and adaptation. The management of water resources requires the use of modelling techniques that recognize variability, both temporal and spatial, so that the analyses, diagnoses and recommendations made do not lose valuable information in solving complex problems. Knowing "*how*" and, ultimately, "*why*" environmental processes change over time gives governments and common protectors a rational means for decision-making.

For Cressie and Wikle (2011), causality is the "*holy grail*" of science, seeking to infer relations of cause and effect, or the "*why*" of things. This thought is followed by the "*when*," since a cause always precedes its effect. Continuing along this line, defining "*where*" things happen denotes the historical and geographical character of the event. So, for a good "*why*" answer to be found, it must be accompanied by "*when*" and "*where*". Incorporating the temporal and spatial dimension within the same variability model remains a challenge for geoscientists since the variations do not occur on the same scale. While in space deals with meters, kilometres (metric distance), in time deals with days, months, years, decades (temporal intervals). The analysis of time series associated with the spatial analysis of geographic data allows access to the temporal spatial dimensions of the variability of the phenomenon under study. Monitoring data, when collected in geospatial networks, allows these techniques to be explored.

Groundwater monitoring is a fundamental tool for assessing the conditions that this natural environment is in, and then can take preventive and/or proactive measures for the predominance of quality and quantity, seeking to develop sustainable use together with an integrated management action (Mestrinho, 2008). A good monitoring program will include planning, implementing, interpreting, evaluating results, and reassessing program effectiveness. The monitoring points should be located in places with known hydrogeological characteristics and should be fixed points so that you can have a historical series of data to better understand the dynamics that operate there. Monitoring data collection requires treatment with statistical, mapping, graphing and modelling methods. Therefore, after a period of monitoring, the data are analysed statistically and the uncertainties are considered. With this information is possible to analyse from a technical-environmental and socioeconomic point of view, to make the necessary decisions and to review the objectives of the network (Moore, 2012).

In water scarcity periods, water supply is reduced, in parallel with the increase in demand, whether by the domestic, industrial or agricultural sector. Knowing the importance of water for society, both for domestic supply, industrial activities and agriculture, groundwater resources arouse great environmental interest in relation to its conservation. Thus, the exploitable volume of an aquifer is a decision variable to be determined as part of a water system management plan for a region. But for this improvement on integrated water management it is necessary to know the dynamics of groundwater and identify the processes that influence the oscillation of its levels. Monitoring the available water in an aquifer turns possible to diagnose the current state of the aquifer in relation to past states and to act appropriately in relation to modifications caused by natural and/or anthropic effects.

In the Médio Paranapanema Hydrographic Region (UGRHI-17), São Paulo State, Brazil, groundwater is a source of supply for several cities, numerous springs and major rivers that support agricultural and forestry systems, as well as remnants of natural Cerrado vegetation (CBH-MP, 2010). Thus, the objective of this work was to verify the effects of climate and seasonality on the oscillation process of groundwater levels from agro-meteorological monitoring data collected in a geospatial network between 2014 and 2016 in an area representative of UGRHI-17. In order to do so, we sought to incorporate the temporal and spatial dimensions of the groundwater oscillation process to infer the dynamics of the Bauru Aquifer System (BAS), one of the main groundwater bodies available at UGRHI-17.

2 Study area

2.1 Ecological station of Santa Barbara

The Ecological Station of Santa Barbara (EEcSB) is located near Rodovia SP 261 – km 58, coordinates 22º48'59" South and 49º14'12" West, in the municipality of Águas de Santa Bárbara/SP-Brazil (Figure 1). The area was regulated by Decree 22.337 of June 7, 1984, which instituted its formation with an area of 4,371 hectares within the boundaries of the Santa Bárbara State Forest, of which 2,712 hectares of native vegetation (Cerrado, swamps and gallery forest) dividing the space with anthropic fields, vegetation in the regeneration stage, ciliary forest and reforestation areas with *Pinus* and *Eucalyptus*.

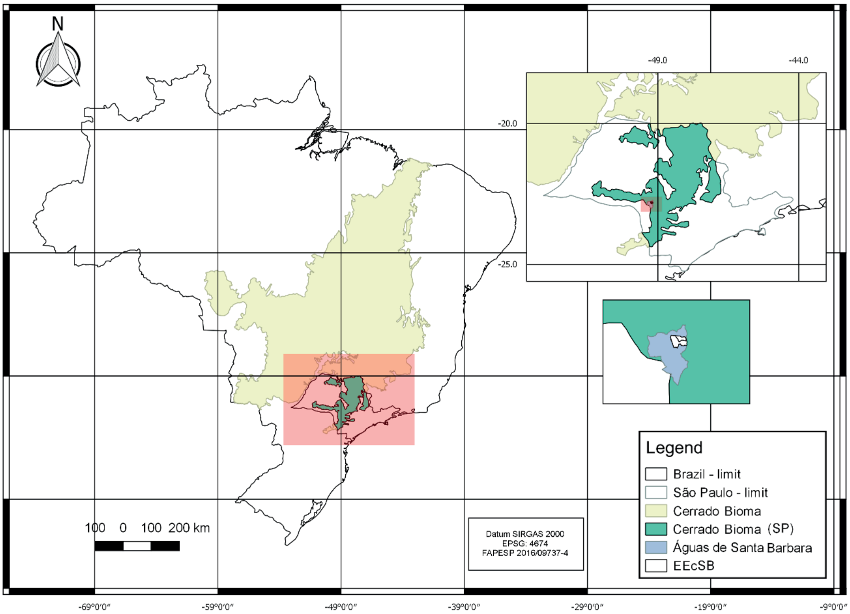

Figure 1 - EEcSB location in the limits of the municipality of Águas de Santa Bárbara (SP/Brazil).

The geological formations in the region include the sandstones of the Adamantina and Marilia Formations, belonging to the Bauru Group, with predominance of the Adamantina Formation in the domains of EEcSB (CPRM, 2006; Melo; Durigan, 2011). The EEcSB is located in the Paraná Sedimentary Basin (morphostructure) and the Paulista Western Plateau (morphosculture) as described in Ross and Moroz (1996), with predominantly broad and low hills, with altimetry around 600 and 680 m. The main soil types present in the EEcSB are Red Latosols (LV56) and eutrophic and dystrophric Red-Yellow and Red Argisols (PVA10) with sandy/medium texture and eutrophieric Nitosols (NV1) with clay texture (Oliveira et al., 1999).

According to Koeppen classification, the characteristic climate of the region is tropical subhumid (Cwa - warm climate with dry winter). The average annual temperature is around 18°C, with temperatures of 16°C in the coldest month and 23°C in the hottest month (CEPAGRI, 2016). The annual precipitations are around 1,000 and 2,086 mm, and can reach 30 mm monthly in winter (Melo; Durigan, 2011).

2.2 Climatic characteristics of the studied period

The summer of 2013/2014 was one of the driest ever recorded in the State of São Paulo (Coelho et al., 2016). This has had direct effects on the hydrological cycle, reducing the aquifer recharge and the spring water production, contributing even more to the picture of water scarcity. By contrast, in 2015 and 2016, the world witnessed one of the strongest El Ninõ Southern Oscillation (ENOS) phenomena ever recorded. The impacts of the El Niño and La Niña events lead to evident difficulties in Southern South America in the hydrological (Boulanger et al., 2005) and agricultural (Podestá et al., 1999) sectors, particularly in the northeast of Argentina, the southernmost part of Brazil and Uruguay (Penalba and Rivera, 2016). The precipitation excess associated with El Niño events contributes to excess conditions observed in soil water content (Spescha et al., 2004) and an increase of about 10% in soil water storage (Penalba et al. 2014). In this last event, several places had their precipitation regimes changed, such as in the interior of the State of São Paulo, where areas of subtropical climate typically with rainy summer and dry winter had a rainy winter, favoring the recovery of surface and groundwaterbodies already in 2016.

2.3 Data avaiable

Assuming that after the dry summer of 2013-214 groundwater levels would be sufficiently lower than normal by the end of the winter of 2014, it was imagined that from the implementation of a water table level monitoring network in the study area would be able to characterize the behavior of the groundwater after this climatic anomaly. A total of 32 wells were drilled near the main drains of the EEcSB (Figure 2). These wells were visited on a monthly frequency between July 2014 and September 2016, and the groundwater levels recorded using a level meter, creating a 26-month database about aquifer behavior in the EEcSB.

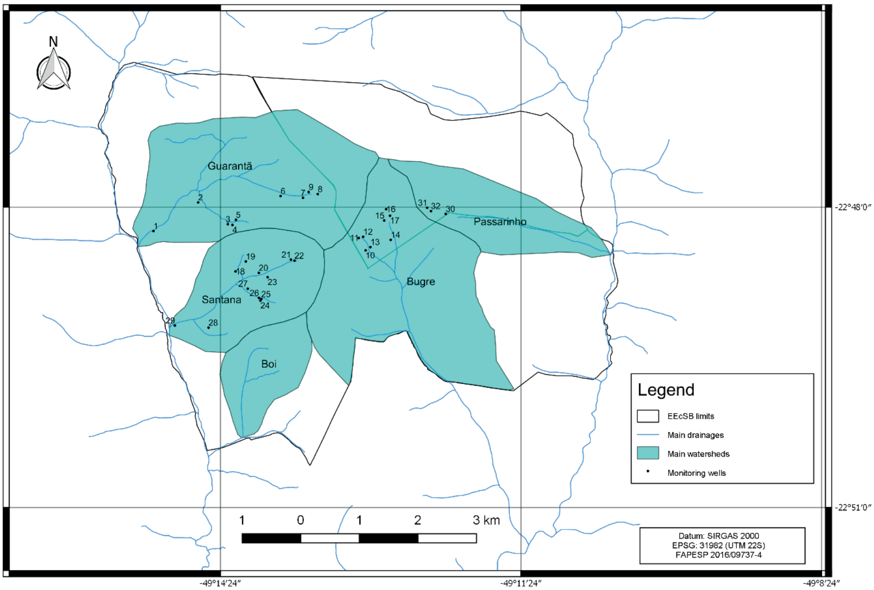

Figure 2 - Monitoring wells location in the major watersheds of EEcSB.

The climatological data used in this study were a series of precipitation and potential evapotranspiration from an automatic compact climatological station (ACS) installed in the study area in July 2014. This ACS was reprogrammed to collect daily data, in hourly frequency, about wind direction, solar radiation, temperature, relative humidity and precipitation. In addition, potential evapotranspiration was calculated using the ASCE (American Society of Civil Engineers) standardized method (Allen et al., 1998). The data used for time series modeling represent two hydrological years counted from from September 2014 (beginning of spring in southern hemisphere) to August 2016 (end of winter). In the first hydrological year (2014/15) the precipitation was 1,280.20 mm and in the second (2015/16) 1,756.80 mm.

3 Data modelling

3.1 Modelling moitoring time series data

The behavior of a linear input/output system can be completely characterized by its impulse/response (IR) function (Ziemer et al., 1998; Von Asmuth et al., 2002). For water table depths, the dynamic relationship between the precipitation and the response in the water levels can be explained by transfer function noise models (TFN) (Knotters, 2001). In TFN models, one or more deterministic transfer components and a noise are determined as additive components. The transfer components describe the part of the process of water levels oscillation that can be explained by the input series (precipitation, evapotranspiration, pumping, abstractions, river flow, among others) from a linear transformation of these input series. The noise model describes the autoregressive structure of the differences between the observed levels and the sum of the transfer components. The input of the noise model is a series of independent and identically distributed perturbations, with zero mean and finite and constant variance, which is called white noise. In this study was used the Pre-defined Impulse Response Function In Continuous Time (PIRFICT) model, which is an alternative to TFN models in discrete time intervals presented by Von Asmuth et al. (2002). In the PIRFICT model, the input block pulse is transformed into an output series by a continuous-time transfer function, and the coefficients of this function do not depend on the observation frequency. Assuming linearity in the system, a series of groundwater levels is a transformation of a series of precipitation surplus/deficit. This transformation is completely governed by the IR function. For the case of a simple linear system with no groundwater disturbance, which is influenced only by precipitation, the TFN model can be used to describe the relation between water table depths and precipitation (Von Asmuth et al., 2002).

TFN models are identified through the choice of mathematical functions that describe the IR relationship and the autoregressive structure of noise. This identification can be done interactively (using correlation structures contained in the available data and diagnoses about models) or physically (based on previous knowledge about the behavior of the system being analyzed). Following the physical identification of the system, the

IR function describes the way in which each water table responds to a pulse caused by precipitation. In this respect, an analogy can be made to a unit hydrograph (Von Asmuth; Maas, 2001), where after a precipitation event there will be changes in the base flow and increase in the surface, subsurface and groundwater flow. A linear trend parameter (LTP) was added as a model parameter to verify the behavior of the water table over the monitored period. The PIRFICT model analyses are performed using the *Menyanthes* software (Von Asmuth et al., 2012).

3.2 Geographical spatial data analises

According to Stein el al. (1991), there are two main methodological approaches for integrating the temporal dimension with the spatial dimension. The first method called "*calculate first/interpolate later* (*CF/IL*)" is to first calculate the data model punctually and then interpolate its results spatially, while the second method called " *interpolate first /calculate later* (*IF/CL*)" would be basically interpolate the input data from the model first and then calculate the data model spatially. In both contexts, geostatistical analysis allows exploring the spatial continuity of natural processes and interpolating the data with minimum deviations and maximum precision (Stein et al., 1991; Becchini et al., 2000). Manzione (2007) proposed an extension to the time series analysis using the PIRFICT model for the spatial dimension through the geostatistical interpolation of model parameters or even water table characteristics estimated from simulations.

In this study, following the *CF/IL* approach, this analysis was performed for elevation trends (LTP parameter of the PIRFICT model) of the groundwater levels during the period studied, which were subsequently interpolated geostatistically. The geostatistical analysis followed the methodology described in Journel and Huijbregts (1978) and Yamamoto and Landim (2013): variography, interpolation by ordinary kriging and cross-validation of the results.

4 Results and discussion

In a general way, Shapooriet al. (2015) highlight that TFN models simulates a model output in a determined instant in time as a data weighting of recent forces influencing the levels (e. g. the transfer function) plus a correlation term for the simulated output not explained by the reining forces (e. g. the noise). The PIRFICT model adjusted for the 32 monitoring wells with a linear trend parameter to verify the elevation levels rates in the period presented a good calibration and tendencies of levels elevation during the period. Table 1 shows the results of calibrations and calculated parameters.

Table 1: Mean PIRFICT model calibrations for 32monitoring wells between 05/09/2014 and 02/09/2016.

	EVP	*RMSE*	*RMSI*	*LDB*	*A*	*a*	*n*	*e*	*LTP*	*noise*
Mean	93.38	0.10	0.09	-3.16	300.50	0.01	1.13	0.20	1.11	15.85

EVP = explained variance percentage (%); *RMSE* = root mean square error (m); *RMSI* = root mean square innovations (m); *LDB* = local drainage base (m); *A* = drainage resistance (days); *a* = porosity (1/days); *n* = number of linear reservoirs (-); *e* = evapotranspiration factor (-); *LTP* = linear trend parameter (m)

The variance explained by the model (*EVP*) is a measure similar to R^2, reflecting the percentage of how much the model explains this variation from the defined input series. The adjustments were considered excellent, above 90% in 28 wells. The exceptions were some wells in the Bugre watershed, but still had good adjustments, over 75%. The root mean square error (*RMSE*) values were considered low, varying from 7 to 22 cm. The same applies to root mean square innovation values (*RMSI*), which ranged from 4 to 14 cm. According to Von Asmuth and Bierkens (2005), innovations are a more robust way of examining the adjustments, since they calculate the average errors between an instant in time and the previous instant. These three measures refer to the statistical adjustments of the model to each data series. Figure 3 shows an example fit for each of the studied watersheds. All watersheds have some wells with surface levels (less than 1.0 meter from the surface). The deepest levels monitored were in the Santana watershed.

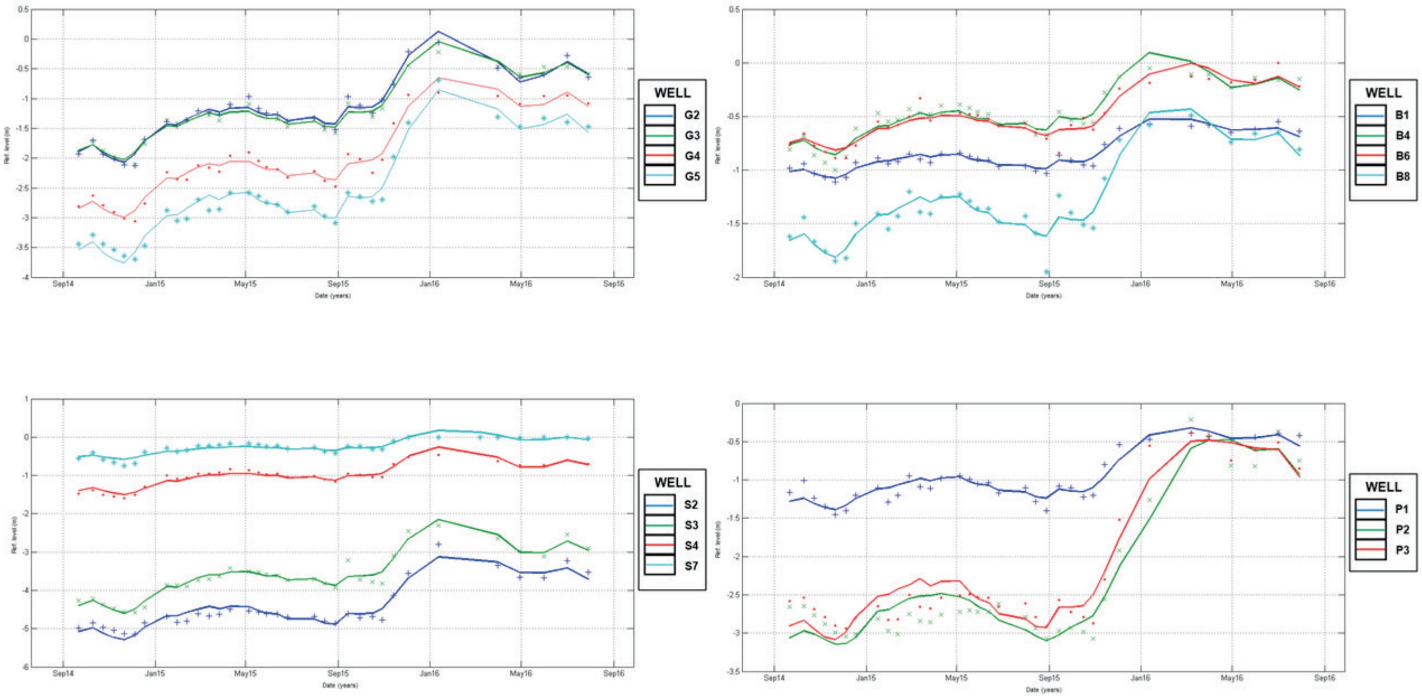

Figure 3 - Examples of PIRFICT model adjustments for monitored wells between September 2014 and August 2016 in the Guarantã (G), Bugre (B), Santana (S) and Passarinho (P) watersheds.

A common feature in all wells was the steeper rise in levels from September 2015. The presence of the ENSO phenomenon that strongly influenced the rainfall regime in Brazil and in the Southeast of the country significantly altered the water table behavior, reaching almost saturation of the vadose zone in some moments. Despite this, the PIRFICT model was able to recreate the data input series from the exogenous variables precipitation and evapotranspiration. The *LTP* calculated for each well was positive in all cases, varying from a few centimeters (44 cm) to a few meters (2.30 m). No differences at elevation pattern were found between the Cerrado and *Pinus* areas. The Bugre watershed was the one that presented the lowest elevation because it had more superficial levels that tended to saturations in 2016. Where the unsaturated zone was bigger the storage was bigger and consequently the elevations in the more pronounced levels. Analyzing other model parameters (*A*, *a*, *n*, *e*) we can observe short memory systems (*A*), with rapid responses (*a*), varying as a function of the distance to the nearest drainage and the thickness of the unsaturated zone (*n*), with a strong influence of precipitation, small influence of evapotranspiration (*e*) and with linear trends of elevation in the levels (*LTP*) between September 2014 and August 2016.

The PIRFICT model has been tested and perfected around the world. The works described in Von Asmuth (2012) are examples of applications in the Netherlands for more than ten years of research and development of the model. Obergfell et al. (2013) advances in the applications of the PIRFICT in the Netherlands using field data. Manzione et al. (2010) successfully tested the PIRFICT model in the Cerrado area under different domains and hydrogeological systems in the region of Planaltina (DF/Brazil). Yihdego and Webb (2011) present a time series study using the PIRFICT model in the suburban region of southwestern Australia, highlighting the good performance of the model.

With the *LTP* calculated for each well, the calculation of the variogram was performed using the initial distance of the half of the sampled field (8.0 km in the east-west direction). It divided 4.0 km in 10 steps (lags) of 400.0 meters. From this initial value, new configurations of distance from the sample field and size of the steps were tested. Table 2 shows the adjusted variogram parameters for *LTP*. Figure 4 shows the variogram of the adjustment performed. For *LTP* an exponential model was fitted. From the total sill value found, the nugget effect accounted for 7.69% of the total variance. The range for elevation trends was 1,765.00 m.

Table 2 - Adjusted variogram parameters for linear trends (LTP) calculated from the PIRFICT model.

Variable	Sample size	Number of lags	Lag size (m)	Nugget Effect	Sill	Range (m)	Model
LTP	32	12	321.00	0.03	0.39	1,765.00	Exponential

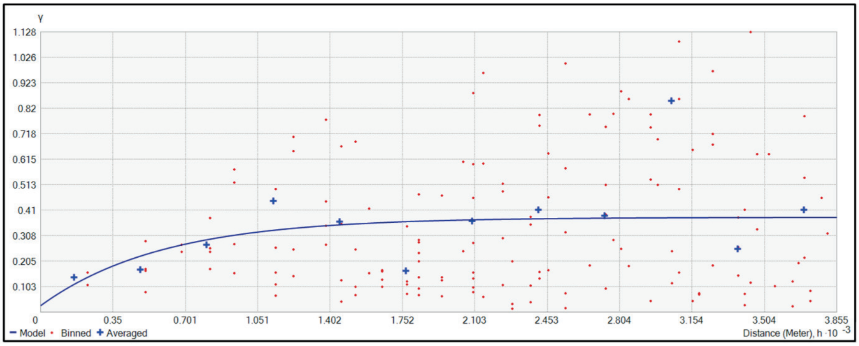

Figure 4 - Sample variogram and theoretical model adjusted for linear trends (*LTP*) calculated from the PIRFICT model.

The elevation trends mapping between September 2014 and August 2016 can be seen in Figure 5. Interpolated elevation trends ranged from 28 cm to 2.17 meters. The highest elevations occurred in the Guarantã and Santana watersheds, which converge to the Rio Capivari and form a sequence of wet and flooded areas, restricting the local flow of surface waters and consequently altering the groundwater dynamics. In the Bugre and Passarinho watersheds, the elevations were smaller, demonstrating the basins ability to drain groundwater and produce water to feed the Rio Capão Rico.

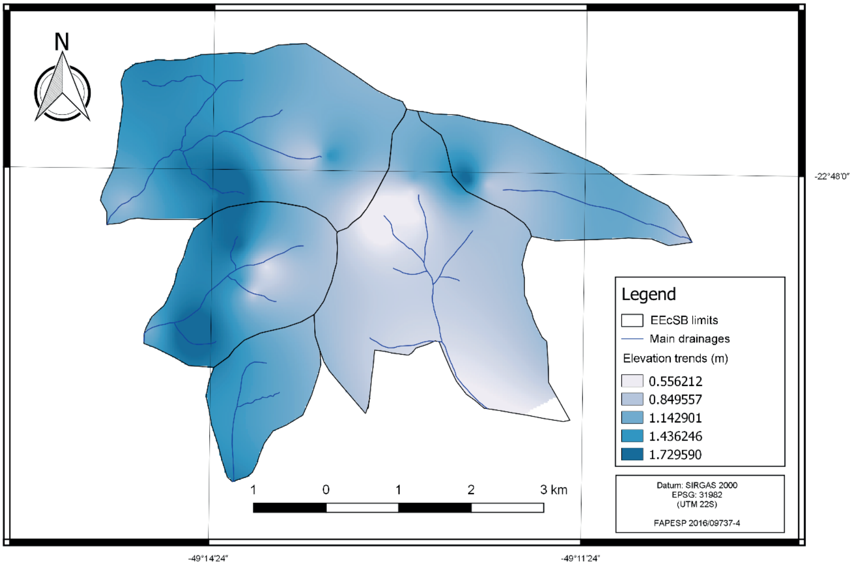

Figure 5 - Water table depths elevation trends map from September 2014 to August 2016 interpolated by ordinary kriging.

In the cross-validation procedure of the results, the sampled value is withdrawn at a certain point and the estimate is obtained by ordinary kriging using the values of the neighboring points, comparing the results. It was considered as the best estimate the one that presents Mean Standardized (MS) close to zero, the lowest possible Root-Mean-Square (RMS), the Average Standard Error (ASE) near the MS and the value of the Root-Mean-Square Standardized (RMSS) near 1. The RMSS is a measure of the accuracy of the interpolated values. According to Johnston et al. (2001), RMSS values below 1 indicate underestimation while values above 1 indicate overestimation of the interpolated values. MS values were close to zero and ASE values were close to RMS values. The RMSS values were all below 1, denoting the underestimation of the data. This is due to the smoothing effect of the interpolator by ordinary kriging, which honors the value of the mean, but ends up presenting errors in the extreme values of the normal data distribution (Yamamoto; Landim, 2016).

5 Conclusions

The main conclusions gathered from the modeling of the agro-meteorological monitoring data in this study were:

- the PIRFICT model presented a good fit, identifying systems with a short memory, fast response and strong seasonal influence, mainly by precipitation;
- the temporal modeling of the monitoring data revealed patterns of levels elevation in the period of September 2014 and August 2016, with the recharge of the BAS in the study area after the drought 2013/2014, influenced by the phenomenon ENSO;
- spatial analysis using geostatistical techniques revealed a spatial pattern of water table elevations in the studied period; and
- groundwater levels oscilation phenomena occurred gradually in the EEcSB area, varying smoothly in space without abrupt changes.

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