Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 89 (2014) 1254 – 1259

Procedia Engineering

www.elsevier.com/locate/procedia

16th Conference on Water Distribution System Analysis, WDSA 2014

Data-Driven Modeling of the Dynamic Response of a Large Deep Karst Aquifer

A. Doglioni[a,]*, V. Simeone[a]

[a]Department of Civil Engineering and Architecture, Technical University of Bari, via E. Orabona 4, 70125, Bari, ITALY

Abstract

The analysis of the dynamic response of a karst aquifer to precipitation is not simple due to the complex structure of the aquifer causing non-linear variations of the groundwater table. This work presents the study of the dynamic response of the large deep karst aquifer of central Apulia, south Italy, based on a data-driven approach, namely Evolutionary Polynomial Regression applied to the data of four wells for which about 15 years of monthly average levels are available. The dynamic response of the aquifer is modeled as prediction of the groundwater levels given total monthly precipitations and past measured groundwater levels.

Peer-review under responsibility of the Organizing Committee of WDSA 2014

Keywords: Data-driven; karst aquifer; water table; dynamic response; EPR.

1. Introduction

Karst aquifers constitute complex systems, denoted by complicated infiltration paths. These can be preferential direct flow paths, like cracks, as well as manifold interlayers with varying hydraulic conductivities. Therefore, the water table levels of deep karst aquifers can fluctuate according to non-linear responses to rainfall, whereas the flow paths of infiltrating rain are partly unknown.

Data-driven modeling constitutes an interesting alternative to physically based models, for investigating the aquifer response to rain infiltration, whereas timeseries of groundwater data are available. This work presents the results of the use of the multi-objective evolutionary modeling technique, namely Multi-objective Evolutionary Polynomial Regression (EPRMOGA) [5], for the prediction of water table levels. EPRMOGA is a multi-objective evolutionary

* Corresponding author. Tel.: +39-099-4733204; fax: +39-099-4733229.
E-mail address: angelo.doglioni@poliba.it

Peer-review under responsibility of the Organizing Committee of WDSA 2014
doi:10.1016/j.proeng.2014.11.430

modeling technique successfully used for manifold problems related to natural systems [2,4,6]. It proved effective at modeling the dynamic relationship between groundwater levels and rainfall heights of porous aquifers [3,6]. The main practical implication of EPRMOGA is its ability of returning closed-form polynomial equations, allowing for some physical speculations about the relationship between the main variables of the investigated phenomena.

In particular, the relationship between water table levels and rainfall is here investigated, for a deep karst aquifer hosted by the Apulian limestone basement in south-east Italy. Timeseries of water levels covering 15 years of monthly data are available for four wells. Starting from these data, four equations are identified, discussed and compared in terms of structures and selected inputs.

2. The methodology

EPRMOGA is a two-stages methodology constituted by a structural model identification based on a Genetic Algorithm [7] and by an estimation of the constant values, based on a least-square approach. The preliminary contribute of the user is particularly valuable, since she/he can make some general assumptions about the main structure of the models, potentially involved functions, maximum length of the polynomial structures, candidate exponents and objective functions. This does not mean the user has to assume an equation, but just some constraints about the structures of the equations, in order to set a limit to the evolutionary search, viz. to the space of solutions. During the equation search, EPRMOGA can simultaneously optimize three objective functions at most. These are the minimization of the Sum of Squared Errors, the minimization of the number of monomial terms and the minimization of the percentage of input selected among the candidates given by the user. This is a multiobjective approach, where three conflicting functions are simultaneously optimized. EPRMOGA already proved to fit particularly to those problems where the input to the process and the boundary conditions are not completely clear or known a-priori [2,4,6], as for the problem under investigation. The comparison between the models of the four wells will prove how EPRMOGA is able to return reasonably good predictions of water table levels as well as models consistent with the dynamics of the aquifer and with their different response to rainfall due to local different hydrogeological features.

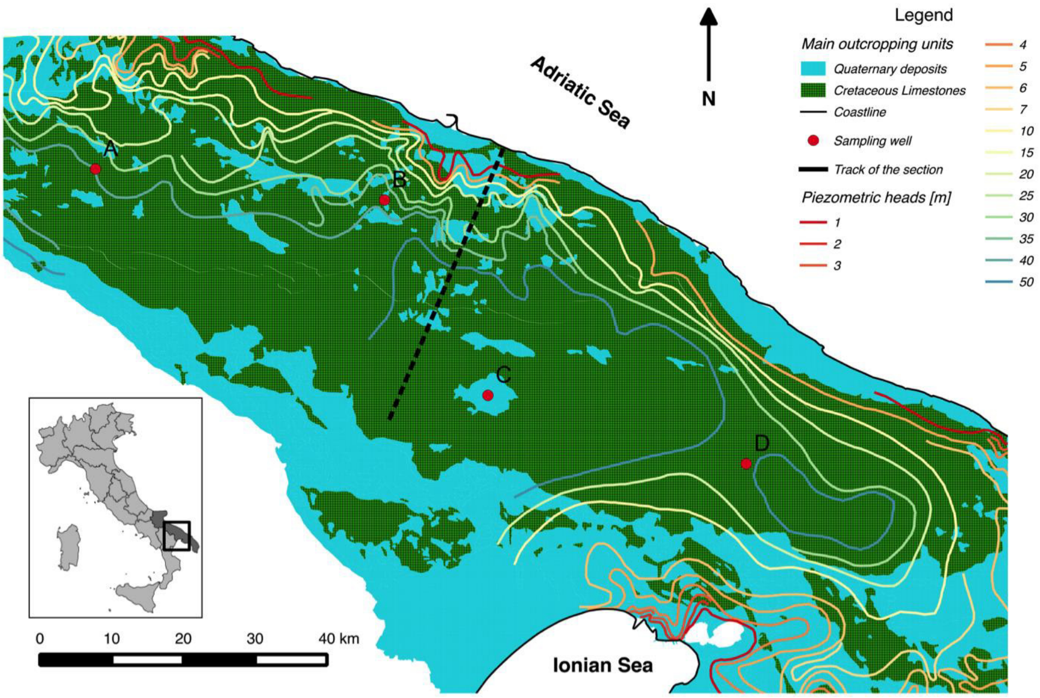

Fig. 1. Location of the sampling wells and main geological layout of the aquifer.

3. The case study: the deep karst Apulian aquifer

The aquifer under investigation is located in the central part of Apulia region, south east of Italy, Fig. 1, namely Murgia. This is a large Cretaceous carbonate platform constituted by a sequence of detrital and bistromal limestones and dolomitic limestone, which are diffusively karstified, sometimes severely. This wide platform can be considered a large asymmetric horst, with a NW-SE direction. Its morphostructural features were superimposed by tectonics with direct faults having their main orientation according NW-SE and NE-SW directions. Wide folds with a large curvature radius gently deform Murgia. The morphology is normally fairly flat, and the limestone layers are normally sub-horizontal with inclinations rarely higher than 10°-15°. Toward the Adriatic sea side, Murgia gently slopes, with a sequence of little terraces and scarps parallel to the coast, while the lower zones are overlain by discontinuous and thin late Pliocene to early Pleistocene transgressive calcarenites, deposited in shallow and agitated marine waters [8,9]. The limestones and dolomitic limestones are karstified and originating a characteristic hydrogeological domain [1], where the hydraulic base level of groundwater circulation corresponds to sea level. The permeability of this karst aquifer is due to fractures and karst phenomena, which allow rainfall to infiltrate quite easily and reasonably quickly. This would imply quick responses of water table to rainfall, while the recharge period starts from September/October of each year ending at the following February/March. Fig. 1 shows the locations of sampling wells from which four timeseries of phreatimetric data are available. These are named in the order: A, B, C and D. Data are available for the years comprised between 1975 and 1990. For each sampling well a timeseries of total monthly rainfall data, covering the same time interval of phreatimetric data, is available too. Rainfall data are collected nearby the wells, this assumption is reasonable due to the medium-high permeability of soils, for which infiltration conditioning the groundwater levels is supposed to be mostly local. Fig. 2 represents a cross section of Murgia area, according to the track in Fig. 1. This section is quite representative of the general layout of Murgia plateau.

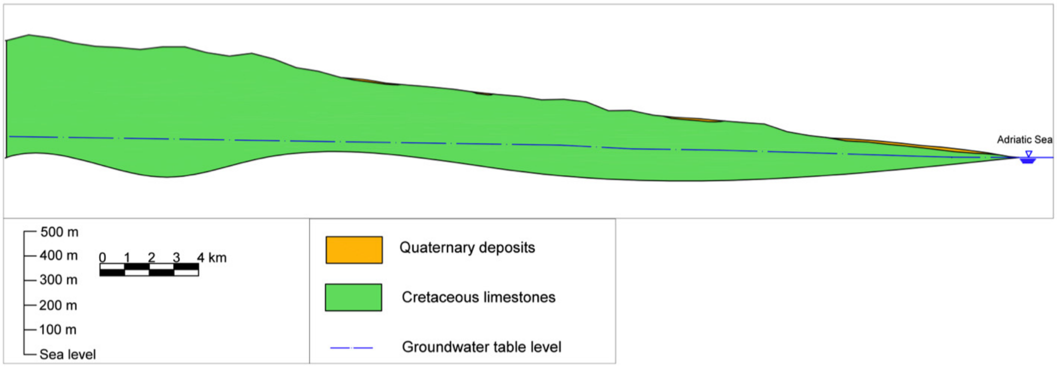

Fig. 2. Cross section of Murgia area, according to the track of Fig.1.

4. Results and discussion

EPRMOGA returned a Pareto set of models for each sampling wells. For each well, an equation is chosen, according the criterion of selecting a parsimonious structure with good predicting abilities. The equations are in the order for A, B, C and D:

$$H_t = 0.00056017 P_t P_{t-1}^{0.5} P_{t-2}^{0.5} + 0.27321 H_{t-2} + 0.48127 H_{t-1} + 0.05312 \quad (1)$$

$$H_t = 0.00031945 P_{t-1}^{0.5} P_{t-3} P_{t-4}^{0.5} + 8.9153 \cdot 10^{-6} P_{t-1}^{0.5} P_{t-2} P_{t-5} P_{t-6}^{0.5} + 0.90301 H_{t-1} + 4.9879 \quad (2)$$

$$H_t = 9.2147\cdot10^{-5}\cdot P_{t-3}^2 + 1.7567\cdot10^{-5}\cdot P_{t-2}^2 P_{t-5}^{0.5} + 0.00010327 P_{t-1}^2 + 0.95456 H_{t-1} + 3.9395 \quad (3)$$

$$H_t = 2.6457\cdot10^{-6}\cdot P_t \cdot P_{t-1}^2 + 0.9884\cdot H_{t-1} \quad (4)$$

Where H is the average monthly piezometric height of water table and P is the total monthly rainfall. The subscripts indicate the time delay in months. These models show some differences, which emphasize behaviours not typical of fractured karst aquifers. All the models contain the past values of the water table as input, they represent the past state of the aquifer, then they can be seen as persistence terms. These terms are supposed to contain the information about those inputs, which are not directly related to rainfall.

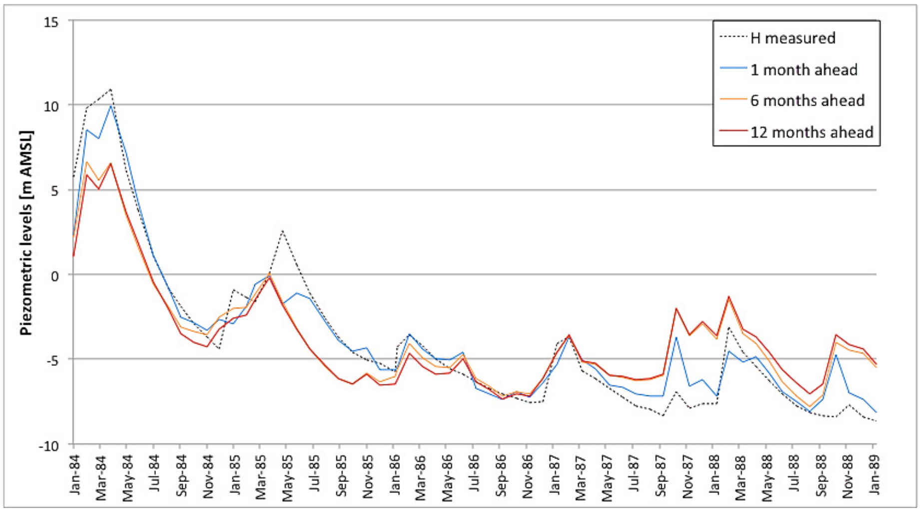

Fig. 3. Time plot of the measured and predicted levels of the sampling well A.

Different wells show different responses, even if the aquifer is the same. Moreover, there are lags between rainfall and level variations. Equation (1) represents a peculiar behavior, the most influencing rainfall terms are those of the same month of the prediction and those of the two months before, even if these have 0.5 as exponent. This is typical of a karst aquifer, since groundwater levels are mostly affected by recent rainfall. A further interesting but difficult to be interpreted characteristic is the persistence: there are two terms H_{t-1} and H_{t-2}, their presence may be related to unknown extra inputs as well as to a pressurized flow of the aquifer, which is consistent with the high oscillations of the levels. Equation (2) is reasonably representative of a karst aquifer, it contains a persistence term, H_{t-1}, which has a strong influence on the output, while the rainfall terms represent the precipitations of the same month or the month before the level prediction. Rainfall has no exponents lower than 1, this implies a direct effect of rainfall on groundwater levels, as expected by fractured media. Equation (3) shows the term of persistence, i.e. the state, as well as terms related to rainfall up to 5 months before the level to be predicted. This behavior seems to be on the edge between a karst and a porous aquifer and then this may indicate a local poor fracturing of limestones. Equation (4) shows a persistence term, which actually has a lower influence on the output than the previous models, as well as rainfall terms ranging between 1 to 6 months before the output. Similarly to equation (1) such relationship is typical of complex flow paths and of the presence of poorly permeable layers. The following Figs 3, 4, 5 and 6 show the time plots of the measured levels and of the predicted levels at 1, 6 and 12 months ahead, for the test set of data, i.e. data not used by EPRMOGA for model identification.

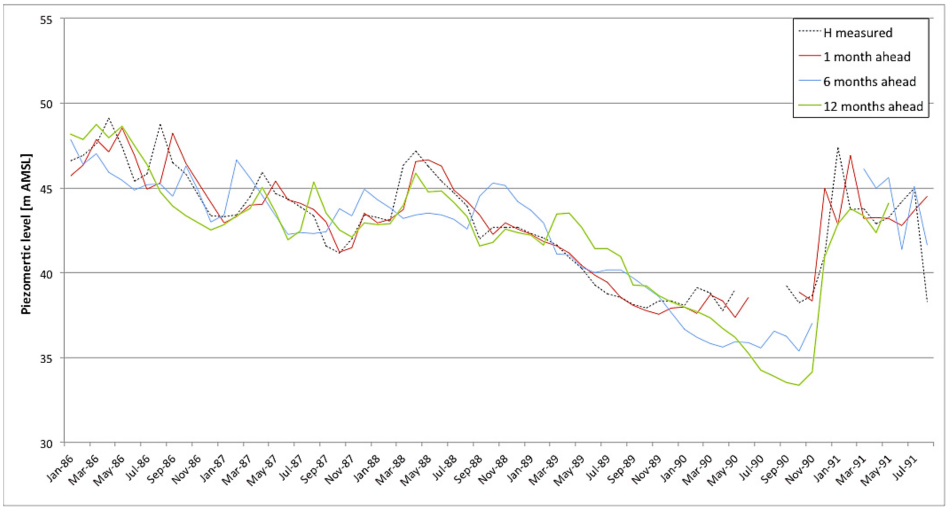

Fig. 4. Time plot of the measured and predicted levels of the sampling well B.

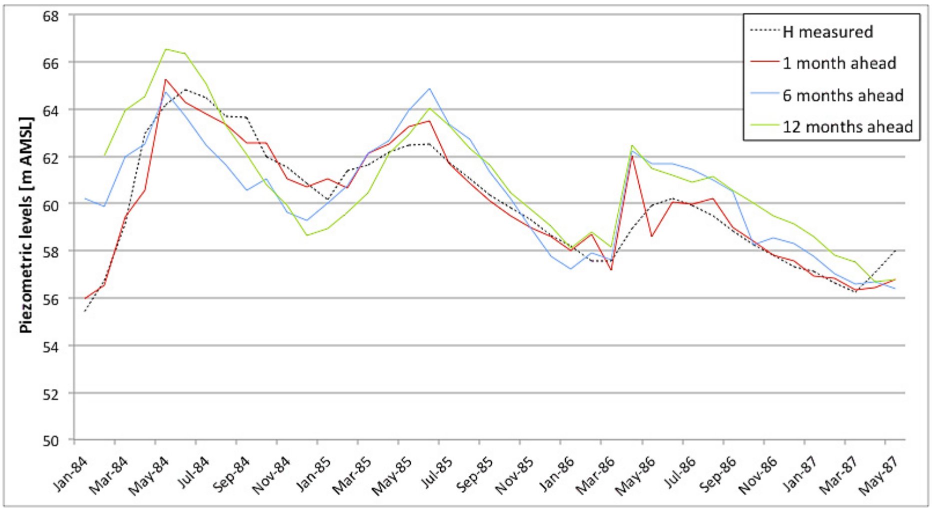

Fig. 5. Time plot of the measured and predicted levels of the sampling well C.

5. Conclusions

The dynamic response of the deep karst aquifer of Murgia, southeast Italy, was here investigated. Four models were identified, starting from four timeseries of available data. The wells are located relatively far from each other, in order to uniformly cover the hydrogeological watershed of the aquifer. Even if similar models were expected, however this did not happen, since the returned models, corresponding to the local responses of the aquifer, are different from each other. This may be due to local flow paths or local variations of hydraulic conductivity. Therefore, the use of a data-driven approach as EPRMOGA was helpful, since on the one hand it allowed to model the groundwater table levels variations and on the other hand, it returned closed form equations. These permit to advance some physical assumptions on the aquifer. Finally, it is important to emphasize that being EPRMOGA a data-driven approach, it returned interpolative equations, with good generalization abilities. However, their physical interpretation, even if sound, cannot be considered exhaustive, it should be coupled with direct physical observations and possibly by physically based modeling.

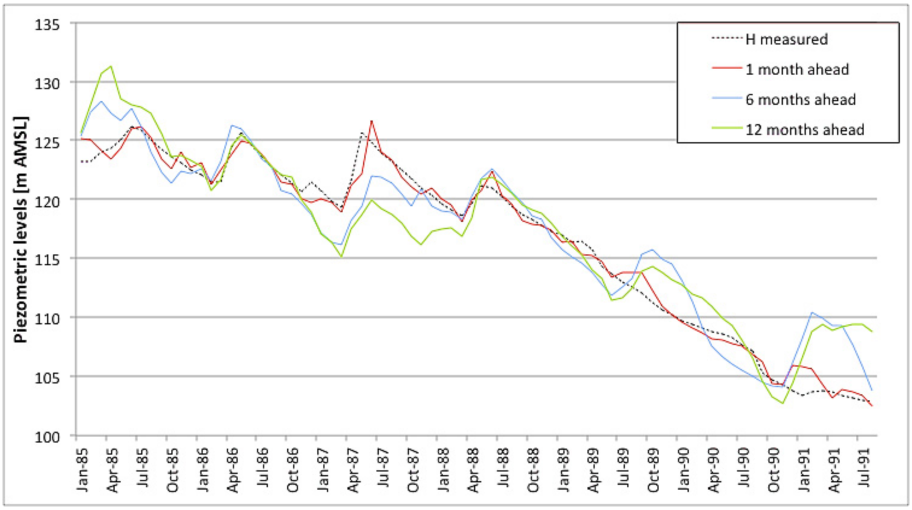

Fig. 6. Time plot of the measured and predicted levels of the sampling well D.

References

[1] V. Cotecchia, D. Grassi, M. Polemio. Carbonate aquifers in Apulia and seawater intrusion. Giornale di Geologia Applicata (Italian Journal of Engineering Geology), 1 (2005) 219–231.

[2] A. Doglioni, F. Fiorillo, F.M. Guadagno, V. Simeone. Evolutionary polynomial regression to alert rainfall-triggered landslide reactivation alert. Landslide, 9(1) (2012) 53-62.

[3] A. Doglioni, A. Galeandro, V. Simeone. A data-driven model of the shallow porous aquifer of south Basilicata – Italy. Advances in the Research of Aquatic Environment - Environmental Earth Sciences, 4 (2011) 233-240.

[4] A. Doglioni, D. Mancarella, V. Simeone, O. Giustolisi. Inferring groundwater system dynamics from time series data. Hydrolog. Sci. J., 55 (2010) 593-608,.

[5] O. Giustolisi, D.A. Savic. Advances in data-driven analyses and modelling using EPR-MOGA. J. Hydroinform., 11(3–4) (2009) 225–236.

[6] O. Giustolisi, A. Doglioni, D.A. Savic, F. di Pierro. An Evolutionary Multi-Objective Strategy for the Effective Management of Groundwater Resources. Water Resour. Res., 44 (2008) W01403.

[7] O. Giustolisi, A. Doglioni, D. Laucelli, D.A. Savic. A proposal for an effective multiobjective non-dominated genetic algorithm: the OPTimised Multi-Objective Genetic Algorithm, OPTIMOGA, Report 2004/07, School of Engineering Computer Science and Mathematics, Centre for Water Systems, University of Exeter, UK, 2004.

[8] G. Ricchetti, N. Ciaranfi, E. Luperto Sinni, F. Monelli, P. Pieri. Geodinamica ed evoluzione sedimentaria e tettonica dell'Avampaese apulo. Mem. Soc. Geol. Ital., 41 (1988) 57–82,.

[9] M. Tropeano, L. Sabato. Response of Plio-Pleistocene mixed bioclastic–lithoclastic temperate-water carbonate system to forced regression; the Calcarenite di Gravina Formation, Puglia, SE Ital. In: Hunt, D., Gawthorpe, R. (Eds.), Sedimentary Responses to Forced Regressions. Geol. Soc. London. Spec. Publ., 172 (2000) 217–243.