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Artificial neural network simulation of hourly groundwater levels in a coastal aquifer system of the Venice lagoon

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A B S T R A C T

Artificial Neural Networks (ANNs) have been successfully employed for predicting and forecasting groundwater levels up to some time steps ahead. In this paper, we present an application of feed forward neural networks (FFNs) for long period simulations of hourly groundwater levels in a coastal unconfined aquifer sited in the Lagoon of Venice, Italy. After initialising the model with groundwater elevations observed at a given time, the developed FNN should able to reproduce water level variations using only the external input variables, which have been identified as rainfall and evapotranspiration. To achieve this purpose, the models are first calibrated on a training dataset to perform 1-h ahead predictions of future groundwater levels using past observed groundwater levels and external inputs. Simulations are then produced on another data set by iteratively feeding back the predicted groundwater levels, along with real external data. The results show that the developed FNN can accurately reproduce groundwater depths of the shallow aquifer for several months. The study suggests that such network can be used as a viable alternative to physical-based models to simulate the responses of the aquifer under plausible future scenarios or to reconstruct long periods of missing observations provided past data for the influencing variables is available.

1. Introduction

The simulation of hydraulic heads fluctuations in groundwater systems is generally carried out by means of *physical-based models*, which demand a proper synthesis of the aquifer parameters to describe the spatial variability of the subsurface. This information is hard to obtain even with expensive site investigations, and the partitioning of the physical domain required for the numerical solution may result in extreme computational costs. Although developing a rigorous numerical model of the flow system is preferable, as it entails a deeper understanding of the aquifer dynamics, when the focus is on the model outputs these issues may be overcome by employing *black box* empirical models. Black boxes perform a mathematical mapping between historical inputs and outputs without requiring physical information on the investigated system. Among these heuristics, artificial neural networks (ANNs) have been widely used in the field of hydrology (on ASCE Task Committee on Application of Artificial Neural Networks in Hydrology, 2000). In particular, feed-forward neural networks (FNNs) have been applied successfully for time series modelling in many hydrological contexts such as rainfall-runoff (Dawson and Wilby, 1998; Hsu et al., 1995), river flow (Cheng et al., 2005; Joorabchi et al., 2007), flood forecasting (Chau et al., 2005), and water quality modelling (Muttil and Chau, 2006; May and Sivakumar, 2009). A detailed review of ANNs applications for modelling water resource variables can be found in Maier and Dandy (2000) and Maier et al. (2010). Relevant applications for prediction and forecasting water table depth time series are also available in the literature. Coulibaly et al. (2001) used different types of ANNs for monthly predictions of groundwater levels in the Gondo Plain, Burkina Faso. The study has shown that ANNs are an effective tool for up to 3 months ahead forecasting of the dry season deep water table depths, and can be employed for water management in semiarid areas. Daliakopoulos et al. (2005) tested the performance of several types of ANNs and training algorithms to forecast monthly groundwater fluctuations in an aquifer in the Messara Valley, Crete, up to 18 months ahead. The best results were obtained with the feed forward neural network architecture trained with the Levenberg–Marquardt algorithm. Nayak et al. (2006) employed ANN for forecasting monthly levels in two different wells of an unconfined coastal aquifer in Godavari Delta System, India. Their study suggests that accurate monthly forecasting up to 4 months ahead can be obtained with relatively simple networks, provided the an accurate identification of the system inputs is carried out beforehand. Trichakis et al. (2009) employed artificial neural networks for daily forecasting of the water stage of a karstic aquifer in the region of Attica, Greece. Their findings

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suggests that major improvements in the neural network predictive performance could be achieved by employing the groundwater head variation between two time steps instead of the hydraulic head as the output variable. When observations from a network of piezometers are available, neural networks can also be employed for modelling the spatial variations in the water table. Nourani et al. (2008, 2011) employed artificial neural networks for spatiotemporal prediction of groundwater levels in the Tabriz and Shabestar plain, northwest Iran. Their results show that neural networks can be employed either as a replacement or in conjunction with existing geostatistical models to increase the performances of spatio-temporal water table predictions for complex multilayered aquifers.

In most of the available literature, artificial neural networks have been employed to reproduce groundwater levels on a monthly or daily basis, since such time resolutions are usually appropriate for most hydrogeologic situations and water management applications. However, in this work we deal with a shallow and very responsive aquifer, for which major changes in the water table levels suddenly occur due precipitation after storm events. The object of this study is thus to check whether neural models are capable of accurately reproduce the variation of groundwater levels on a hourly basis, with particular focus on their performances over long period simulations. The case study is a coastal aquifer sited in the Venetian Lagoon (Italy), where a defence system (Mo.S.E. system) is being developed to protect the inland from high tides (Bras et al., 2001; Rinaldo et al., 2008). A network of piezometers has been subsequently emplaced in the study area to monitor the effects of construction works on groundwater dynamics (Magistrato delle Acque di Venezia, 2008). As mentioned before, the depth to groundwater found in the aquifer is usually low, and the aquifer is highly responsive to rainfall infiltration. High-frequency monitoring of the water table is then required for detecting the sudden rises occurring after storms, i.e., for issuing flooding warnings if the levels are beyond the safety thresholds. A neural network is then employed to model such high-frequency variations on a hourly basis and produce long term simulations of groundwater levels. Simulations are obtained by using only observed data for the influencing external variables, rainfall and evapotranspiration, as direct inputs as well as past predicted values of the groundwater head as recursive inputs. Therefore the model can be harnessed for reconstructing the aquifer responses under plausible future scenarios or to reconstruct long periods of missing observations provided past data for the influencing variables is available.

2. Feed-forward neural networks (FNN)

Feed forward neural networks are biologically inspired distributed parallel processors which are known to approximate any continuous function with an arbitrary degree of accuracy (Hornik et al., 1989).These heuristics are particularly suited for predicting and forecasting hydrologic variables because of their ability to model nonlinear, nonstationary and nongaussian processes like those encountered in hydrological contexts (Maier and Dandy, 1997). FNNs consist of a number processing *units*, or *neurons*, linked by *synaptic connections* and arranged in *layers*. The inputs are fed through the input layer and, after being multiplied by synaptic weights, are delivered to the first hidden layer. In the hidden units, the weighted sum of inputs is transformed by a nonlinear activation function, which is usually chosen as the logistic or the hyperbolic tangent. The same process takes place in each of the following hidden layers, until the outcomes reach the output nodes. In this work, all the developed FNN models will have one hidden layer and will be fully connected, i.e., each node of the previous layer is linked to each node of the next layer. For further details on FNNs the reader is referred to the bibliography (Haykin, 1998; ASCE Task Committee on Application of Artificial Neural Networks in Hydrology, 2000). However, for the remaining of the discussion here, it is worth noting that the scalar predicted output $\hat{\boldsymbol{y}}_t$ of a FNN with one output node is a function

$$\hat{\boldsymbol{y}}_t = \boldsymbol{f}(\mathbf{x}_t, \boldsymbol{w}), \tag{1}$$

where $\mathbf{w}$ is the ensemble of the synaptic weights and $\mathbf{x}_t$ the input variables currently fed to the network. After initialising the synaptic weights, the model calibration, or *training* in ANNs jargon, is performed by minimising an error function of the predicted and the observed outputs on a given data set. If $\boldsymbol{Z}=[\mathbf{x}_t, y_t]$, $t=1 \ldots N$ is the training data set made of N input-output pairs, and the error function is chosen as the sum of the nonlinear least squares

$$E(\mathbf{w}) = \frac{1}{2}\sum_{t=1}^{N}(y_t\text{-}\hat{y}_t(\mathbf{x}_t, \boldsymbol{w}))^2, \tag{2}$$

then the optimisation is achieved by searching the optimal set of weights $\tilde{\mathbf{w}}$ such that

$$\tilde{\mathbf{w}} = \mathrm{argmin}E(\mathbf{w}) = \mathrm{argmin}\left(\frac{1}{2}\sum_{t=1}^{N}(y_t\text{-}\hat{y}_t(\mathbf{x}_t, \boldsymbol{w}))^2\right) \tag{3}$$

This search is usually performed using first-order or second-order optimisation algorithms, with the latter being preferred because of being faster and more reliable. In particular, in this study the developed FNNs will be trained using the second-order Levenberg–Marquardt method (Coulibaly et al., 2000).

3. Case study

The case study area is located in Punta Sabbioni, the edge of the Cavallino coastal strip of the Venetian Lagoon (Fig. 1(a)). The strip is part of the system of coastlines that constitutes the natural barrier protecting the City of Venice from the open sea. The study area is facing the Lido inlet, which is the widest of the three openings connecting the lagoon with the Adriatic sea. In Punta Sabbioni, two different aquifer layers of silty sands can be identified, separated by an aquiclude of clayed silt around 5 m thick, which is deemed to prevent vertical flow between the aquifers. The depth to groundwater of the shallow aquifer is very low, being usually between 0.6 and 1.8 m. The water table is thus very susceptible to the effects of the natural driving forces, which also regulate groundwater flow throughout the year. Evapotranspiration in summer causes strong decrease in the water levels which, in turn, engenders a net water flow from the sea to the inland. This effect is reversed in the autumn when heavy rainfalls recharge the aquifer. Apart from the natural forces, other influences on groundwater dynamics may result from past and current anthropic activities in the area. In the past, for land reclamation purposes, a dense network of secondary channels and gullies was built to drain the excess water in Punta Sabbioni. Due to their limited size, however, flow in these channels is assumed not to influence the levels in the shallow aquifer. Other disturbances might be engendered by works undergoing in the nearby construction site in Fig. 1(b). These activities are included in the design of the high-water defence system (Mo.S.E. system) which, after its completion, is meant to protect the population and cultural heritage of the City of Venice from high waters (Bras et al., 2001; Magistrato delle Acque di Venezia, 2008; Rinaldo et al., 2008). The defence system includes mobile flood gates realized at the lagoon inlets and a series of complementary works capable of abating the level of the most frequent tides. In Punta Sabbioni works are taking place to build a navigation lock for small vessels. The project entails complete isolation of the construction site by emplacement of diaphragms along the