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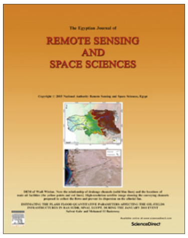

RESEARCH PAPER

A stochastic simulation model to early predict susceptible areas to water table level fluctuations in North Sinai, Egypt

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Risk assessment;
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Abstract Water table depth (WTD) is an important map layer for many environmental models' assessments. To develop an early water table prediction model for North Sinai, Egypt, four approaches were considered in this study: GIS, remote sensing, simulation and stochastic methods. Stochastic (using time-series) modeling enables us to characterize the water table dynamics in terms of risk, and it allows model uncertainty to be taken into account without the complexity of physical mechanistic models. The results indicate that, time-series modeling is an effective method to characterize the seasonal patterns of WTDs in the area. The model performs very well using Nash and Sutcliffe coefficient of efficiency (NSE) which indicates a fit of the model to the data. Sequential Gaussian Simulation was explored as a way to model water table spatial variability. A 95% probability level was calculated as a measure for risk of shallow water tables. The limits established for risks of shallow WTDs at April 1st were 0.5 m below the ground surface. A map showing the risk that the WTD at April 1st and October 1st in a future year will be shallower than 0.5 m was presented. If the risk is close to 50%, it will be difficult to take a decision in water management or land use planning. The results found a negligible risk of shallow water tables for this date. The level of WTD will be about 0.30–0.45 m higher than the present level in the next 20 years. There is a better agreement between the simulated and measured data (8 cm difference) which may be associated with an overestimation of the evaporative losses from the surface. Finally, Landsat image was not useful for WTD prediction; however, it may be useful for soil moisture prediction.

1. Introduction

The depth of phreatic water below the surface is called water table depth, WTD (Knotters, 2001). WTD influences several soil characteristics, like temperature, aeration, nutrients, soil trafficability, water availability, aquifer susceptibility to contamination, and thickness of the root zone. In contrast with

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WTD, these features are hard to be observed (Knotters, 2001; Thompson et al., 2012). There is a need for reliable information on the configuration of the water table for agricultural sustainability. Knowledge about the spatio-temporal dynamics of the water table is important (Von Asmuth and Knotters, 2004). Predicting susceptible areas to water table rising in both space and time in arid and semi-arid areas are challenging.

Different approaches for WTD prediction in which remote sensing is one of these approaches were reviewed. (Gong et al., 2004) found that the normalized difference vegetation index (NDVI) has a better correlation with WTD. Al-Khudhairy et al., 2002 estimated the width of wet water channels from Landsat TM data to correlate WTD. Al-Saifi and Qari, 1996 analyzed Landsat thematic mapper (TM) imagery over salt-enriched flat areas and suggested that WTD can be differentiated by image colors. However, no quantitative analysis was done with remote sensing which was not useful for predicting WTD (Becker, 2006; Meijerink, 2007). Only, microwave remote sensing (i.e., passive radar) data can be used for the estimation of the shallow water table (less than a few meters). However, it has not yet been investigated in various conditions and very little is known about the accuracy of such assessment (Meijerink, 2007). Ground penetrating radar (GPR) seems to be the most suitable tool for efficient water table depth assessment (Meijerink, 2007). The most accurate, non-invasive assessment of water table depth seems to be possible with the magnetic resonance sounding (MRS) method. However it is not yet widely used for such application, mainly because it is too expensive and too time consuming to be efficient in surveys focused on water table assessment only (Lubczynski and Roy, 2003, 2004).

Other approaches for predicting the spatio-temporal variation of WTD use either physically-deterministic flow models (McDonald and Harbaugh, 1988) or space–time geostatistics (Arun and Katiyar, 2013; Omran, 2012; Rouhani and Hall, 1989). The full-fledged models require a large amount of information (disadvantage) to be able to predict WTD at sufficient accuracy, while building and calibration of these models is time-consuming. The problem with purely statistical approaches is that they require many observations to be accurate and they often become overly complicated when accounting for nonstationarity in space and time (Angulo et al., 1998). Statistical spatio-temporal prediction methods can roughly be divided into three approaches: (i) methods starting from geostatistical methodology (Kyriakidis and Journel, 1999), (ii) methods based on multivariate time-series modeling (Pfeifer and Deutsch, 1998), and (iii) methods based on time-series models with regionalized parameters (Van Geer and Zuur, 1997).

Time-series modeling provides an empirical stochastic method to model monitoring data from observation sites without the complexity of physical mechanistic models. In addition, the stochastic component in the model allows model uncertainty to be taken into account. Time-series modeling allows us to simulate and predict the system behavior and to quantify the expected accuracy of these predictions (Salas and Pielke, 2003). In time-series analysis, transfer function-noise (TFN) models describe the dynamic relationship between climatological inputs and WTDs (Von Asmuth et al., 2008; Von Asmuth and Knotters, 2004). The behavior of linear input-output systems can be completely characterized by their impulse response (IR) function (Von Asmuth et al., 2002a). The dynamic relationship between precipitation and WTD can be described using physical mechanistic flow models. However, much less complex TFN model predictions of the WTD can be obtained which are often as accurate as those obtained by physical mechanistic modeling (Knotters, 2001; Von Asmuth and Knotters, 2004). Risk assessment is also needed to find optimal solutions for water management in areas where WTD is a problem.

Therefore, there is a demand for stochastic methods that enable to describe the water table dynamics in terms of probabilities. Such probabilities are underestimated when using only the deterministic model (Knotters and VanWalsum, 1997). To develop useful models, the uncertainty of the predictions to increase the value of the water table models in decision-making should be considered. However, observed time-series of WTDs are generally not long enough to represent the prevailing climatic conditions. Thus, simulation models are applied to extrapolate the observed time-series. By using stochastic methods the probability distribution of the WTD can be estimated more accurately than by applying deterministic methods, because the unexplained part or noise component is taken into account. All existing methods fail to include observation uncertainty; and produce poor measures of prediction uncertainty. It may be desirable, however, to not only be informed about the dynamic behavior of the water table at the observation sites, but also at other locations. To this end, the WTD needs to be early predicted in both time and space.

Nourani et al. (2011) believe that problems in data interpretation given by the lack of strong predictive tools contribute to a failure to reach consensus water management actions. So, in order to overcome these limitations and to make better use of the observation data, the main objective of this study is to develop an early warning technique incorporate GIS, simulation method and stochastic methods for spatio-temporal WTD prediction. A stochastic model is interesting for estimations of WTDs because uncertainties can be quantified. Using a time-series model, it is possible to simulate over periods that do not have observations, as long as data on explanatory series are available. The uncertainty about the true WTD can be accounted for in stochastic methods by generating large numbers of possible realizations using simulation. In order to achieve the main objective, the following specific objectives are identified:

1. Propose a methodology to model and map the water table elevation by different approaches.
2. Modeling the systematic changes in WTDs from 2005 to 2007 in North Sinai, Egypt.
3. Develop stochastic methods to predict WTD probabilities for application in regions where suitable observations are scarce.
4. Predict the potential susceptible “areas at risk” for water table rising in any future date.

2. Materials and methods

2.1. Study area and time-series database

The study area, El-Salam Canal basin, is located (30°40″–31°05″N, 32°20′–33°15″E) in the North Sinai province, Egypt (Fig. 1). WTDs across much of the El-Salam basin have been