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Modeling the impacts of dryland agricultural reclamation on groundwater resources in Northern Egypt using sparse data

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SUMMARY

Demand for freshwater in many dryland environments is exerting negative impacts on the quality and availability of groundwater resources, particularly in areas where demand is high due to irrigation or industrial water requirements to support dryland agricultural reclamation. Often however, information available to diagnose the drivers of groundwater degradation and assess management options through modeling is sparse, particularly in low and middle-income countries. This study presents an approach for generating transient groundwater model inputs to assess the long-term impacts of dryland agricultural land reclamation on groundwater resources in a highly data-sparse context. The approach was applied to the area of Wadi El Natrun in Northern Egypt, where dryland reclamation and the associated water use has been aggressive since the 1960s. Statistical distributions of water use information were constructed from a variety of sparse field and literature estimates and then combined with remote sensing data in spatio-temporal infilling model to produce the groundwater model inputs of well-pumping and surface recharge. An ensemble of groundwater model inputs were generated and used in a 3D groundwater flow (MODFLOW) of Wadi El Natrun's multi-layer aquifer system to analyze trends in water levels and water budgets over time. Validation of results against monitoring records, and model performance statistics demonstrated that despite the extremely sparse data, the approach used in this study was capable of simulating the cumulative impacts of agricultural land reclamation reasonably well. The uncertainty associated with the groundwater model itself was greater than that associated with the ensemble of well-pumping and surface recharge estimates. Water budget analysis of the groundwater model output revealed that groundwater recharge has not changed significantly over time, while pumping has. As a result of these trends, groundwater was estimated to be in a deficit of approximately 24 billion m^3 (±15%) in 2011, compared to 1957. A significant trend in water level declines beginning in the 1990s that has been observed in monitoring records was evident in the model results and is directly attributed to abstraction.

1. Introduction

Groundwater is often the sole source of freshwater in drylands, and is thus critical both human wellbeing and ecosystem health in these environments. Globally, groundwater is also an important input to agriculture, accounting for approximately 43% of worldwide irrigation consumption (MacDonald et al., 2012), and satisfying nearly all irrigation requirements in many dryland environments, especially in the Middle East, Northern Africa, the U.S. High Plains and many parts of India and China (Voss et al., 2013; Scanlon et al., 2012). Although groundwater abstraction has enabled commercially viable agriculture to develop in drylands through the use of land reclamation techniques, over-pumping in these areas is leading to serious impacts on groundwater quality and quantity (Aeschbach-Hertig and Gleeson, 2012; Scanlon et al., 2012). For example, in Egypt, Libya and Saudi Arabia, groundwater abstraction exceeds the total availability of annual renewable groundwater resources by between 300% and 900%, and this usage trend has led to significant aquifer depletion (Giordano, 2009). Salinization of local groundwater is also a common issue in areas where over-abstraction of groundwater is present (Zammouri et al., 2007).

Many groundwater management programs and policies, including demand management incentives, irrigation retrofits, the optimization of water allocation, alternative land uses and livelihoods, and aquifer recharge have successfully been implemented

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in dryland environments to improve the sustainability of groundwater use and manage the risks of its degradation (Mukherji and Shah, 2005). Information on local and regional groundwater systems derived from groundwater models is often a critical input in the development of such strategies. Groundwater models are essential tools for assessing trade-offs among potential land and water use scenarios, and in diagnosing the drivers of aquifer depletion and changes in water quality. A common concern in many dryland environments, particularly in low and middle income countries (LMICs), is the lack of data required to develop, run and calibrate groundwater models for land and water resource management decision making, particularly when transient simulations are required. Modeling the impact of land use changes on groundwater requires sufficient input data and observational records to support the calibration of the model over a range of conditions. The typical approach to modeling the impact of land use change on groundwater has been to develop, calibrate and validate a 3D or quasi-3D finite element or finite difference groundwater model, and run it under plausible scenarios of change by adjusting the boundary conditions influenced by land use, namely recharge, evapotranspiration and pumping (Holman et al., 2012; Green et al., 2011; Liggett and Allen, 2009). In many circumstances, the datasets required as inputs for groundwater models may not be readily available, contain sparse records, or be of poor quality or unknown accuracy. Time series of hydrologic, climatological and water use variables required as inputs for transient scenario development may also contain significant gaps, and the spatial density of monitoring network is often too low for the use of common interpolation and infilling methods. Even when data are available, interpreting and using them in model development can be a challenge, as key metadata or information on data collection methods may be missing, resulting in the data being of unknown accuracy.

Data scarcity is a common issue in the development of groundwater models, but is particularly evident in LMICs, where water and land management agencies are often constrained by financial, technical and human resource capacity to undertake regular monitoring programs, conduct rigorous modeling exercises, and maintain up-to-date databases. In contexts where groundwater information does exist, much of it may be privately owned by drilling companies, housed in disparate government repositories, available only in print format in remote locations, have significant commercial value, or may be considered sensitive and confidential. Together, these issues result in significantly restricted data sharing and access, which in turn hampers to the creation, validation, use and improvement of groundwater models (Tujchneider and van der Gun, 2012). In a recent synthesis of groundwater knowledge in developing nations, the United Nations concluded that the aforementioned issues have resulted in a trend of groundwater models being unconvincingly validated or incompletely conceptualized (Tujchneider and van der Gun, 2012). Yet, as population grows, rates of land reclamation increase, demand for freshwater rises, and climate change shifts the dynamics of local hydrologic processes in drylands, groundwater models capable of capturing these dynamics will be key tools in planning and management (Enfors, 2013; Green et al., 2011).

The overall aim of this study is to assist in advancing the state of practice in dryland hydrologic modeling by presenting a framework for assimilating a range of sparse data sources to develop estimates of groundwater recharge and pumping, along with other model parameters, for use in transient groundwater model simulations. More specifically, this study demonstrates how such an approach can be used for modeling transient, long-term impacts of dryland agricultural land reclamation on regional groundwater resources using a limited number of datasets of unknown quality. The discussion considers whether it is possible to successfully infer transient, spatially distributed model input variables of surface recharge and groundwater well-pumping from a combination of limited qualitative and quantitative field records, literature, and remotely sensed data. Assuming that this approach could be transferred to other dryland environments with similar data constraints, an emphasis was placed on using open source and publically available code and datasets. The approach is applied to the area of Wadi El Natrun, located in the Egyptian Western Desert, where significant dryland reclamation and associated groundwater quality and quantity impacts have occurred since the 1960s. In Wadi El Naturn, any attempt to model the groundwater system without considering the non-stationarity and cumulative nature of the stresses on groundwater associated with land reclamation would represent an incomplete conceptualization of the system. A key output of this study is a regional analysis of Wadi El Natrun's groundwater resources, with the view that this information would be useful in developing targeted management measures to reduce aquifer depletion and degradation. The model was also intended for testing future land and water use scenarios by governmental agencies and local NGOs working in the area.

2. Study area

Wadi El Natrun is an endorheic depression situated at the eastern boundary of the Egyptian Western Desert, adjacent to the Cairo-Alexandria Desert Road between Cairo and Alexandria (Fig. 1). Local aquifers provide communities with a reliable source of domestic water, while also supporting an extensive swath of agricultural irrigation developed under the Egyptian government's desert reclamation program (Abdel-Hamid et al., 2010). Activities associated with salt processing, construction and a growing bottled-water industry are also increasingly important water uses, however irrigation far exceeds these in terms of volumetric use (King, 2011).

Since the late 1980s, the Wadi El Natrun area has experienced significant degradation of groundwater quality and quantity due to the over-exploitation of local and regional aquifers, and contaminating land use practices (e.g., wastewater ponding, waste disposal, and agrochemical application) (King and Salem, 2012; Masoud and Atwia, 2010; Awad, 2002). Salinization of groundwater resources in the area is also an important impact that has been directly associated with the high levels of abstraction (Fattah, 2011).

Local groundwater extraction rates began increasing significantly around 1990, and by 2000, total volumes are estimated to had increased by between 87% and 2000% (Baietti et al., 2005). Most of this abstraction is associated with an expansion of irrigated land (Baietti et al., 2005). Rates of water level declines over the long-term have been measured in the order of 1 m year^{-1} (Baietti et al., 2005; Ibrahim, 2005) and this trend, driven by extensive groundwater pumping, is much greater in magnitude than seasonal fluctuations (Figs. 2 and 3). Analyzes of monthly groundwater level trends from multiple monitoring wells in the El Tahrir irrigation district prior to extensive land reclamation demonstrate that ambient seasonal groundwater fluctuations range between approximately 0.5 m and 4 m, with peak levels occurring from September through March, minimum levels occurring from March to August (Fig. 3). These wells were in close proximity to the Nile River's Rosetta Branch in a location undergoing the first reclamation projects in the study area (REGWA, 1962) (Fig. 1). Surface recharge from irrigation return-flow and influences of the Rosetta Branch are attributed as the principal factors controlling the seasonal oscillation of groundwater levels in the study area.

2.1. Hydrogeology and groundwater flow

Eleven saline lakes are located at the base of the Wadi El Natrun depression, and represent a regional groundwater discharge zone. Groundwater has been observed to flow toward the depression