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A hydrological–economic model for sustainable groundwater use in sparse-data drylands: Application to the Amtoudi Oasis in southern Morocco, northern Sahara

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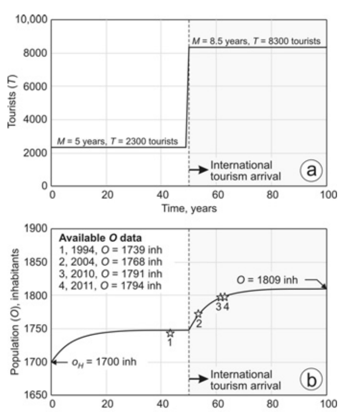
HIGHLIGHTS

- Sustainability of groundwater-dependent agriculture and tourism in sparse-data oases.
- Dynamic model linking hydrology and water consumers, both locals and tourists.
- Application to Amtoudi Oasis in southern Morocco in northern Sahara.
- Tourism reduces emigration and introduces new water-consumption habits.
- Low-technology actions are proposed to mitigate groundwater degradation.

GRAPHICAL ABSTRACT



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ABSTRACT

A hydrological–economic model is introduced to describe the dynamics of groundwater-dependent economics (agriculture and tourism) for sustainable use in sparse-data drylands. The Amtoudi Oasis, a remote area in southern Morocco, in the northern Sahara attractive for tourism and with evidence of groundwater degradation, was chosen to show the model operation. Governing system variables were identified and put into action through System Dynamics (SD) modeling causal diagrams to program basic formulations into a model having two modules coupled by the nexus 'pumping': (1) the hydrological module represents the net groundwater balance (G) dynamics; and (2) the economic module reproduces the variation in the consumers of water, both the population and tourists. The model was operated under similar influx of tourists and different scenarios of water availability, such as the wet 2009–2010 and the average 2010–2011 hydrological years. The rise in international tourism is identified as the main driving force reducing emigration and introducing new social habits in the population, in particular concerning water consumption. Urban water allotment (P_U) was doubled for less than a

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100-inhabitant net increase in recent decades. The water allocation for agriculture (P_I), the largest consumer of water, had remained constant for decades. Despite that the 2-year monitoring period is not long enough to draw long-term conclusions, groundwater imbalance was reflected by net aquifer recharge (R) less than $P_I + P_U$ ($G < 0$) in the average year 2010–2011, with net lateral inflow from adjacent Cambrian formations being the largest recharge component. R is expected to be much less than $P_I + P_U$ in recurrent dry spells. Some low-technology actions are tentatively proposed to mitigate groundwater degradation, such as: wastewater capture, treatment, and reuse for irrigation; storm-water harvesting for irrigation; and active maintenance of the irrigation system to improve its efficiency.

1. Introduction

Groundwater evaluation aimed at maintaining sustainable use constitutes a challenge in applied hydrology, in particular in drylands where this resource is crucial to socioeconomic development and, in some cases, for human survival (Kovalevskii, 2007).

Like other developing arid regions, northern Sahara typifies this water scarcity (Revenga et al., 1999). In this region, aquifers forming irrigated date-palm oases play a critical role in buffering the advance of the Sahara Desert and keeping the population. Traditional crops are being transformed into marketable crops favored by modern pumping technology to yield deep groundwater reserves (Foster and Chilton, 2003). Since the decade of the 2000s, international tourism had become a new economic activity (Heidecke, 2009; Dobruszkes and Mondou, 2013) that has begun to compete for groundwater resources (Martin, 2006). This is true for most of the oases framed in the protected category 'Oases of Southern Morocco' from UNESCO (MADRPM, 2008). This programme is aimed at developing quality tourism to preserve oasis ecosystems and to enhance the livelihoods of local communities. However, signs of groundwater degradation have been reported in most cases (De Jong et al., 2008; Heidecke, 2009; Dahan et al., 2012).

Understanding the complex hydrological and economic interactions that take place in these remote areas is the first step in making stakeholders aware of the opportunities, threats, and importance of their natural resources (Ibáñez et al., 2008). This knowledge departs from a conceptual model that represents the essential features of the aquifer functioning coupled with its economic use. Groundwater numerical models allow the aquifer response to be represented over time (Custodio, 2002). They improve the conceptual model as new data are incorporated (Poeter and Anderson, 2005), especially with respect to uncertainty assessment (Hojberg and Refsgaard, 2005; Beven, 2007). Unfortunately, these evaluations are not supported in sparse-data areas because aquifer and economic databases are often skewed, cover only a few years at most, or do not include the most sensitive system variables (Beven, 2007; Candela et al., 2012).

System Dynamics (SD) modeling has proven to be a robust alternative operational framework to imbricate the dynamics of complex system variables (Ford, 1999; Ibáñez et al., 2008; Khan et al., 2009; and references therein) in order to provide quantitative evaluations and uncertainty assessment. Regarding groundwater-dependent economics, SD modeling was successfully used to assess the risk of aquifer overexploitation in a sparse-data oasis in southern Morocco (Martínez-Valderrama et al., 2011) by considering the interaction between hydrology and agriculture, the largest consumer of water. However, additional groundwater withdrawal for domestic use can be critical in small aquifers supplying a growing population. In fact, water resources in most remote oases can be endangered by the boost in tourism, which encourages the population to settle in the area (Martin, 2006; Heidecke and Heckelei, 2010).

Although SD models can work well in sparse-data areas, in some contexts having limited data coverage it is more appropriate to sketch the web of relationships between the governing system variables and pay attention to field surveys in order to test the conceptual model and improve it as new data are incorporated. Reporting results and promoting ideas is considered by Phillips (2012) in Earth Science as a form of storytelling. Storytelling, put into action through SD causal diagrams, is an effective choice for intricate problems in areas where governing system variables are unknown. System conceptualization is the first step in introducing basic formulations.

This paper introduces a new model linking hydrology and economics for sustainable groundwater use in sparse-data drylands. The model imbricates the dynamics of two state variables: groundwater saturated thickness in the aquifer and consumers of waters, both locals and tourists. The Amtoudi alluvial aquifer (Robles-Marín et al., 2015), a remote oasis in southern Morocco, in the northern Sahara attractive for tourism and with evidence of groundwater degradation (MAPM, 2001; MADRPM, 2008; Dahan et al., 2012), was chosen to: (1) sketch the web of relationships between the governing system variables identified through SD modeling causal diagrams; and (2) introduce basic hydrological and economic formulations for quantitative results. The model is intended to provide the basis for understanding groundwater degradation as a prerequisite to enable sustainable solutions in this particular dryland context. Field surveys were carried out during the wet 2009–2010 and the average 2010–1011 hydrological years to anchor the magnitude of governing system variables under similar influx of tourists and different scenarios of water availability.

The paper is organized as follows. Section 2 presents guidelines of the Amtoudi area. Section 3 conceptualizes the system functioning. Section 4 introduces basic hydrological and economic formulations. Section 5 describes the model operation and results. Section 6 discusses the sustainability of the system and proposes some feasible mitigation measures. Section 7 presents the main conclusions.

2. Study area

2.1. Location and climate

The Amtoudi Oasis is located at the outlet of the 'Wadi des Argan' basin (9°01′–9°12′ W, 29°12′–29°27′ N) in the province of Guelmim in southern Morocco (Fig. 1a). The Wadi des Argan basin covers an area of 286 km^2, has a mean elevation of 1230 m a.s.l. (outlet is 839 m a.s.l. on the south and peak elevation is 1465 m a.s.l. on the north), and flows into the Noun watershed southwards in the western Anti-Atlas Chain (Revenga et al., 1999).

This area shows a subtropical dry climate with a warm temperate desert scrub biozone and a bimodal precipitation distribution (Esper et al., 2007). Most of the precipitation (P) occurs during the autumn and spring with erratic events of high spatiotemporal heterogeneity. Extreme rainfall events over 50 mm per day have been documented. In winter, cold northern winds predominate, while in summer dry easterly winds prevail (Born et al., 2008). Annual mean P is around 125 mm with a coefficient of variation of 0.45 over the period 1973–2011. Precipitation follows a decreasing gradient from west to east and from north to south controlled by the incoming Atlantic cloud fronts and elevation, respectively (Esper et al., 2007; Born et al., 2008). Annual mean temperature is around 19.5 °C, with minimums in January and maximums in August; the daily amplitude may be as high as 30 °C. Insolation is high, with more than 3500 h per year in low-lying places. Annual mean potential evapotranspiration is around 1500 mm.