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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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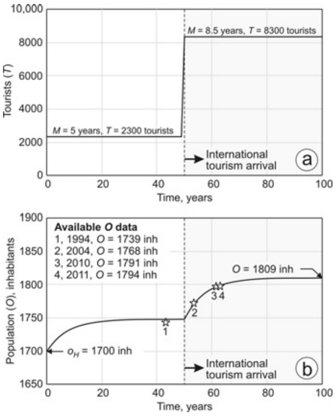
HIGHLIGHTS

- 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.

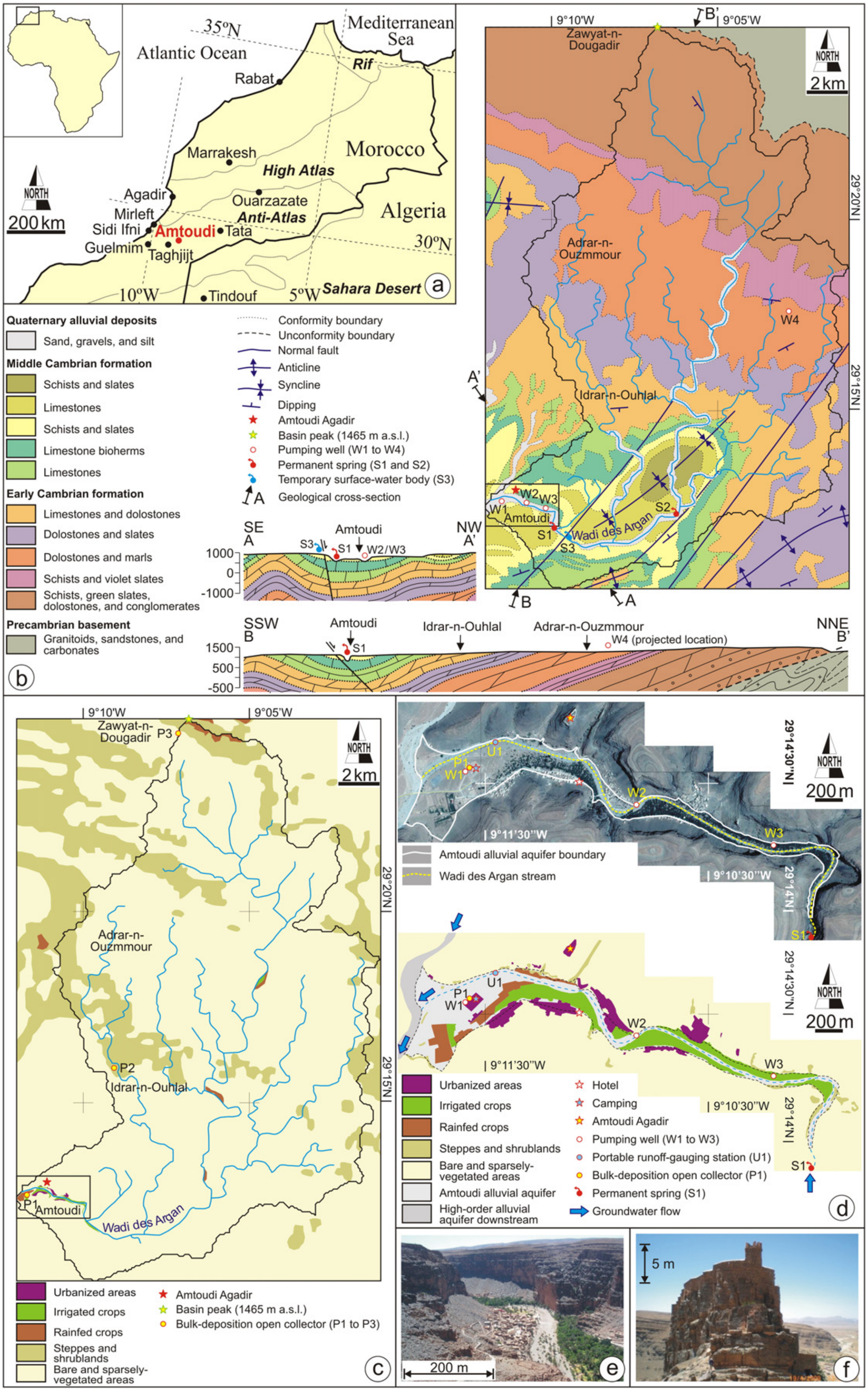

Fig. 1. (a) Location of the Amtoudi area in southern Morocco, showing the main geographical features and sites cited in the text. (b) Geological map (scale 1:100,000) of the Wadi des Argan basin after Robles-Marín et al. (2015), showing geological cross-sections A–A′ and B–B′. (c) Land-use Units of the Wadi des Argan basin according to 300-m resolution ESA-GlobCover 2009 (Arino et al., 2012), aerial photographs, and direct field observations, showing sites cited in the text. (d) Amtoudi alluvial aquifer area showing detailed Land-use Units, and geographical features and sites cited in the text. (e) View of the Amtoudi Village and Oasis from the Amtoudi Agadir. (f) North-west close-up view of the Amtoudi Agadir.

2.2. Geological and hydrogeological setting

The study area (Fig. 1b) belongs to the western segment of the Anti-Atlas Chain from the West-African Craton (Burkhard et al., 2006). In the Wadi des Argan basin, the Anti-Atlas belt outcrops as buckle folding of the contact between Precambrian basement and Palaeozoic sedimentary cover, with the following synthetic succession from bottom to top: (1) a Precambrian basement composed by a complex of 2070 Ma metasediments intruded by 2050–2032 Ma granitoids attributed to the Eburnean orogeny (Walsh et al., 2002); (2) a coarse siliciclastic conglomerate linked to the pan-African rifting unconformably deposited over folded Precambrian assemblages at around 680 Ma (Inglis et al., 2004); (3) an Early Cambrian metasedimentary formation composed of schists and slates, massive dolostones, and marls; and (4) a Middle Cambrian metasedimentary formation composed of limestones and dolostones, archaeocyate bioherms, and schists and slates (Walsh et al., 2002; Burkhard et al., 2006; Robles-Marín et al., 2015). Late Quaternary alluvial deposits fill the valleys.

In hydrogeological terms, geological formations can be classified into four groups according to the permeability type and storage capacity reported by Bouhlassa and Aiachi (2002), Naser (2006), and Ettayfi et al. (2012): (1) Precambrian crystalline basement and Early Cambrian metapelitics are low-permeability formations forming the impervious boundary of local aquifers; (2) Early and Middle Cambrian carbonate formations form moderately to highly permeable aquifers with thickness up to 500 m having some epikarst features as solutions and travertines; (3) Early and Middle Cambrian slates and marls are considered impervious formations, often confining the above Early and Middle Cambrian carbonate formations; and (4) Late Quaternary alluvial deposits comprise sand, gravels, and silt of 10 m to 40 m in thickness forming the Amtoudi Oasis, an unconfined aquifer of 0.63 km^2 at the basin outlet (Fig. 1b).

The hydrogeological functioning of the Wadi des Argan basin depends on: (1) the low permeability of Precambrian and Cambrian metapelitic formations and the high fissuring of Cambrian carbonates; (2) the extent of weathered scree slopes; and (3) the thickness and extent of the porous, coarse-grained Amtoudi alluvial aquifer downstream. Despite high evaporation rates in the area (Naser, 2006; De Jong et al., 2008; Ettayfi et al., 2012) effective net aquifer recharge to the alluvial aquifer is possible from: (1) direct rainfall and runoff infiltration during intense rainfall events; (2) contribution of interflow runoff from fissured and weathered low-permeability formations; and (3) net lateral inflow from Early and Middle Cambrian carbonates, just where the alluvial aquifer begins and the incisive valley topography intersects the piezometry of Cambrian carbonates to produce permanent springs (Fig. 1b).

2.3. Land use and agriculture

The Wadi des Argan basin is covered 87.1% by xerophytic vegetation over bare crust-forming soils, lithosols, and regosols, and 12.2% by sparse vegetation (steppes and shrublands) at the summits over luvisols and calcisols as powdery lime or concretions (Fig. 1c) (MAPM, 2001; Arino et al., 2012). Rain-fed crops over luvisols occupy 0.4% in the northern mountains and in the Amtoudi Oasis, 0.2% are irrigated crops in the oasis, and less than 0.1% is occupied by the village of Amtoudi (Fig. 1d).

Irrigated crops such as different fruit trees and vegetables and small fields of rain-fed crops are used mostly for family consumption, and complemented with commercial crops such as henna, date palms, and market-oriented vegetables. The 24.8 ha of irrigated crops in the oasis has long been cultivated (Fig. 1e). The new practices do not substantially alter the demand for irrigation water, traditionally around 4800 m^3 per hectare and year (UNDP, 1994; DRPE, 1998; Naser, 2006). Galleries locally called '*khettaras*' drain shallow groundwater (Lightfoot, 1996). These were historically used for irrigation and complemented by permanent springs and handmade open wells in dry spells. Today, pumping wells that yield the entire alluvial aquifer saturated zone are preferably used for irrigation.

2.4. Population and tourism

The community of Amtoudi had 1739 inhabitants censused in 1994 and 1768 in 2004, according to the High Commission for Planning of Morocco (RGPH, 2004). Local authorities reported 1794 inhabitants in 2011 with 45% of the population under 18 years and 13% over 60 years old. Historically, people had to fetch water from particular open wells at traditional Moroccans homes and from public fountains. In the 1970s the water allotment around 25 L per inhabitant per day was estimated (UNDP, 1994; Naser, 2006). This rate increased to 30 L per inhabitant per day when electricity arrived in the 1990s and a primary pipeline system was implemented to supply water to houses. In the decade of the 2000s, the local authorities constructed two pumping wells that yield around 10 L per second and a cistern of 100 m^3 to store, chlorinate, and distribute water on demand. The pipeline system currently covers 78% of the houses or 85% of the population. This means a daily water provision of 50 L per inhabitant.

Since the decade of the 2000s, the Amtoudi Oasis has been included in the protected category 'Oases of Southern Morocco', a programme framed in the MaB Biosphere Reserves Directory from UNESCO and funded with 3.25 M€ through 2011 (MADRPM, 2008). Besides the ecological interest, the Amtoudi Oasis also hosts one of the best-conserved medieval fortified granaries or '*agadirs*' of southern Morocco (Fig. 1f). This is one of the main tourist attractions of the area for its architectural and historic value (Naji, 2003; Robles-Marín et al., 2015; Raffaelli et al., 2015). The Amtoudi Agadir was constructed around the 12th century by the Berber Iznaguen tribe to store resources. Agadirs are part of the Berber culture resulting from the origin of the Moroccan Nation. Rock engravings and petroglyphs of savannah animals from a wetter past dating to around the Neolithic and late Palaeolithic boundary, about 10,000 to 12,000 BC (Kaache, 2001; Amara, 2003), is another tourist draw.

From the 1990s onward, tour operators and regional authorities included the area in the tourist circuits of the cities Marrakesh, Agadir, and Ouarzazate, which have international airports less than 300 km away from Amtoudi Oasis (Fig. 1a). Since the decade of the 2000s, the surge in airline travel (Dobruszkes and Mondou, 2013) has increased the international tourism in these remote areas (Leroux, 2007). The consequence in the Amtoudi area was that the existing camping facility was complemented with a hotel with small gardens, restaurant services, and the possibility of overnight stays in rooms with showers and toilets (Fig. 1d). Tourist facilities are equipped with pumping wells that can yield around 10 L per second. The water consumption is around 100 L per tourist per day (Martin, 2006). Tourist season in the area covers September through May (9 months) since summer is very hot for visits. Tourism attracts about 8300 visitors per year (GSR, 2010, 2012, 2013).

3. Conceptualization of the system functioning

Essential features of the physical system coupled with the economic use of the Amtoudi Oasis were conceptualized through a web of relationships. The main cause–effect feedbacks were sketched in System Dynamics (SD) causal diagrams (Ford, 1999; Ibáñez et al., 2008; Khan et al., 2009; and references therein), which integrated both quantitative and qualitative pieces of information. These feedbacks are common to other groundwater-dependent economics developed in unconfined aquifers, both including well-developed market economies and more local emerging economies (Ibáñez et al., 2008; Martínez-Valderrama et al., 2011).

In Amtoudi Oasis, feedbacks for sustainability of the system were conceptualized both in natural regime (Fig. 2a) and after disturbance (Fig. 2b). Negative feedbacks drive the system to long-term stability (Fig. 2a). The groundwater dynamics involve two stabilizing loops:

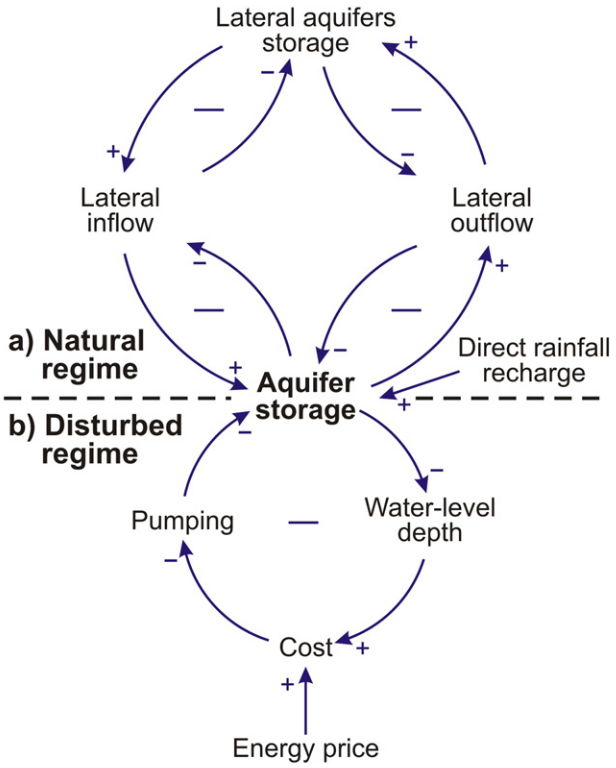

Fig. 2. Conceptual hydrological–economic model for Amtoudi Oasis system under (a) natural regime and (b) disturbed regime.

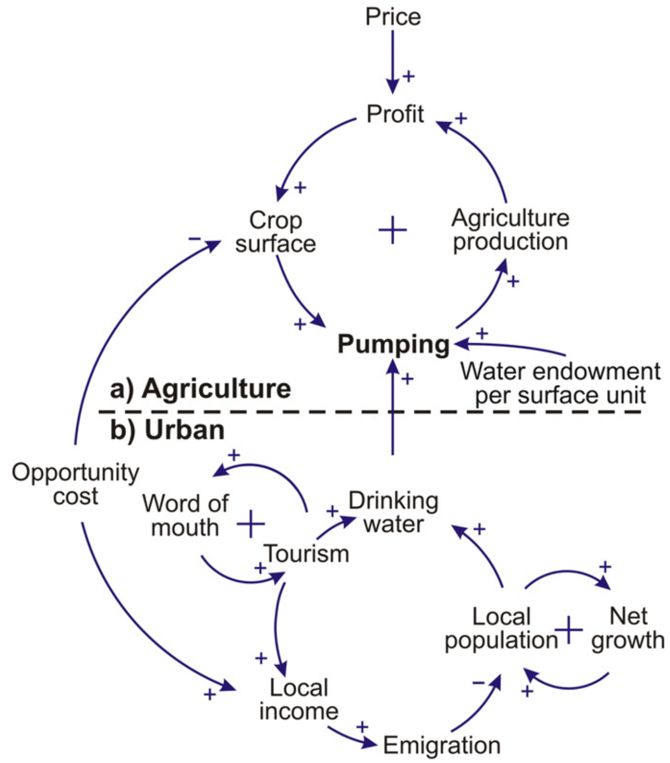

Fig. 3. Coupling hydrological (physical) and economic systems based on the nexus groundwater pumping for (a) agriculture and (b) urban uses.

(1) as net aquifer discharge drops groundwater storage decreases and the water table tends to stabilize at a positive value; and (2) net lateral inflow from Cambrian formations contributes to storage, but inflow becomes null or negative (outflow) when the storage is maximum.

Modern pumping technology has opened full access to groundwater (Foster and Chilton, 2003). Even in this circumstance, a new stabilizing negative feedback comes into action. That is, as the water table falls, pumping becomes more expensive due to higher energy costs (Fig. 2b). Lower prices of energy or subsidies can alter this feedback. However, when the economy is decoupled from the system the positive net aquifer recharge-to-discharge ratio tends to restore aquifer storage over the long term. The length of these 'water crises', i.e. the period in which the aquifer is almost exhausted, is key for the environment, economy, and society.

The nexus between the physical system and economics is groundwater pumping. In Amtoudi Oasis, agriculture and urban supply are the two main water consumers (Fig. 3).

The agricultural feedback is positive (Fig. 3a). In a classical scheme, water availability triggers productivity and profit. The expected behavior of population is to increase the crop surface area to generate more income (Heidecke and Heckelei, 2010; Martínez-Valderrama et al., 2011). Available crop surface and opportunity cost are two factors controlling this expansion. The latter is the profit that could be gained by engaging in any activity other than agriculture in the closest cities or in alternative businesses such as tourism. That is, as tourism expands, investment in agriculture becomes less attractive. In remote areas, opportunity costs are low, meaning that the aforementioned relation works in the opposite sense. However, for Amtoudi Oasis, tourism represents a new opportunity cost.

The structure of loops explains urban water consumption (Fig. 3b), when the positive net growth of population is taken into account, i.e. birth rate higher than mortality rate. Historically, emigration has kept the population stable in the Amtoudi area. Emigration is in turn linked to opportunity cost. As the area offers more job opportunities people settle and the population rises, as reported in other oases of southern Morocco (RGPH, 2004; MADRPM, 2008; Heidecke, 2009).

Three important factors can threaten the sustainability of the system: (1) more tourism implies more population settling through the effect of the opportunity cost; (2) most of the tourists come from urban areas with greater water consumption rates; and (3) capital inflow into the area foments the demand of services, dissuading inhabitants from emigrating. As a consequence, the ratio of local incomes vs. opportunity costs increases, as tourism triggers a positive feedback loop. The main forces encouraging visits to the area are publicity and the word of mouth.

4. A dynamic model linking hydrology and economics

4.1. Overall basis

Hydrological and economic feedbacks screened out in Section 3 (Figs. 2 and 3) were parameterized by using formulations well documented in the literature. The rationale was the selection of formulations based on governing system variables and parameters identified, and available information. Formulations were programmed into a model, which is ultimately intended to imbricate the dynamics of two state variables: groundwater saturated thickness in the aquifer and consumers of water. The equations refer to the end of the hydrological year, thus allowing for steady (long-term) and transient (short-term) evaluations depending on the time-series coverage. Throughout the description, capital letters refer to endogenous and exogenous variables while small letters denote parameters. Tables 1 and 2 include the notation for variables and parameters used, respectively.

4.2. Hydrological module

The model represents the net groundwater balance (G) in an unconfined aquifer. For simplified geometry, the aquifer was considered a parallelepiped with the upper boundary being the fluctuating water table, as in Martínez-Valderrama et al. (2011). Groundwater storage was evaluated through the one-dimensional average groundwater saturated thickness (H) measured from the aquifer bottom to the water table.

Table 1
Notation for variables used, source of data, and results for hydrological years 2009–2010 and 2010–2011.

Variable	Description	Units	Year 2009–2010	Year 2010–2011	Source of data
C_P	Average chloride concentration in P	mg $L^{-1} \equiv g\ m^{-3}$	4.031	4.682	DM
C_R	Average chloride concentration in R	mg $L^{-1} \equiv g\ m^{-3}$	37.419	48.826	DM
C_U	Average chloride concentration in U	mg $L^{-1} \equiv g\ m^{-3}$	12.891	28.219	DM
D	Net aquifer discharge	m $year^{-1}$	4.086	2.344	MR
G	Net groundwater balance	m $year^{-1}$	0.574	−0.475	MR
G_T	Average groundwater-turnover time	year	0.423	0.551	MR
H	Groundwater saturated thickness	m	14.955	11.479	DM
I_A	Annual investment in publicity	€ $year^{-1}$	350,000	350,000	MADRPM (2008), OBG (2011, 2012)
I_N	Standard investment in publicity	€ $year^{-1}$	200,000	200,000	MADRPM (2008), OBG (2011, 2012)
M	Delay time of emigration	year	8.4	8.6	MR
O	Population in the area	inh	1791	1794	FS
O_B	Birth rate	inh $year^{-1}$	32	34	FS
O_M	Mortality rate	inh $year^{-1}$	11	10	FS
P	Average precipitation in the area [a]	m $year^{-1}$	0.192	0.122	DM, DS
P_I	Groundwater allotment for irrigation	m $year^{-1}$	2.863	2.863	MR
P_U	Groundwater allotment for urban supply	m $year^{-1}$	0.718	0.721	MR
R	Net aquifer recharge	m $year^{-1}$	7.381	4.594	MR
S_I	Surface of irrigated crops	ha	24.8	24.8	FS
T	Number of tourists visiting the area	tr	8180	8570	FS
T_P	Potential tourists coming through publicity	tr $year^{-1}$	25,419	25,419	MR
T_S	Satisfied tourists	tr $year^{-1}$	6544	6856	MR
T_W	Potential tourists coming by word of mouth	tr $year^{-1}$	98,160	102,840	MR
U	Surface runoff leaving the aquifer surface	m $year^{-1}$	0.008	0.001	DM

Data source: DM data monitoring; DS data from State agencies; FS field survey; MR model result.

[a] Daily precipitation data from the World Meteorological Organization [http://www.wmo.int] and the Meteorological Survey of Morocco [http://www.meteomaroc.com/].

The groundwater stored is subjected to variations due to: (1) net aquifer recharge (R) from direct rainfall and runoff infiltration on the aquifer surface as well as net lateral inflow from adjacent geological formations; (2) net aquifer discharge (D); (3) surface runoff leaving the aquifer surface (U); (4) groundwater allotment for irrigation (P_I) and urban supply (P_U) for population (O) and tourists (T); and (5) the return of a fraction of groundwater used for irrigation (r_I) and urban supply (r_U). The indefinite operator '*delay*' is used to express the delay between variations in flows and fluctuations observed in the water table. The following equations describe this dynamic:

$$G = R - D - P_I(1 - r_I) - P_U(1 - r_U) \tag{1}$$

$$dH/dt = delay(G) \tag{2}$$

$$R = [(P\ C_P - U\ C_U) s_B]/(C_R\ g_S\ s_A) \tag{3}$$

$$D = (H\ g_S)^{g_D}/G_T \tag{4}$$

$$G_T = (g_D\ s_A\ g_S)/(g_K\ H) \tag{5}$$

$$P_I = (w_I\ S_I)/(e_I\ g_S\ s_A) \tag{6}$$

$$P_U = (w_O\ O + w_T\ T)/(e_U\ g_S\ s_A). \tag{7}$$

The atmospheric chloride mass balance (CMB) method (Claasen et al., 1986; Scanlon, 2000; Alcalá and Custodio, 2014, 2015) was used for R (Eq. (3)). The CMB method assumes: (1) chloride ion is from

Table 2
Notation for parameters used, source of data, and results for hydrological years 2009–2010 and 2010–2011.

Parameter	Description	Units	Value	Source of data
e_I	Average efficiency of the irrigation system	dmnl	0.60	FS, FAO (2008)
e_U	Average efficiency of the urban supply system	dmnl	0.70	FS, FAO (2008)
g_D	Flow-path form parameter induced by aquifer geometry	dmnl	1.10	Chapman (1999)
g_K	Aquifer hydraulic conductivity	m $year^{-1}$	12,045	FS
g_S	Aquifer storage coefficient	dmnl	0.11	FS
i_E	Elasticity of investment	dmnl	2	MR
m_M	Minimum emigration time	year	2	FS, CIA (2012)
m_T	Normal emigration time	year	8	MR
o_H	Historical record of population in the area	inh	1700	FS, RGPH (2004)
s_A	Aquifer surface receiving lateral inflow	m^2	630,000	FS
s_B	Basin surface receiving recharge and transmitting lateral inflow [a]	m^2	28,600,000	FS, Robles-Marín et al. (2015)
r_C	Rate of contact	dmnl	15	MR
r_I	Irrigation return flow coefficient	dmnl	0.25	FS, Martínez-Valderrama et al. (2011)
r_M	Emigration form parameter	dmnl	0.0002	MR
r_T	Fraction of potential tourists that visit the area	dmnl	0.065	MR
r_U	Urban return flow coefficient	dmnl	0.20	FS, Martínez-Valderrama et al. (2011)
t_E	Evaluation of the place by tourists	dmnl	0.8	FS
t_N	Normal tourists visiting the area	tr	8300	FS, GSR (2010, 2012, 2013)
w_I	Water supplied to crops per hectare [b]	$m^3\ ha^{-1}\ year^{-1}$	4800	FS, UNDP (1994), DRPE (1998), Naser (2006)
w_O	Water consumption per inhabitant	$m^3\ inh^{-1}\ year^{-1}$	18.25	FS, UNDP (1994), Naser (2006)
w_T	Water consumption per tourist [c]	$m^3\ tr^{-1}\ year^{-1}$	0.26	FS, Martin (2006)

Data source: DM data monitoring; FS field survey; MR model result.

[a] Surface of Cambrian permeable formations hydraulically connected to the Amtoudi alluvial aquifer, after geological survey from Robles-Marín et al. (2015).

[b] Average-weighted value by surface devoted to different staples after direct field observation.

[c] Value obtained by using the average 2.6-day stay per tourist reported by GSR (2010, 2012, 2013).

atmospheric sources (Alcalá and Custodio, 2008a); (2) atmospheric chloride bulk deposition is $A_P = P\,C_P$ from adequate sampling (Alcalá and Custodio, 2008b); (3) the concentration of atmospheric chloride dissolved in infiltrating water increases due to actual evapotranspiration (Alcalá and Custodio, 2014); and (4) there is no permanent retention of chloride in the unsaturated zone (Scanlon, 2000). Actual evapotranspiration is not involved into CMB equations because it is chloride-free water vapor (Claasen et al., 1986). The CMB formulation was updated to specify the surface of adjacent geological formations (s_B) receiving recharge and transmitting its chloride mass flux through lateral inflow to the hydraulically connected aquifer surface (s_A).

The Coutagne (1948) formulation was used for D under unconfined flow conditions (Eq. (4)). The g_D parameter was used to capture the effect of aquifer geometry on groundwater discharge flow paths (Chapman, 1999). Formulation assumed that storage decreases while groundwater transmits through the aquifer outlet (Martínez-Valderrama et al., 2011). No thresholds for D due to aquifer geometry and hydraulic-head limitations were imposed. Thus, D will be zero only when G is exhausted. The average groundwater-turnover time (G_T) was deduced from aquifer geometry and hydraulics data (Eq. (5)) by assuming a predominant piston (plug) flow condition (Custodio and Llamas, 1983; Alcalá et al., 2011).

P_I was the irrigation surface (S_I) times the unitary water supplied to crops per hectare (w_I), which is calculated by considering the surface devoted to different staples (Eq. (6)). P_U depended on O and T and their unitary water consumptions w_O and w_T, respectively (Eq. (7)).

4.3. Economic module

The model reproduces the variation in water consumers, both O and T. The set of equations considered that: (1) the surge in tourism reduces emigration from the area; (2) the economic upturn will not attract people to immigrate to this remote area; and (3) the only way in which O can grow is by reducing the emigration rate. The indefinite operator '*max*' is used to prevent immigration. Given the absence of detailed economic data in most of the remote oases (Martin, 2006; Heidecke and Heckelei, 2010) this approach omitted profitability and postulated a direct link between O and T. The following equations describe this dynamics:

$$dO/dt = (O_B - O_M)O - \max[0, (O - o_H)/M] \tag{8}$$

$$M = m_M + m_T(1 - \exp(-r_M\ T)) \tag{9}$$

$$dT/dt = (T_P + T_W)r_T \tag{10}$$

$$T_P = t_N(I_A/I_N)^{i_E} \tag{11}$$

$$T_W = T_S\ r_C \tag{12}$$

$$T_S = \ t_E\ T. \tag{13}$$

Population (Eq. (8)) followed the classical pattern where the first term is the net vegetative growth (birth rate minus mortality rate) and the second is emigration (Turchin, 2003). As the population grows beyond its historical record (o_H), the surplus $O - o_H$ leaves the area at a rate that depends on the delay time needed to make the decision of emigrating.

Delay time of emigration (M) controls the speed of population releases (Eq. (9)). M was composed of two terms. The parameter m_M represents the floor of M, i.e. the minimum time that the population waits to leave the area when the economic condition is disadvantageous; for its calibration, historical O data are needed. The second term was an inverse exponential function that rises until reaching its maximum value $m_M + m_T$ as tourists visit the area. This means that: (1) M increases and the emigration rate decays in Eq. (9); and (2) the second term diminishes while the population in the area increases in Eq. (8).

The number of tourists (T) depends on the dissemination of information about the natural attractions and assets of cultural interest of the area (Eq. (10)). This was estimated through potential tourists coming through publicity campaigns (T_P) and by word of mouth (T_W). Only a fraction of potential visitors (r_T) will finally reach the area (Martin, 2006).

The ratio between annual (I_A) and standard (I_N) investments to promote the site determined T_P (Eq. (11)). Elasticity (i_E) allows the tuning of the response to investments. Note that when investments reach expected levels, i.e. $I_A = I_N$, then $T_P = t_N$, as the average number of tourists visiting the area in a normal year.

Finally, T_W was proportional to the degree of satisfaction of previous visitors. This was implemented by multiplying satisfied tourists (T_S) by a rate of contact (r_C) between visitors and people to whom they describe their trip (Eq. (12)). T_S is a fraction of T which depends on the evaluation of the site by tourists (t_E) (Eq. (13)).

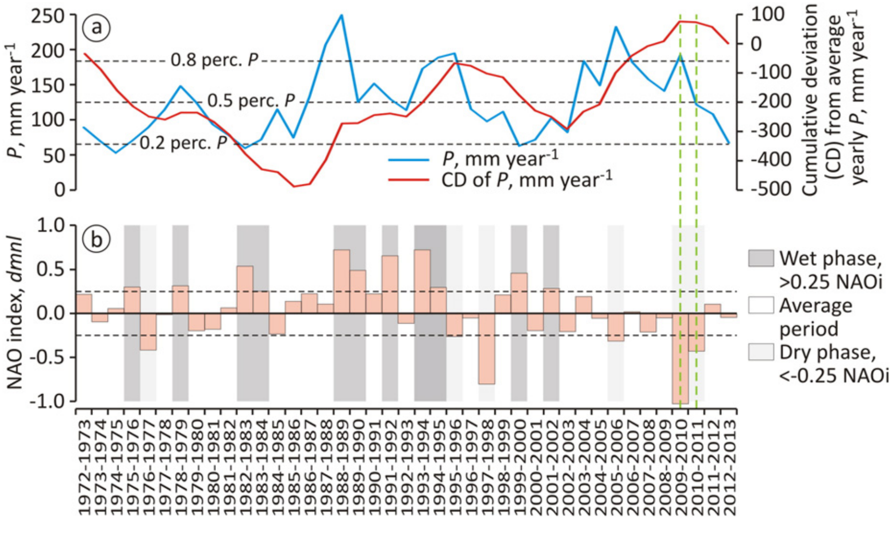

Fig. 4. For hydrological years 1972–1973 to 2012–2013, (a) Normalized North Atlantic Oscillation (NAO) index [NAO website: http://www.cpc.ncep.noaa.gov/]; and (b) yearly precipitation (P) time series and cumulative deviation from average yearly P in the Amtoudi area, showing 0.2 percentile, average, and 0.8 percentile. Vertical dotted lines indicate study years 2009–2010 and 2010–2011.

5. Model operation and results

5.1. Overall framework

The model was operated for the wet 2009–2010 and the average 2010–2011 hydrological years (Fig. 4a) (October through September in the region). Long-term significance for selected years was evaluated from the cyclicity analysis of the global North Atlantic Oscillation index [NAO website: http://www.cpc.ncep.noaa.gov/] (Fig. 4b). The NAO index controls long-term precipitation and temperature regimes in southern Morocco (IPCC, 2007; Esper et al., 2007). During this 2-year period, hydrogeological surveys were carried out to define

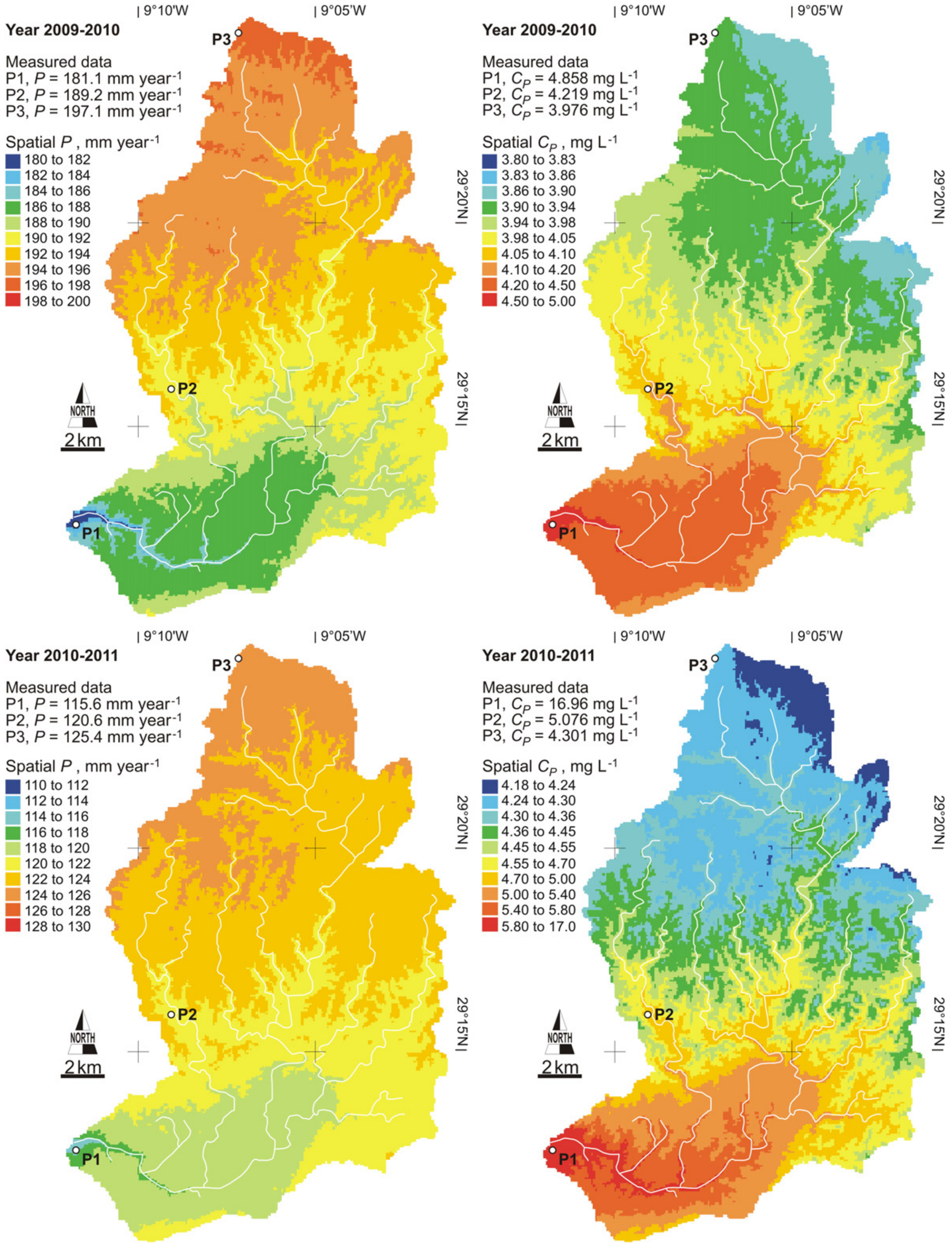

Fig. 5. Spatial yearly P (mm year^{-1}) and C_P (mg L^{-1} ≡ g m^{-3}) for hydrological years 2009–2010 and 2010–2011 in the Wadi des Argan basin. Measured yearly P and C_P data are singled out. Data are discretized in 90 m × 90 m cells.

the aquifer functioning, and data on population, agriculture, and tourism were gathered from State agencies, local authorities, farmers, camping and hotel managers, and the literature (Tables 1 and 2).

5.2. Hydrological input data

Daily records of P from 1972 onward (Fig. 4a) were downloaded from the *World Meteorological Organization* [WMO website: http://www.wmo.int] for Agadir (30°18′N, 9°24′W, 74 m a.s.l.), Ouarzazate (30°55′N, 6°54′W, 1139 m a.s.l.), Sidi Ifni (29°18′W, 10°10′W, 58 m a.s.l.), and Tindouf (27°42′N, 8°07′W, 431 m a.s.l.) weather stations (Fig. 1a). Additionally, daily records of P from 1985 onward were downloaded from the *Meteorological Survey of Morocco* [MSM website: http://www.meteomaroc.com/] for Taghjijt (29°03′N, 09°25′W, 610 m a.s.l.) and Tata (29°46′N, 07°58′W, 713 m a.s.l.) weather stations (Fig. 1a). Atmospheric chloride bulk deposition ($A_P = P\,C_P$) was sampled yearly in Amtoudi Village (P1: 29°14′50″N, 9°11′44″W, 849 m a.s.l.), Idrar-n-Ouhlal site (P2: 29°17′39″N, 9°09′06″W, 1188 m a.s.l.), and Zawyat-n-Dougadir site (P3: 29°26′21″N, 9°07′14″W, 1438 m a.s.l.) (Fig. 1c). Information was used for spatiotemporal P and C_P in the Wadi des Argan basin.

Incoming cloud fronts from Atlantic Ocean constitute the main driving force controlling spatial P and C_P in western North Atlantic seaboard regions (Goovaerts, 2000; Delalieux et al., 2006; Born et al., 2008; Alcalá and Custodio, 2008b, 2014, 2015). Elevation was the unique covariate used for spatial yearly P. In the Wadi des Argan basin, yearly P increased by 2.5 mm per 100 m in elevation. This figure agrees with data reported by Naser (2006) and Born et al. (2008) in the region. Distance from the coast (coastal distance hereafter) and elevation were covariates used for spatial yearly C_P (Guan et al., 2010; Alcalá and Custodio, 2014, 2015). In the Wadi des Argan basin, the decay of C_P was lineal with increasing coastal distance by 0.02 mg L^{-1} km^{-1} and by 0.16 mg L^{-1} per 100 m in elevation. The one grid spacing of the 90-m DEM from Shuttle Radar Topography Mission [SRTM website: http://srtm.csi.cgiar.org/] was the distance used for spatial yearly P and C_P in the Wadi des Argan basin (Fig. 5). Average A_P was 0.77 g m^{-2} year^{-1} and 0.57 g m^{-2} year^{-1} in years 2009–2010 and 2010–2011, respectively. These figures are around 0.05-fold the value of A_P estimated by Lekouch et al. (2011) in Mirleft, a coastal city located 85-km northwest of the Amtoudi area (Fig. 1a).

Seven flood events were recorded at the basin outlet (portable gauging station U1: 29°14′51″N, 9°11′28″W, 852 m a.s.l.; Fig. 1d), five in year 2009–2010 and two in year 2010–2011 (Fig. 6a). The experimental threshold for runoff generation was 13.1 mm of 24-h P, while the concentration time of the basin after rainfall began was about 12 h, as corroborated from expressions by Témez (1978) and Chow et al. (1988). The peak discharges were sampled for average, discharge-weighted yearly C_U (Alcalá and Custodio, 2014, 2015).

The frequency of groundwater data monitoring was based on a preliminary evaluation of G_T around 0.5 years after the alluvial aquifer geometry was defined by Robles-Marín et al. (2015). Average $g_K =$ 33 m day^{-1} and $g_S = 0.11$ were deduced after two pumping tests performed in pumping wells W1 (29°14′28″N, 9°11′46″W, 851 m a.s.l.) and W2 (29°14′25″N, 9°10′49″W, 865 m a.s.l.). Piezometry was monitored monthly in wells W1 and W2, and quarterly in pumping well W3 (29°14′15″N, 9°10′12″W, 883 m a.s.l.) for average yearly H (Fig. 6b). Groundwater was sampled quarterly for C_R in wells W1 and W2, both yielding the entire saturated zone in the alluvial outlet and in a pristine area upstream, respectively (Fig. 1d). C_R integrates the chloride mass flux produced by variable R rates and its chloride content throughout the basin. Average yearly C_R from well W2 (Fig. 6b) was used to estimate R. The Cl/Br molar ratio (Alcalá and Custodio, 2008a) was used to distinguish the atmospheric origin of C_R. The Cl/Br molar ratio was in the 550–650 range in bulk deposition, runoff, and groundwater samples, thus ruling out a significant chloride contribution from lithology and human activities to groundwater. Atmospheric origin of chloride in lateral inflow was verified by sampling groundwater recharge and discharge flow from Cambrian formations in pumping well W4 (29°19′39″N, 9°02′53″W, 1230 m a.s.l.) and permanent spring S1 (29°13′40″N, 9°09′57″W, 938 m a.s.l.), respectively (Fig. 1b). The atmospheric origin of chloride is consistent with findings of Ettayfi et al. (2012) for those hydrogeological formations.

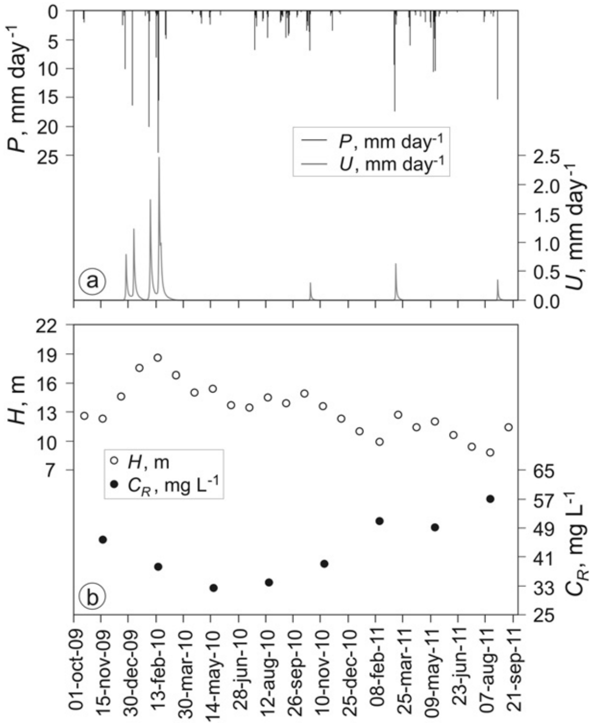

Fig. 6. For the period 1 October 2009 to 30 September 2011, (a) the 24-h P–U distribution in the Wadi des Argan basin, after daily P (mm) records from Taghjijt and Tata weather stations (see Fig. 1a), and daily U (mm) records from portable gauging station U1 (see Fig. 1d); and (b) monthly H (m) and quarterly C_R (mg L^{-1} ≡ g m^{-3}) records from pumping well W2 (see Fig. 1b).

D was estimated by taking $g_D = 1.1$ into account, as pointed out by Chapman (1999) for unconfined alluvial aquifers having longitudinal flow paths. G_T increased from 0.42 years in 2009–2010 to 0.55 years in 2010–2011 according to the increasing ratio of net recharge to aquifer storage (Table 1).

$P_I = 2.813$ m year^{-1} was considered constant. This is a local particularity because topography shows that available surface for cultivation cannot be enlarged beyond the canyon that encloses the Amtoudi Oasis, as described in Section 2.3. Water-consumption rates w_I, w_O, and w_T, efficiency parameters e_I and e_U, as well as P_I and P_U allocations for years 2009–2010 and 2010–2011 were deduced from field surveys and the literature (UNDP, 1994; DRPE, 1998; Naser, 2006; Martin, 2006; FAO, 2008; Heidecke, 2009; Martínez-Valderrama et al., 2011), as described in Tables 1 and 2.

5.3. Economic input data

As in most remote areas, in Amtoudi Oasis, economic and demographic data are scarce and State agencies do not often update them. Available information was channeled through simulation exercises to anchor the order of magnitude of unknown model variables and parameters, as well as to identify inconsistencies due to gaps in time series and biases in isolated data gathered from the literature.

Local authorities as well as camping and hotel managers provided data on O and T (Table 1). The population slightly increased to 1790 inhabitants in recent years. O_B and O_M were around 30 and 10 inhabitants per year, respectively (Table 1). Hence, the annual growth rate was around 1.2%, similar to the official average growth rate for rural

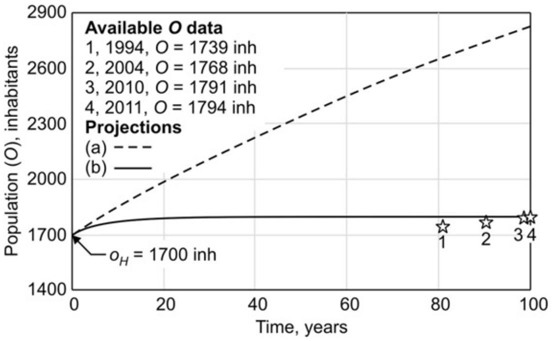

Fig. 7. Projection of population (O) in the Amtoudi area by using (a) the official net emigration rate of 0.37% in 2011 reported by CIA (2012) (dotted line); and (b) the net emigration rate of 1.11% found to stabilize O data for $o_H = 1700$ inhabitants reported by RGPH (2004) and $M = 5$ years (solid line). Available historical O data were overimposed.

population in southern Morocco reported by RGPH (2004). This positive growth rate, together with the fact that the population has been historically stable at around 1800 inhabitants leads to the conclusion that people have historically emigrated.

In southern Morocco, net emigration rate was 3.88 and 3.77 emigrants per 1000 population in 2010 and 2011, respectively, as reported by CIA (2012). According to these data, the population in Amtoudi should increase (Fig. 7a). However, these official figures about emigration were insufficient to explain the horizontal trend observed in O data. To stabilize O around its historical record, appropriate values for M (Table 1) and o_H (Table 2) had to be deduced. After several simulation exercises, the population trend was found to stabilize at 1800 inhabitants for $o_H = 1700$ inhabitants reported by RGPH (2004) and $M = 5$ years (Fig. 7b); this figure is very close to the current O (Table 1; Fig. 7b). This yields a net emigration rate of 1.11%, which is 3-fold the above official figures reported by CIA (2012).

Once M is set at 5 years, reasonable parameter values for Eq. (9) had to be deduced. Some hypotheses were formulated. In the Amtoudi area, m_M is quite tightly controlled by the ability of single men to emigrate; $m_M = 2$ years after the field survey and CIA (2012). On the contrary, a maximum delay of $m_M + m_T = 10$ years was assumed according to the ability for family reunification in the host country, i.e. the population takes longer to leave the area if they finally do so; $m_T = 8$ years. The function that best fitted current T data was found for $r_M = 0.0002$ (Fig. 8).

A basic simulation was run to check the performance of the model under a change in the number of tourists. When T increases from 2300 visitors per year to the normal 8300 visitors per year (Fig. 9a), a population boost follows, as stated by previous hypotheses that emigration time increases. Note that the normal number of 8300 visitors per year means 2 out of 3 tourists visiting the province of Guelmim (GSR, 2010, 2012, 2013). In this exercise $M = 8.5$ years was found to stabilize O around 1800 inhabitants (Fig. 9b). A surge in international tourism was deduced after 1995 (Fig. 9), when tour operators and regional authorities included the Amtoudi area in the circuits of touristic cities, as described in Section 2.4.

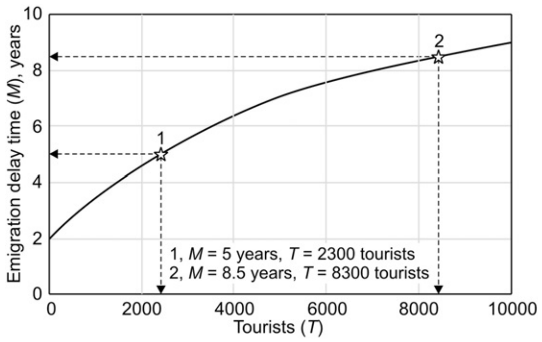

Fig. 8. Function of tourists (T) vs. emigration delay time (M) that best fit current T in the Amtoudi area. $m_M = 2$ years after field survey and CIA (2012) and $m_T = 8$ years were input parameters used to deduce $r_M = 0.0002$. Two system-state for tourism arrival for $M = 5$ years and $M = 8.5$ years that best fit normal 8300 tourists per year visiting the area were indicated.

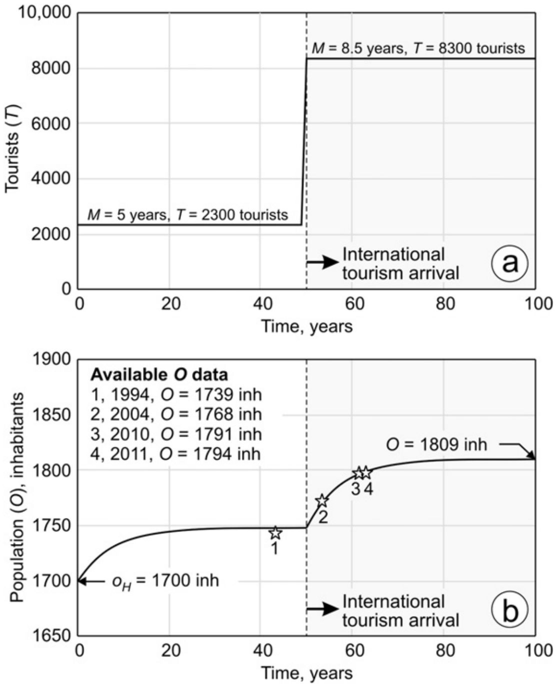

Fig. 9. Functions of (a) tourists (T) and (b) population (O) in the Amtoudi area that best fit input variables and parameters of Eqs. (8) and (9). Available historical O data were overimposed.

In this top-down calibration, the next task consisted of parameterizing Eqs. (10), (11), (12), and (13) in order to determine the current T. A lack of data makes it unavoidable to deduce some quantities. It was assumed that $i_E = 2$ (Table 2) as a reasonable figure based on investments programmed by State agencies. Investments $I_N = 0.2$ M€ and $I_A = 0.35$ M€ reported by MADRPM (2008), OBG (2011, 2012), and Dahan et al. (2012) yield T_P over 25,000 (Table 1).

A direct survey to 250 tourists provided the percentage of satisfied tourists at around 80%, i.e. $t_E = 0.8$; a basic questionnaire provided by the Guelmim Tourism Office was used. r_C was set at 15 persons (Table 2). Note that the calculation of T_W involved one simultaneity, i.e. T determines T_W and T_W determines T. This was solved by considering that T_W actually depends on the number of tourists of the previous year. This scenario yields T_W at around 100,000 (Table 1).

A value for r_T was required in order to convert T_P into T. For 6.5% of T_P, i.e. $r_T = 0.065$, T stabilizes at 9000 visitors. Note that the model is quite sensitive to r_T.

5.4. Model results

Hydrological and economic input data were used to operate the model. Model results are presented in Tables 1 and 2. Throughout the description, the magnitude of some governing system variables in the current stage of disturbance and in natural regime from the 1970s are compared in order to confirm the conceptualization of the system functioning (Fig. 10).

In Amtoudi Oasis, the increase in population (O) from 1700 inhabitants in the 1970s to the current 1794 inhabitants (Fig. 10) has increased water allocation from 25 L inh^{-1} day^{-1} to 50 L inh^{-1} day^{-1}. This means that annual groundwater allotment for urban supply (P_U) has been doubled from 15,500 m^3 to 32,700 m^3 in this period for less than a 100-

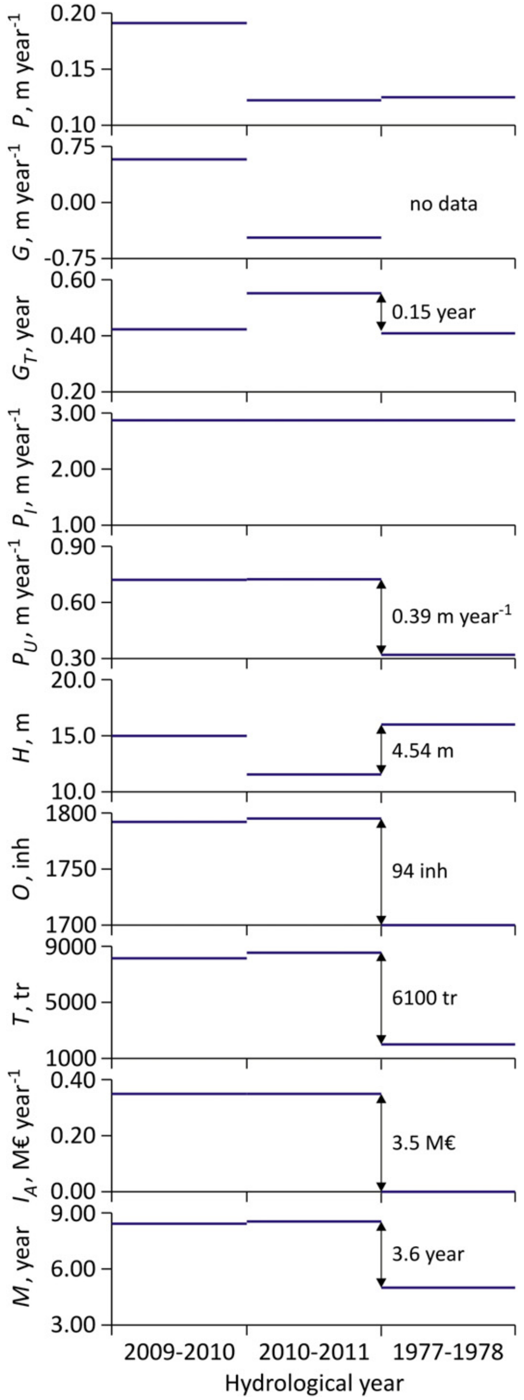

Fig. 10. Magnitude of some governing system variables after the hydrological–economic model operation in the Amtoudi area in the current stage of disturbance. In the natural regime, data available from the literature for the average hydrological year 1977–1978 are included for comparison; for the year 1977–1978, model parameters as in Table 2 were used for G_T (Eq. (5)) and M (Eq. (9)). Notation for variables as in Table 1.

inhabitant net increase (Fig. 7). In turn, tourism has become a new water-competing sector which has raised the water allocation from 25 L tr^{-1} day^{-1} in the 1970s for an average 1.5-day stay per tourist to the current 100 L tr^{-1} day^{-1} for an average 2.6-day stay per tourist (Martin, 2006; GSR, 2010, 2012, 2013). This means that annual water consumption has grown from 82 m^3 to 2160 m^3 in this period for more than a 6000-tourist net increase (Fig. 9). This rate is 0.05-fold the water consumption for population, i.e. the water provision for 20 new inhabitants. Thus, tourism does not pose a direct risk to the system sustainability. However, new habits for water consumption adopted by the population and settlers attracted by the tourism pull could upset the system sustainability. This indirect cause is identified as the main driving force in disturbing the natural regime of the Amtoudi alluvial aquifer (Fig. 2). Although agriculture is the largest consumer of water, the groundwater allotment for irrigation (P_I) is not initially identified as a source of unsustainability because the irrigated-crop surface is limited to 24.8 ha and the water allocated for irrigation has remained virtually constant around 4800 m^3 ha^{-1} year^{-1} for decades (UNDP, 1994; DRPE, 1998; Naser, 2006) (Fig. 10).

Because climate trends may intensify or diminish human-induced stress on the net groundwater balance (G), the response of groundwater saturated thickness (H) to net aquifer recharge (R) may be significant when climate cycles coincide, having positive (wet/cool) or negative (dry/warm) phases (Kovalevskii, 2007; Candela et al., 2012; Alcalá and Custodio, 2015). But R was programmed as a function of direct rainfall and runoff infiltration as well as the net lateral inflow; the former being a highly fluctuating resource that varies according to short-term climatic cycles (Fig. 4a), the latter being the largest, less fluctuating recharge component. Note that average groundwater-turnover time (G_T) was about 0.5 ± 0.1 years evaluated for this small alluvial aquifer (0.63 km^2). This figure may seem insufficient to guarantee a stable water supply if only direct rainfall and runoff infiltration contributes to R. However, G_T depends mainly on the net lateral inflow from Cambrian formations having higher G_T (Bouhlassa and Aiachi, 2002; Ettayfi et al., 2012), thus attenuating water scarcity in the current stage of disturbance.

Regarding the relevance of net lateral inflow on the system functioning, in natural regime (Fig. 2a), inflow and outflow phases occur in accordance with negative and positive phases of climate cycles, as reported by Naser (2006) and Ettayfi et al. (2012). In the current stage of disturbance (Fig. 2b), a forced positive inflow-to-outflow ratio is deduced from $G < 0$ in average year 2010–2011 (Fig. 10) for an R-to-P ratio around 0.09. It is expected that positive inflow-to-outflow ratio increases in recurrent dry spells extending over 3 or 4 years in the northern Sahara (Esper et al., 2007) (Fig. 4b). How long the current positive inflow-to-outflow ratio will remain until H and $P_I + P_U$ would reach an equilibrium over the long term may be critical for the environment, economy, and society. Unfortunately, there are no historical records of H and discharge flow from Cambrian formations to clearly define unsustainability.

6. Discussion

6.1. Sustainability of the Amtoudi Oasis system

Sustainability of a natural, groundwater-dependent system can be interpreted as the combination of sustaining environment, economy, and society (Loucks and Gladwell, 1999; Custodio, 2002). However, three questions arise: (1) how can groundwater resources be conceptualized and evaluated? (2) What are the challenges associated with sustainable development in each water-competing sector? and (3) What areas of water management can be improved?

Sustainable groundwater use means that groundwater saturated thickness (H) and groundwater allotments for irrigation (P_I) and urban supply (P_U) would reach an equilibrium over the long term if all the exogenous variables were held constant over time. However, it is not easy to make a judicious definition of this equilibrium in remote, sparse-data areas because: (1) the resource is hidden underground; (2) renewal rates (net aquifer recharge, R) are partially dependent on aquifer storage induced by global climate and aquifer hydraulics (Custodio, 2002); and (3) P_I and P_U depend on new opportunity costs such as tourism, changing, unreported social habits, and the ability to monitor the governing system variables during short monitoring periods under disturbance. The definition of these quantitative and qualitative feedbacks may involve an unnoticed uncertainty affecting the model results. To corroborate complex relationships, long data series are desirable (Ibáñez et al., 2008).

In the Amtoudi area, the behavior of governing system variables confirms that programmed cause–effect feedbacks capture the features of the system functioning and identify the causes for groundwater degradation induced by: (1) the population increase through the effect of new opportunity costs; (2) the greater water-consumption rates induced by tourism; and (3) the capital inflow into the area, dissuading inhabitants from emigrating (Fig. 10). In fact, public investment favoring new opportunity costs is found to be a main driving force increasing the delay time of emigration (M) in southern Morocco in recent decades (RGPH, 2004), and thus M is positively related to tourism and negatively related to groundwater saturated thickness (H) (Fig. 10). Consequently, P_U doubled while H decreased accordingly, as deduced when data for similar average hydrological years 1977–1978 and 2010–2011 are compared (Fig. 10). Despite this favorable conceptualization, a question arises: can sustaining environment, economy, and society be compatible in the current stage of disturbance? Certainly, mitigation measures seem necessary to restore H, as discussed below.

6.2. Some measures to mitigate groundwater degradation

The socialization of the hydrological–economic model with decision-makers and stakeholders is a desirable framework to design sustainable mitigation measures. In this theoretical context, mitigation measures begin with the study of primary sustainable water-management objectives by sectors, as well as the main challenges and potential solutions for groundwater use diagnosed according to financial capability and technical feasibility to undertake the measures (Russo et al., 2014) in this developing dryland context. In the urban sector, including tourism, equitable delivery and system flexibility are objectives that have been accomplished; the challenge comes with wastewater management while the solution may involve low-technology capture, treatment, and reuse of wastewater. In the agriculture sector, food security is an objective that has been accomplished; the challenge deals with low-irrigation-system efficiency while solutions concern crop-water productivity optimisation and supplemental irrigation water through basic technology. In the ecosystem sector, official protection of ecosystem services promoted by UNESCO is an objective that has been accomplished (MADRPM, 2008); the challenge is low water-use efficiency while the solution is related to active communication of ecosystem service value.

The hydrological–economic model was not initially intended to transfer results to decision-makers and stakeholders because the current low financial capability and technical feasibility in the Guelmim region, as well as in other regions of the northern Sahara, prevent the implementation of such action. Despite this constraint, a combination of public and private technical initiatives for supplemental water resources is tentatively proposed in Amtoudi Oasis. Note that the public annual 0.325 M€ funded by State agencies and UNESCO for oasis preservation and restoration in southern Morocco (MADRPM, 2008; OBG, 2011, 2012) were used mainly for environmental education programmes without specific technical actions for groundwater protection and recovery of degraded ecosystems.

Wastewater reuse is a plausible public initiative in water-stressed drylands (Kivaisi, 2001). In the Amtoudi area, urban wastewater may be about 0.3 P_U, i.e. about 9800 m^3 per year, although explicit data could not be gathered during the field survey. A pipeline under planning during the field survey was intended to manage wastewater. Low-technology systems including constructed ponds or layering with indigenous rock materials (Rahman et al., 2005; Angin, 2007; and references therein) can be effective to treat and purify low-mineralized wastewater upstream to reuse for irrigation downstream, both directly through the existing '*khettara*' network (Lightfoot, 1996) or by artificial infiltration into the alluvial aquifer (Tien-Chang et al., 1992; Ouelhazi et al., 2014; and references therein). Assuming that 50% of wastewater could be reused and the efficiency of ponds for artificial infiltration of tertiary-treated wastewater may be around 0.5, the annual water surplus could be around 2450 m^3, i.e. 0.02-, 0.07-, and 1.6-fold the annual water allocation for irrigation, urban supply, and tourism, respectively.

Storm-water harvesting in small catchments contributing to the Amtoudi Oasis is another public (or communal) initiative that could be promoted simultaneously (Fleskens et al., 2005; Frot et al., 2008; and references therein). In the Wadi des Argan basin, experimental threshold for runoff generation of 13.1 mm of 24-h P (Fig. 6) points out potentiality for storm-water harvesting. Taking the following design data into account: (1) 24-h rainfall records for wet 2009–2010, average 2010–2011, and dry 2012–2013 hydrological years, representative of percentile 0.8, average, and percentile 0.2 of yearly precipitation time series, respectively (Fig. 4a); (2) catchment surface from 1 km^2 to 10 km^2; and (3) efficiency of the harvesting system in the 0.4–0.6 range depending on maintenance, distribution losses, and heterogeneity of the bedrock permeability (Frot et al., 2008), annual storm-water harvested could range from 50,000 m^3 in wetter years under high efficiency to negligible values in driest years under low efficiency (Fig. 11).

Regarding the irrigation system, the *khettara* network was historically operated and efficiently maintained by the commune. The emergence of private initiatives to use pumping wells for irrigation in the 1990s has led to a gradual reduction in the irrigation-system maintenance practiced by farmers. Consequently, evaporation losses of interflow runoff collected by the *khettara* network have increased, as reported by the FAO (2008) in similar oases in the northern Sahara. Basic technical actions to recover the active maintenance of the *khettara* network again could be promoted by the commune. These actions could

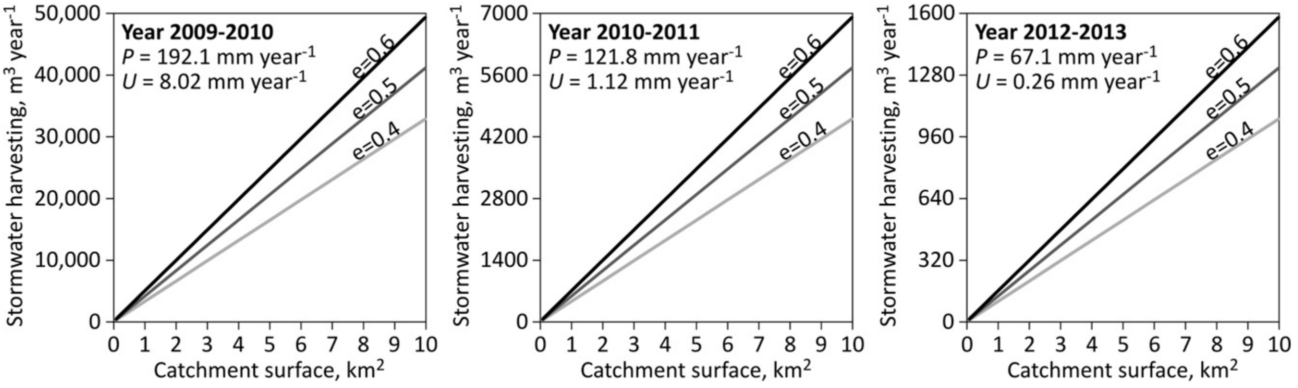

Fig. 11. Parameterization of potential storm-water harvesting in 1–10 km^2 catchments contributing to the Amtoudi Oasis for selected wet 2009–2010, average 2010–2011, and dry 2012–2013 hydrological years, representative of 0.8 percentile, average, and 0.2 percentile of yearly precipitation (P) time series, respectively (Fig. 4a). Efficiency (e) from 0.4 to 0.6 (dimensionless) after Frot et al. (2008), yearly P and surface runoff (U), and experimental threshold for runoff generation of 13.1 mm of 24-h P (Fig. 6a) were design values used.

increase the current irrigation-system efficiency of 0.6 (Table 2) to around 0.7, providing a water surplus of about 11,900 m^3 per year. Note that low water-use efficiency is related to the scarce communication of ecosystem service value to stakeholders.

The combination of the above-described low-technology actions is proposed to mitigate the groundwater degradation. Despite that annual supplemental water is tentatively estimated to be in the 20,000–50,000 m^3 range, i.e. 0.1- to 0.2-fold the imbalance estimated in the average year 2010–2011, its efficient use may contribute to better system functioning, especially in recurring dry spells, as well as for reducing pumping costs for agriculture and urban supply. This is a primary goal to stabilize ecological and economic feedback loops over the long term (Fig. 3) of degraded natural systems in drylands.

7. Conclusions

Oases are fragile natural systems. Thus, strategies for sustainable tourism involve ascertaining the feedbacks determining groundwater dynamics in order to identify causes for groundwater degradation reported in most aquifers forming irrigated date-palm oases. This is the case of the Amtoudi Oasis in southern Morocco in the northern Sahara. This area was chosen as key case to introduce a hydrological–economic model to describe the dynamics of groundwater-dependent economics in sparse-data drylands having water-competing sectors. System Dynamics modeling causal diagrams were used to program basic formulations. The model is intended to provide the basis for understanding groundwater degradation as a prerequisite to enable sustainable solutions. Long-term (steady) and short-term (transient) evaluations can be performed, depending on the time-series coverage.

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. Available short-term information allowed a transient hydrological evaluation while the economic one is tentatively given due to the limited coverage of data.

The international tourism that arose in the 1990s is identified as the main driving force for improving local economy and thereby reducing emigration and instilling new social habits in the population, in particular concerning water consumption and services. Consequently, the urban-water allocation (P_U) was doubled for less than a 100-inhabitant net increase over recent decades while the groundwater saturated thickness (H) decreased accordingly. Note that the direct influence of tourism on the net groundwater balance (G) is low. Agriculture, the largest consumer of water, does not provoke unsustainability because the water allocation for irrigation (P_I) has remained virtually constant for decades. However, low efficiency of communal irrigation system may make the current urban-water allocation unsustainable.

Despite that the 2-year monitoring period under a disturbed regime is not sufficient to draw long-term conclusions, groundwater imbalance is shown by net aquifer recharge (R) less than $P_I + P_U$ ($G < 0$) in the average year 2010–2011. The net lateral inflow from Cambrian formations having higher average groundwater turnover time than alluvial aquifer is identified as the largest recharge component. R is expected much less than $P_I + P_U$ in recurrent dry spells, thus increasing the current positive inflow-to-outflow ratio. This situation could not recover in subsequent wetter periods, thus inducing a new equilibrium of H and $P_I + P_U$ in the long term. However, this is not a sufficient condition to assert irreversible groundwater degradation, unless the aquifer is already threatened to be exhausted in the near future.

The combination of low-technology capture and treatment of wastewater upstream to reuse for irrigation downstream, storm-water harvesting in small catchments for irrigation, and private (or communal) active maintenance of the irrigation system to improve its efficiency is tentatively proposed to mitigate groundwater degradation in Amtoudi Oasis. Environmental, economic, and social sustainability of these scattered inhabited areas is essential to buffer the advance of the Sahara Desert and to promote durable policies meant to reduce emigration in similar developing dryland contexts.

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