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SPECIAL ISSUE: ADVANCING SOCIO-HYDROLOGY

Modelling the mutual interactions between hydrology, society and water supply systems

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ABSTRACT

We developed a simple conceptual socio-hydrological model to explore the mutual interactions between water management systems and society. We examined the feedback among climate, population, wealth and water availability and capital investment. Given the focus on the interplay among these multiple variables, some simple schemes were designated in order to simulate rainfall inputs, surface and aquifer hydrology and to mimic economic and social mechanisms. The proposed model is applied to synthetic cases in order to explore the dynamics of the water demand, water availability and water deficit that in turn influence the capital invested in water infrastructures. The results show how societal wealth, the number of people living in a given area and the local climate can determine societal efforts in exploiting water resources, the frequency of water deficits and the amount of money invested overall in infrastructures.

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1 Introduction

Water resource management involves public investments with long-ranging impacts that cannot be addressed by traditional economic approaches. Traditional planning tools fare poorly over 30- to 50-year time horizons because the human–water systems are rapidly changing (Sivapalan *et al.* 2012). Mathematical models often treat separately land use, economic patterns and governance systems over a long planning horizon, which results in inaccurate projections leading to sub-optimal or paradoxical outcomes or crises (Srinivasan 2015). As such, most models fail to account for adaptive responses by humans, which in turn influence water resource availability, resulting in the coevolution of the human–water system (Srinivasan 2015).

Socio-hydrological theories and frameworks have been developed to explain the phenomena generated by the interplay of water and society (Sivapalan *et al.* 2012) in order to support sustainable water resource use under changing climatic and environmental conditions (Ceola *et al.* 2016). However, a particular challenge in incorporating such feedback is the simulation of possible social, political and technological future scenarios that could alter water demand, allocation, and use (Srinivasan 2015, Di Baldassarre *et al.* 2016). In a world facing human population growth and global change, the mere understanding of the natural processes governing the water cycle does not guarantee an efficient use of water resources, but it is essential to know the cultural and socio-economic reasons influencing water management systems (Friesen *et al.* 2017) . Nowadays, governance of hydrosystems requires a new scientific approach, which is able to account not only for the state of the art in underlying hydrological processes in natural systems but also for past and future effects of human intervention (Pataki *et al.* 2011, Di Baldassarre *et al.* 2013, Gober and Wheater 2014).

Hence, advances are needed in order to understand how to combine social and hydrological processes, and the way in which they interact, in our studies and models. Incorporating human behavioural responses to water scarcity and hydrologic extremes in mathematical models constitutes one of the main challenges in socio-hydrology (Troy *et al.* 2015). In the context of long-term projections, the goal of socio-hydrological models is not to present a snapshot of the system at a future scenario, but rather a projection of alternative, plausible scenarios of co-evolving trajectories of the system (Srinivasan *et al.* 2016).

Several conceptual socio-hydrology models, consisting of coupled, nonlinear differential equations that link hydrology and social dynamics, have been developed in the past years. A review of socio-hydrological models is presented by Blair and Buytaert (2016). It is possible to distinguish between models (i) trying to describe the interaction and feedback between society and flood events and (ii) depicting the coupled dynamics of society and water infrastructures. The works of Di Baldassarre *et al.* (2013) and Gober and Wheater (2014) belong to the first case. Indeed, they explored the interactions between human settlements and flooding. With regard to the second case, Van Emmerik *et al.* (2014) and Elshafei *et al.* (2014) developed conceptual models of the dynamics of society and hydrology in river basins with significant irrigation. Pataki *et al.* (2011) developed a framework to integrate urban hydrologic budgets, decision-making, governance, and socio-economic factors in a study that combines social and biophysical dimensions of the urban water system. They implemented the model on western US cities, which have been facing critical issues in water supply and demand, and which can benefit from a more comprehensive understanding of the factors that determine water consumption, distribution and availability. Liu *et al.* (2015) developed a simplified conceptual socio-hydrological model based on four subsystems to represent the

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dynamics of the hydrological, the social, the economic, and the ecological sub-systems. The results show a costly pendulum swing between a balanced distribution of socio-economic and natural ecological resources among the upper and lower reaches and a highly skewed distribution towards the upper reach. Srinivasan (2015) developed a model that simulates the feedback between the human, engineered and hydrological systems over a 40-year period in India. The study demonstrated that urban household water security goes beyond the piped water supply. When the piped supply fails, users turn to their own wells. If the wells dry up, consumers purchase expensive tanker water or curtail water use and thus become water insecure. Kuil *et al.* (2016) conceptualized the interactions between an agricultural society and its environment using a socio-hydrological model which was applied to the case of the ancient Maya. The hypothesis that modest drought periods played a major role in the society's collapse was explored. Simulating plausible feedback between water and society, they showed that the construction of reservoirs results in lower impacts from meteorological drought; at the same time, if stored water becomes scarce, drought impact may be more severe and the population drop may be larger.

The models described above (case ii) were developed for specific case studies; in fact, cited literature refers to a single historical situation (i.e. the Maya water-induced decline) or a specific geographic area (i.e. US or India) with focus on a water system (complex, with dams and pipe systems or basic, with wells). Here, we aim to contribute to this rich body of literature and complement these modelling efforts by proposing a general model to simulate the interactions and feedback between water management systems and social processes. Indeed, the proposed model can be employed as a useful tool to address some of the numerous and still unresolved scientific questions related to such interactions, even in the simple case of a closed system in stationary conditions. As an example of such applications, in this paper we show how the proposed model contributes to providing an answer and a quantitative evaluation to two unresolved questions. (a) The first question that we address is the evaluation of the fraction of exploited water resources. Given a certain climate, a certain population and its wealth (defined as the average personal income), our aim is to quantify the amount of water that is necessary to withdraw from natural resources and to evaluate whether such an amount is sufficient to support water demand or, conversely, will lead to intolerable water deficit. (b) The second scientific question behind this work is about the amount and timing of capital investment in water infrastructures. Namely, our aim is to explore basic social mechanisms that trigger political-economic decisions oriented to building or maintaining water infrastructures.

In order to address these questions, we implemented the proposed conceptual model to explore the dynamics of water demand, water availability and water deficit as a function of a society's wealth, the population dimension and the local climate.

2 Socio-hydrological modelling

The proposed model aims to reproduce coupled dynamics of hydrological bodies, water availability, water supply systems, water demands, deficits and their feedback that could exert on society in terms of capital invested in water infrastructure. The main idea of the model is that water management systems rely on both capital invested in their construction and maintenance, as well as on stochastic climatic forcing. While the latter unavoidably depends on the specific location (i.e., rainfall and potential evapotranspiration dynamics), the former is a complex product of societal history, political decisions, and economic conditions. Some of the secondary feedback, such as the gross income and population variations due to water deficit or abundance, are neglected. These two assumptions entail independent dynamics of population P and average salary *SAL* over time, here assumed as constant.

2.1 Socio-hydrological model framework

The conceptual scheme of the model is depicted in Fig. 1, whose centre is the water management system, characterized by an amount of capital, CAP, invested in water infrastructures. This core element has interactions with water bodies, which in turn are stochastically forced by rainfall inputs, and with the society living in a specific area. The two main descriptors determining the water demand from society to the water supply system are the population P and the average salary *SAL* [€/year person]. The first statement is trivial, since the higher the population, the greater the water demand, while the interlink between water demand and the average income is well documented in socio-economic sciences (Arbués *et al.* 2003).

The two-way interactions between society and the water management system are defined by the water demand and the

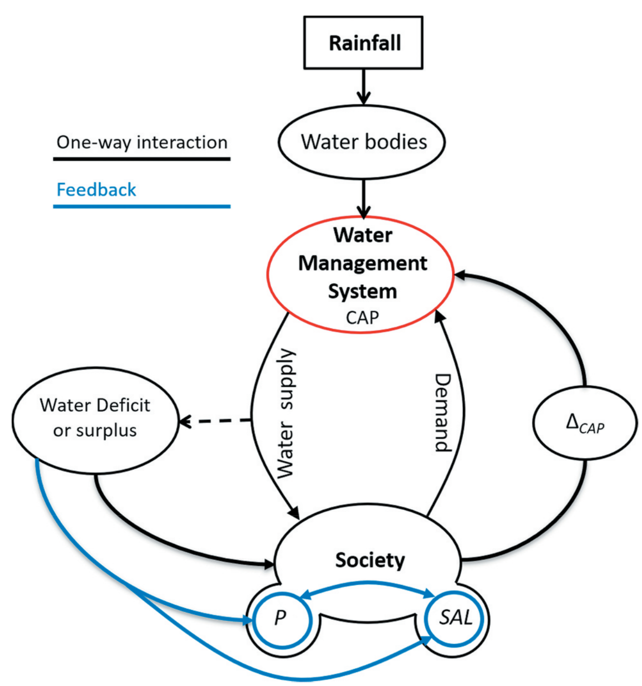

Figure 1. Conceptual scheme of the interactions between climate, water bodies and society (one-way in black, feedback in blue in the online version). The water management system (red circle in the online version), by storing a volume of water, is able to satisfy the water demand arising from the society (characterized by population *P* and average salary *SAL*). If the water supply is less than demand (dashed black line), water deficit impacts on society, triggering a decision (capital investment) to improve the water management system.

water supply; if there is no balance, and thus some water deficit arises, a societal reaction could trigger a capital injection into the water supply system. Figure 1 depicts this simplified scheme: the water supply system influences the society by the water deficit, while the society could shape the water supply system by capital investments, which in turn are commensurate with population magnitude and wealth. Of course, there are also external drivers shaping the water supply system: climate, in terms of average rainfall inputs, its seasonality, and hydrological response have tremendous influence in determining the ease of collecting water for human purposes.

Considering that water resource management is usually carried out at monthly time scale, the latter was chosen as the temporal scale for simulating water demand and supply, while the climatic forcing is simulated at the daily scale to provide a more realistic representation of the rainfall process. With regard to the spatial scale, following the evidence that humans have exploited water resources close or proximal to places where they live, and that, vice versa, civilizations have developed close to water bodies (Mård *et al.* 2018), the spatial scale chosen for the socio-hydrological model is the mesoscale. This working hypothesis is even supported by the evidence that the earliest civilizations thrived due to the availability of rivers such as Mesopotamian cultures with the Euphrates River and Tigris River, Egyptians with the Nile River, Indians with the Indus River and Chinese with the Huang River and Yangtze River (Behringer 2010, Diamond 1998).

2.2 Climatic forcings

Climatic forcings were modelled at daily scale, following Viola *et al.* (2017), as an external independent input to the social-water system. We focused our attention on the main climatic variable influencing water dynamics, that is the rainfall R, whose occurrence is idealized as a series of events at a daily time scale, arising from a non-stationary and cyclic Poisson point process with parameter $1/\lambda(i)$ *(rate of the Poisson process occurrences, [1/days]) and corresponding interarrival time* $\lambda(i)$ [days], here modelled through a cyclic sinusoidal function of the i-th day of the year ($i = 1, \ldots, 365$), with a 1-year period, according to the following equation:

$$\lambda(i) = \bar{\lambda}\left[1 + \delta_\lambda sin\left(\frac{2\pi i}{365} + \omega_\lambda\right)\right] \quad (1)$$

where $\bar{\lambda}$ is the average interarrival time [days] between rainfall events, the standardized semi-amplitude δ_λ is the ratio between the semi-amplitude of the annual harmonics of $\lambda(i)$ and the annual average (i.e. $\bar{\lambda}$), while ω_λ is the initial phase.

Rainfall rates during each event (rainy days) are assumed to be a random process described by an exponential distribution, with mean $\alpha(i)$ [mm/day] varying with the i-th day of the year as follows:

$$\alpha(i) = \bar{\alpha}\left[1 + \delta_\alpha sin\left(\frac{2\pi i}{365} + \omega_\alpha\right)\right] \quad (2)$$

where $\bar{\alpha}$ is the average amount of rainfall [mm/day], the standardized semi-amplitude δ_α is the ratio of the semi-amplitude of the annual harmonics of $\alpha(i)$ to the annual average (i.e. $\bar{\alpha}$), and ω_α is the initial phase. Notwithstanding its simplicity, the model has been proved to be able to reproduce observed rainfall variability in time.

Except for the rainfall generation process, which has been simulated at daily scale according to previous parametrization, the proposed socio-hydrological model is run at monthly time scale, indexing by t the t-th month from the beginning of the simulation. Thus, daily rainfall time series have also been then aggregated at monthly time scale, so that monthly rainfall $R(t)$ [mm] is the main driver of hydrological processes, which is supposed to have direct control of water availability in rivers and lakes. The amount of water that could be directly withdrawn from water sources by a population P living within a basin of area A [km^2] is defined by $W_{wb}(t)$ [m^3] as the sum of a surface component, which is a linear function of the monthly rainfall and a groundwater storage component $GR(t)$ [m^3], as follows:

$$W_{wb}(t) = \phi R(t)A + GR(t) \quad (3)$$

The runoff is assumed proportional to rainfall through the ϕ coefficient $[\frac{m^3}{mm\ Km^2}]$, thus assuming a strong simplification of the hydrological transformation from rainfall to runoff. Indeed, this process has complex nonlinear dynamics depending on climate, seasonality, soil characteristics, land cover, vegetation presence and so on; in order to focus better on result interpretation, without additional sources of uncertainties, we decided to use just one parameter to describe rainfall to runoff process. The groundwater dynamic has been modelled according to the following scheme: the water table is considered free to move from a bedrock which is distant D [m] from the ground and the ground itself; the aquifer is fed by monthly pulses $\Delta^+ GR(t) = \psi R(t)A$, where ψ coefficient $[\frac{m^3}{mm\ Km^2}]$ determines the fraction of rainfall water that reaches the groundwater. In general, this contribution is influenced by soil moisture and by the presence of macropores or soil fractures; here, again with the aim of reducing the model uncertainties, we focus only on the direct link between rain and volume increase. Finally, in the absence of inputs, the groundwater level decays with an exponential law with a constant k_{dec} [1/month].

The Equation (3) describes the availability of water resources as they are found in nature; there is a flowing component (surface runoff) and a groundwater component (which could be, indeed, very deep). If water management systems rely only on $W_{wb}(t)$ the stochastic rainfall variability directly influences water availability at the same temporal scale. This is the case for poor countries where rainfed agriculture productivity, for instance, is dramatically linked to climatic variability and a prolonged drought may cause water shortage, poor yields and economic crisis.

2.3 Water management system

Exploitation of water resources by human society evolved from a condition strictly driven by natural climate stochasticity (e.g. Equation 3) through artificial storage systems with increasing complexity in infrastructures and technologies. This emancipation was possible where economic resources were available and properly invested after right political decisions. Capital investments can be addressed to exploit conventional (i.e. by storing water available from surface water bodies and pumping water from groundwater) or non-conventional resources (e.g. by producing fresh water through desalination processes). In this work, we focus only on the exploitation of conventional water resources, describing the level of water infrastructure development as proportional to the current value of capital invested $CAP(t)$, which accounts also for obsolescence of the water system as described in the following. The water system allows an amount of water $W_{sto}(t)[\mathrm{m}^3]$ to be stored that will be used to meet the water demand. The monthly water input Δ^+ to the water system arising from natural bodies can be expressed in symbolic terms as follows:

$$\Delta^+ W_{sto}(t) = k_{exp}(t) \cdot W_{wb}(t) \tag{4}$$

where k_{exp} [−] is the fraction of exploited water resources, which is assumed to be the same for surface and groundwater. This parameter can vary between zero, when there are almost no infrastructures to pump or store water to one when all the water is used. The higher k_{exp} is, the safer and more redundant the water supply system is; this is because climatic fluctuations are equalized by the presence of reservoirs that store water in wet periods and make it available when it is effectively needed. At the same time, if k_{exp} increases, water supply system costs increase too because of the increased storage volumes W_{sto_max} and the need for interconnections between storages. To account for possible economic development, also k_{exp} is allowed to slowly vary as a function of t. These concepts are expressed as:

$$\begin{cases} k_{exp}(t) = \frac{CAP(t)}{k_{€}} \\ W_{sto\_max}(t) = k_{exp}(t) \cdot 12 \cdot \bar{W}_{dem} \end{cases} \tag{5}$$

where $k_{€}$ [€] is the cost for the full exploitation of natural resources within the considered area A; it is also worth noting that $k_{€}$ is a function of the water table depth D, because the deeper the water table, the higher the cost for pumping and well construction. $\bar{W}_{dem}$ is the average monthly water demand, under the hypothesis that the maximum storable volume is equal to the yearly water demand.

The complex dynamics of a water system are governed mainly by water availability and demand. Both these actors are mutually influenced and inter-dependent. The connection is constituted by personal wealth, here represented as the annual average salary, *SAL*, which on the one hand influences the invested capital on water infrastructures, as will be explained later, and on the other hand, is related to average water demand, $\bar{W}_{dem}$, for instance with a linear function:

$$\bar{W}_{dem} = P\, k_{sal} \frac{SAL}{12} \tag{6}$$

where k_{sal} [m^3/€] defines the monthly water demand per unit of salary. It is worth noting that water demand often has a seasonal variability. In order to include this feature, we modelled the water demand as a harmonic, out of phase with precipitation, so that:

$$\mathrm{W_{dem}}(t) = \bar{\mathrm{W}}_{\mathrm{dem}} \left[1 + \delta_{\mathrm{dem}} \sin\left(\frac{2\pi t}{12} + \omega_{\mathrm{dem}}\right) + \varepsilon(\mathrm{t})\right] \tag{7}$$

where δ_{dem} is the standardized water demand semi-amplitude, computed as the ratio of the semi-amplitudes of the annual harmonics of $\mathrm{W_{dem}}(t)$ to the annual average (i.e. $\bar{\mathrm{W}}_{\mathrm{dem}}$), ω_{dem} is the initial phase and $\varepsilon(t)$ is a zero-mean random noise.

2.4 Water deficit

Once the water demand and its availability is defined, the water deficit W_{def} is consequently computed as the difference between the first two:

$$\begin{cases} W_{def}(t) = W_{dem}(t) - W_{sto}(t) & if\ W_{dem}(t) > W_{sto}(t) \\ W_{def}(t) = 0 & if\ W_{dem}(t) < W_{sto}(t) \end{cases} \tag{8}$$

which will be positive when water demand exceeds water availability and zero in the opposite case. This stochastic variable has a tremendous importance in shaping societal decisions and dynamics.

Water deficit occurrences have the power to frighten public opinion and trigger political decisions according to their severity, which is, of course, related to the fraction of unsatisfied water demand. Here, we suppose the existence of a psychological societal threshold:

$$Psy(t) = k_{psy} \cdot W_{dem}(t) \tag{9}$$

which triggers decisions in terms of capital inputs into the water system. The parameter k_{psy} depends on the economic well-being, namely on the personal average income. Thus, the higher the *SAL*, the lower k_{psy} is because of the lesser propension to accept water supply failures. In the model, we calculated k_{psy} as a decreasing linear function of *SAL*, so that it is zero when *SAL* is equal to 55 000€ (average annual salary in the USA), while it is one when *SAL* is 5000€ (average annual salary in Honduras).

2.5 Immobilized capital

When severe water deficit occurs, exceeding the psychological threshold (i.e., $W_{def}(t) > Psy(t)$), money is supposed to be instantaneously invested in water infrastructure and/or maintenance, thus increasing the immobilized capital of a fixed amount Δ_{CAP}:

$$\Delta_{CAP}(t) = k_{CAP} \cdot SAL \cdot P \tag{10}$$

The invested amount of money is supposed to be directly dependent on the average personal income through a constant k_{CAP} [€ (invested)/€/year] that expresses the fraction of the salary diverted in taxes for water infrastructures amelioration. Moreover, in normal conditions, the water system undergoes exponential obsolescence, so that:

$$CAP(t) = (1 - k_{obs})CAP(t-1) + \Delta_{CAP}(t) \tag{11}$$

k_{obs} being the coefficient expressing the capital reduction in a unit of time due to the obsolescence of the water systems.

3 Model application

3.1 Constant population, salary, and annual rainfall

Here we define and analyse a synthetic experiment, with the aim of illustrating model outcomes and discuss basic interrelations among climate, water supply system and society. We refer to an area A of 25,000 Km^2.

As a demonstration of model capability and in order to illustrate a typical condition, Fig. 2 shows synthetic time series of modelled variables, referring to a population of 5 million with an average annual salary $SAL = 20{,}000€$ and a $k_{psy} = 0.5$. The average climatic conditions are constrained by $\bar{\lambda} = 5$ and $\bar{\alpha} = 8$, while all the other climatic parameters are listed in Table 1, thus mean annual rainfall is approximately 600 mm/year, which is a typical value in Mediterranean countries. The stochastic rainfall (not shown) creates runoff and feeds the groundwater; part of this water is temporarily stored within the system. The fraction of exploited water resources is shown in Fig. 2(d), while the stored volume is depicted in red in Fig. 2(a). When available water overpasses the storable volume (blue line in Fig. 2(a)), overflow events occur (Fig. 2(b)); the same panel of Fig. 2(a) shows the water demand, which has a seasonal variability and a degree of stochasticity, but its long-term mean is constant, being dependent from population and salary, both constant. The comparison between water demand and the water supplied is shown in Fig. 2(c): whenever the water demand meets water availability, the water supply line (black line) coincides with the demand line (blue line). On the other hand, when the demand is higher, water deficits occur: if the water deficit exceeds the psychological threshold, capital is invested into the water system. As Fig. 2(e) illustrates, not all the water deficit occurrences generate capital jumps. It is also worth noting that whenever injections of capital occur, even the percentage of exploited water resources increases, as well as the storable amount of water. The exponential decrease of the capital invested is supposed to be generated by the obsolescence of infrastructures, which have direct repercussions on the capability of the whole system in intercepting and storing natural resources. Another consideration in Fig. 2 is related to the frequency with which society intervenes in the water supply system. There is an initial period, when the population is settled in a certain area, with recurrent water deficits, continuous investments aimed at creating favourable conditions for water exploitation. As a result of complex dynamics involving climate, hydrology, water demand and political-economic-technical choices, a sort of equilibrium is reached after an initial transition

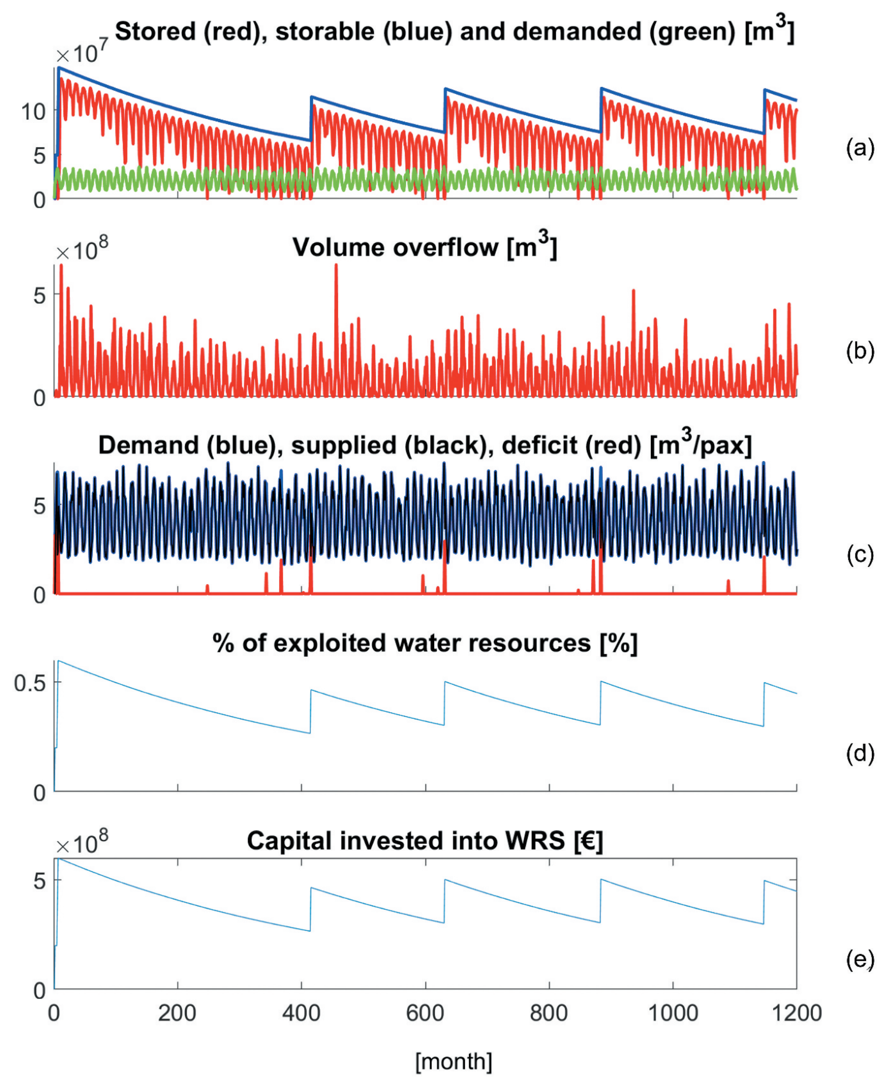

Figure 2. Model outputs in a reference condition described in Section 3.1 for a period of 100 years with monthly time scale. (a) stored and storable water within the management system and water demand from society; (b) occurrences and amounts of overflows; (c) occurrences and entities of water deficit compared with water demand and supply; (d) time series of the fraction of exploited water resources and (e) the consequent capital invested in water infrastructures. Colors refer to the online version.

Table 1. Model parameters and outputs.

Parameter or model symbol	Units	Brief description	Values[a]	Ranges[b]
A	[Km^2]	Basin area	25.000	
P	[pax]	Number of equivalent people living in the basin		2×10^6–6×10^6
SAL	[€/year]	Average annual salary		5.000–55.000
$\bar{\lambda}$	[days]	Average interarrival time between rainfall events	5	
δ_λ	[–]	Semi-amplitude of the annual harmonics of interarrival times	0	
ω_λ	[rad]	Initial phase	−π/2	
$\bar{\alpha}$	[mm/day]	Average amount of rainfall	8	
δ_α	[–]	Semi-amplitude of the annual harmonics of rainfall rates	0.9	
ω_α	[rad]	Initial phase	π/2	
ϕ	$[\frac{m^3}{mmKm^2}]$	Runoff coefficient (see Equation 3)	0.2×10^3	0.1×10^3–0.5×10^3
ψ	$[\frac{m^3}{mmKm^2}]$	Leakage coefficient	$0.1 \times \phi$; $\psi < (1 - \phi)$	0.1×10^2–0.5×10^2
k_{dec}	[1/month]	Groundwater exponential decay constant	10^{-2}	10^{-2}–10^{-3}
$k_€$	[€]	Cost for the full exploitation of natural resources	10^8	10^7–10^9
k_{sal}	[m^3/€]	Monthly water demand per unit of salary	0.0025	0.0001–0.5
δ_{dem}	[–]	Semi-amplitude of the annual harmonics of water demand	0.5	
ω_{dem}	[rad]	Initial phase of water demand	−π/2	
k_{psy}	[–]	Fraction of non-satisfied water demand triggering decisions [0–1]	*f(SAL)*	*f(SAL)*
k_{CAP}	[€/€]	Fraction of the salary for water infrastructures	1/500	0.0001–0.5
k_{obs}	[1/month]	Capital reduction in a unit of time due to the obsolescence	0.002	0.0001–0.5
$W_{wb}(t)$	[m^3/month]	Water in water bodies	Variable	
k_{exp}	[–]	Fraction of exploited water resources	0–1	
$W_{sto}(t)$	[m^3/month]	Water stored in water infrastructures	Variable	
$W_{dem}(t)$	[m^3/month]	Water demand	Variable	
$W_{def}(t)$	[m^3/month]	Water deficit	Variable	
$CAP(t)$	[€]	Capital invested in water infrastructures	$<k_€$	

[a]Refer to model application, paragraph 3.1 and Fig. 2.
[b]Refer to sensitivity analysis, paragraph 4 and Fig. 6.

period. This is of course a model interpretation of human settlement dynamics, neglecting population dynamics, under the hypothesis that only water deficits and population wealth drive the water supply system development. After the initial period, one could individuate the emergence of a stochastic process, namely the societal intervention on the water supply system by capital investments, which seems to have its mean interarrival time and mean value of course both depending on the frequency and the severity of water deficits occurrences.

3.2 Varying population, salary and annual rainfall

In order to go beyond the vision given by the reference case study, which is limited to a specific climatic-demographic-economical condition, we explore the influence of varying population, salary, and annual rainfall in determining the percentage of exploitation on natural resources, the invested capital in water infrastructures and the mutual feedback between society and the water supply system in terms of the frequency of deficit occurrences. To do that, we use massive numerical simulations, each of which explores a hypothetical condition characterized by a population P with a salary SAL, living in the same basin with area A (as in subsection 3.1) where the climate is defined by the long-term annual rainfall. The range of variability of population P is between 2 and 6×10^6, while SAL is allowed to change between 10 000 and 40 000€: they were chosen in order to explore the reasonable and documentable extent of population density and wealth. Climate forcings reproduce a typical Mediterranean transect, so that $\bar{\alpha}$ has been chosen between 5 and 18: consequently, annual rainfall could vary between 300 and 1300 mm per year. Each simulation involves a triple $(P, SAL, \bar{\alpha})$ randomly extracted from uniform independent distributions. Each of the 50 000 runs explores 1000 years, according to the model scheme described in Section 2.

The outcomes of the simulations are represented through 4D plot in Figs. 3–5, where the external conditions (Population, Salary and Annual rainfall) are plotted against long-term values of the main variables.

The influence of society and climate in determining the percentage of exploited water resources in a given area is illustrated in Fig. 3: this result allows the scientific question (a) mentioned in the introduction to be addressed. Namely, each point of the 3D space represents the long-term percentage of water resources exploited by a population P with an average salary SAL living in an area A characterized by a specific annual rainfall value. Some of the outcomes of this analysis were expected and their interpretation is straightforward, for example, the percentage of exploited water resources is: (i) increasing with the number of people living in an area and average salary, (ii) decreasing as the annual rainfall decreases. The highest water exploitation is obtained when considering a high number of people living in a dry area with a high personal income; costly technologies such as desalination and water reuse can be eventually implemented. Indeed, in order to meet the high water demand it is necessary to use almost all the available water. On the other hand, the lowest impact on water resources is from a low-income, low-density community living in a wet place. In this condition, in fact, because of the low water demand, even if the average salary is low, it is quite easy to set up a water supply system that is able to satisfy the water needs, exploiting just a small fraction of available resources.

A different point of view is offered by the analysis of two intimately linked variables, as the average allocated capital into the water supply system and the average stored volume within the system, shown in Fig. 4(a and b) respectively. These figures allow the scientific question (b) posed in the introduction to be addressed, regarding the amount of capital invested which in turn determines the average stored volume. The condition

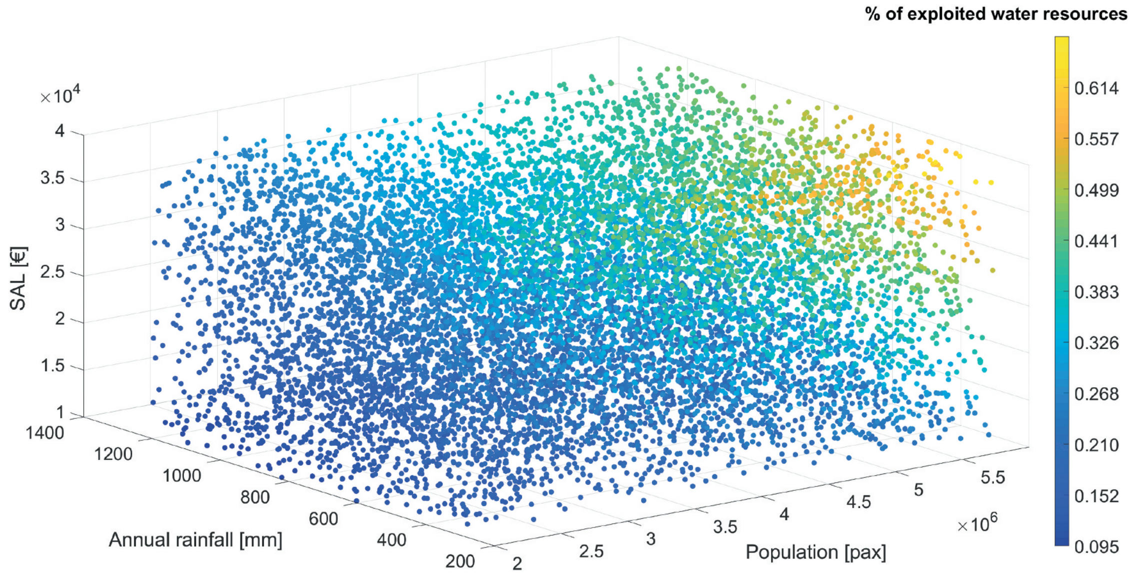

Figure 3. Influence of population, average annual income and climate in determining the percentage of exploited water resources.

characterized by the highest exploitation of water resources is the same that implies the maximum average stored water volume, while the lower exploitation gives also the lower average stored volume (see Fig. 4(b)). This is because water supply systems serving highly populated rich and dry areas have to modulate climate stochasticity and seasonality in order to meet the water demand, preventing frequent deficit events. This task is made possible by accumulating water in the wet seasons and releasing it whenever it is requested. Consequently, as a result of this high-volume storage, even the cost of such a system is high (Fig. 4(a)). On the other hand, the cost of water supply systems is low for poor, small communities living in wet areas due to the small amount of water that needs to be carried from season to season.

Finally, we analyse the occurrences of water deficit in the considered scenarios. This variable exerts a major control in determining the timing of capital investment, and thus studying its evolution provides key information to reply to scientific question (b) given in the introduction. Again, we plotted the mean frequency of water deficit against population, salary and annual rainfall in Fig. 5. Interestingly, the highest frequency is observed for low population, low income and low annual rainfall, while the safer condition has been obtained for highly populated rich and wet areas. This is counterintuitive, because one could expect less water deficit occurrences when less people live in a given area. In order to clarify this statement, we sliced the cube of Fig. 5 by considering fixed conditions of annual rainfall (800 mm) and average salary (20 000€/year): the representation of water deficit against population revealed that as population increases, the deficit occurrences decrease (see the inset of Fig. 5). This could be interpreted as one of the main benefits of living in large communities. At the same time, results (not shown) indicated that there is a limit for the maximum number of people living in a given area, because at a certain level, the frequency of deficit occurrences became intolerable (more than one occurrence per year). This limit is directly linked to the full exploitation of water resources and implicitly defines the carrying capacity of the environment.

4 Sensitivity analysis

The sensitivity analysis performed in this study aims to assess the influence of different model parameters on model output averaged over a long time. Namely, we investigated how the average stored volume $\langle W_{sto} \rangle$, the mean discharged volume $\langle W_{over} \rangle$, the average water demand $\langle W_{dem} \rangle$, the long-term percentage of exploited water resources $\langle k_{exp} \rangle$ and the average capital invested <CAP> are influenced by model parameter variations. We used a variance-based approach proposed by Van Emmerik *et al.* (2014) to evaluate the sensitivity of the parameters P, *SAL*, ϕ, k_{obs}, k_{sal}, k_{CAP}, and $k_{€}$. An ensemble of 5000 model runs is generated by uniformly perturbing one parameter at a time within a minimum and maximum value (indicated in Table 1) while the remaining parameters are kept unchanged. The rain input is generated by simulating 1000 years with constant values of the six parameters used in Equations (1) and (2) (central values of Table 1), in order to neglect the influence of climate in the sensitivity analysis. The variance of the cumulated time series of each ensemble member is calculated for each model parameter. The sensitivity index S of a given parameter *p* for a specific model output is calculated as:

$$S_p = \frac{\sigma_p^2}{\sum_{p=1}^{T} \sigma_p^2} \quad (12)$$

where T is the total number of model parameters, σ_p^2 is the variance of the specific model output ensemble corresponding to parameter *p*. Results of the sensitivity analysis are depicted in Fig. 6. In the abscissa model, parameters are indicated, while different coloured lines represent model outputs.

The monthly water demand per unit of salary k_{sal} determines water demand, as expected by Equation (6). Increasing the water demand, the capital invested CAP increases too, as the mean stored volume. This concept is correctly depicted in Fig. 6. The sensitivity analysis revealed that *SAL* is one of the most important parameters, largely influencing the amount of

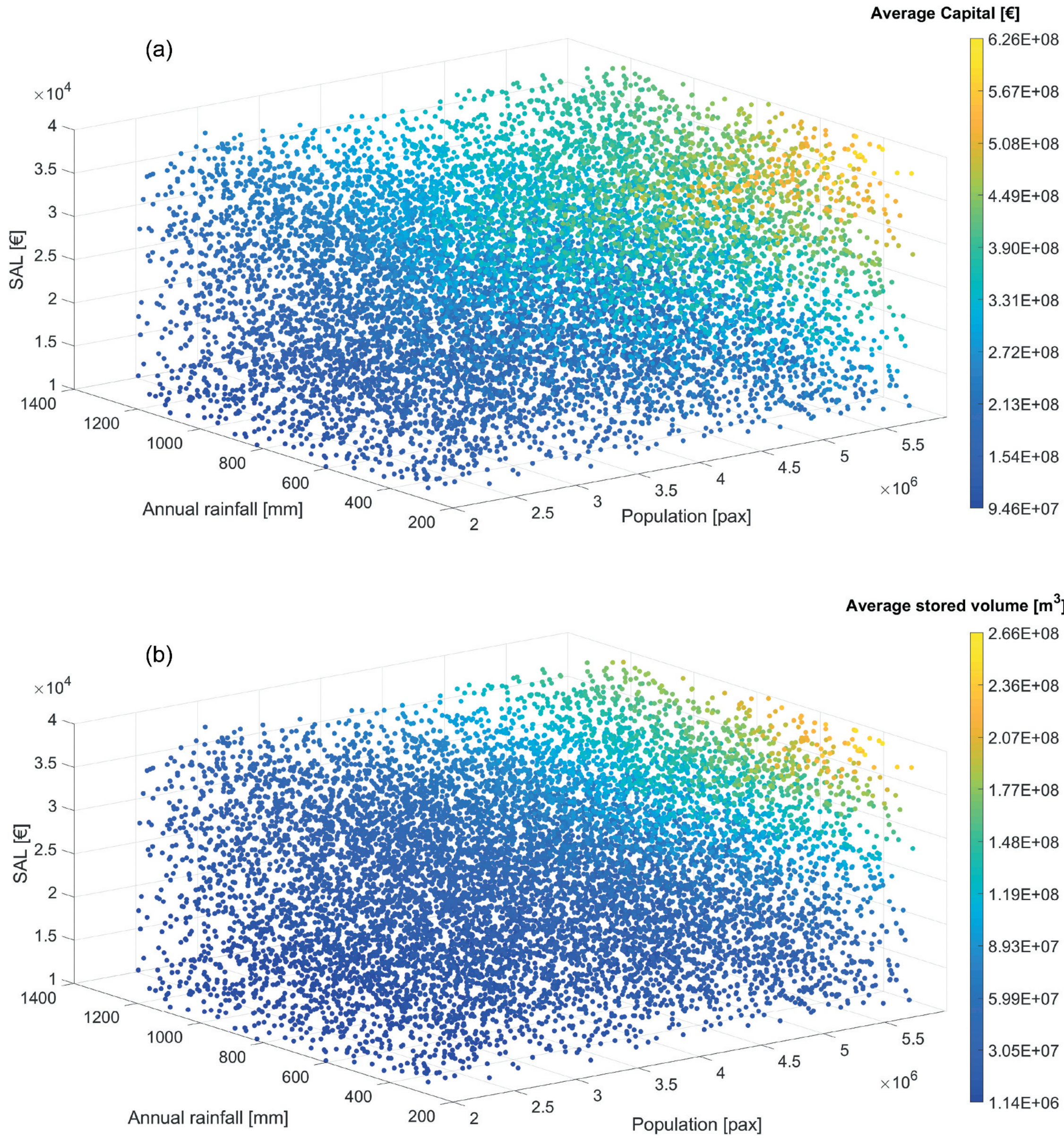

Figure 4. Influence of population, average annual income and climate and their relationship with the average capital invested (a) and water stored (b).

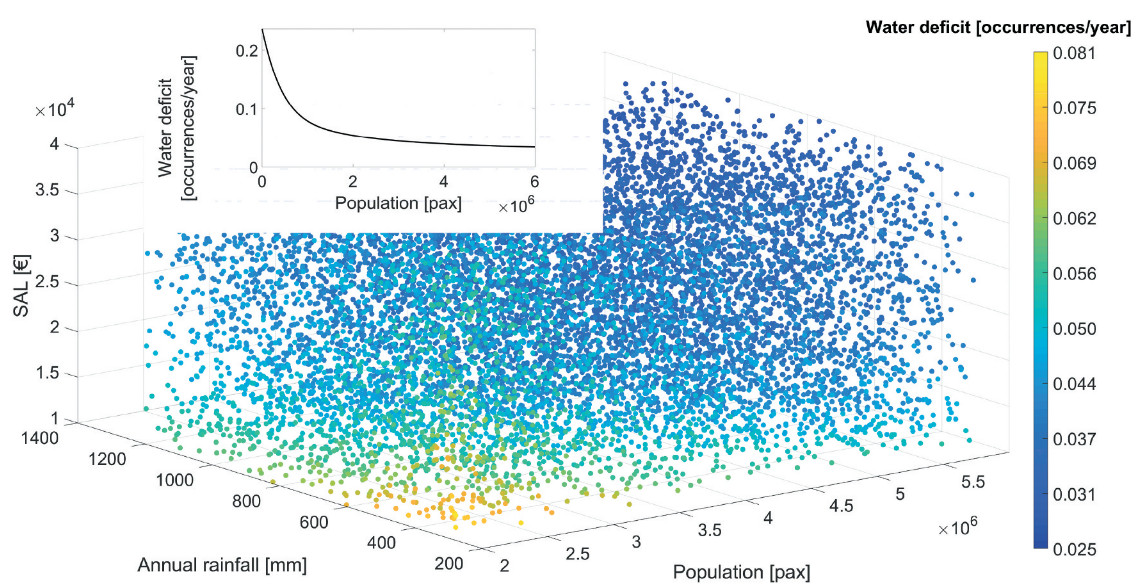

Figure 5. Average number of deficit occurrences as a function of population, average annual income and climate. In the inset: a slice for annual rainfall equal to 800 mm and average salary equal to 20 000€/year.

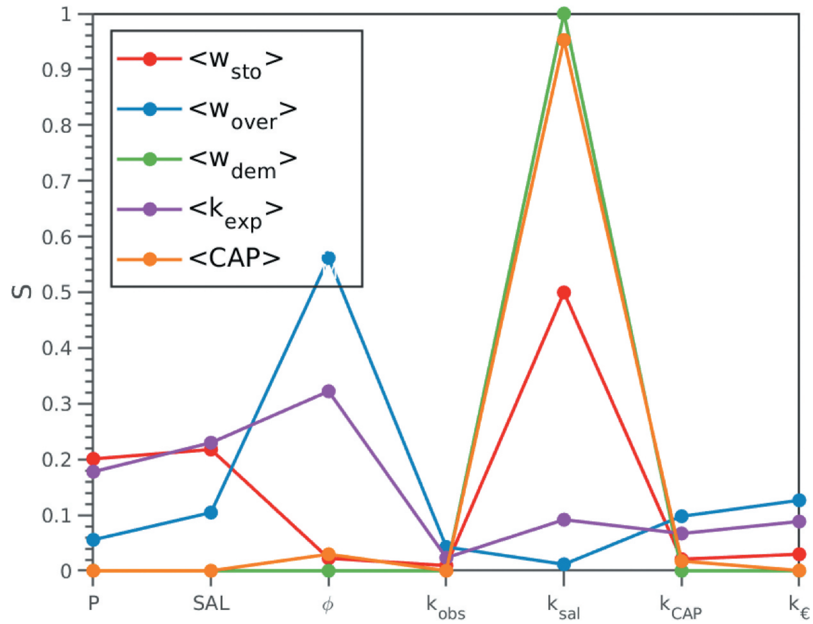

Figure 6. The sensitivity index S for a given parameter (x-axis, refer to Table 1 for description) for a specific long-term model output (inset). Rainfall parameters are kept constant, as reported in Table 1.

stored water and consequently the fraction of exploited water resources. Indeed, a given population in a given climate exerts pressure on natural resources commensurate with its lifestyle. A rich population employs a high quantity of water resources, has low propensity to accept water deficits and thus invests more money in infrastructures to store, on average, much more water therefore exploiting a higher fraction of natural resources. The hydrological basin response, epitomized into the ϕ parameter, has a large influence on the exploitation of natural resources. Indeed, if for the same rainfall, there is more runoff and more water in the aquifers, withdrawals on natural resources will decrease, as a percentage. At the same time, for the same reason, overflow event occurrences are strongly influenced by this parameter.

From an economical point of view, the most influential parameter is the cost of the full exploitation of water resources $k_€$; the variation of this parameter influences the fraction of exploited water resources and the average stored volume. The increase of this value set up a limit of water resource exploitation. For instance, if groundwater is deep ($k_€$ is a linear function of D), exploitation of this resource will not be economically convenient. The second most influential parameter is the fraction of the salary invested in water infrastructures, while the third is the coefficient governing the system obsolescence.

5 Conclusions

In this paper, we identified interactions and feedback between human and water systems. Because of our focus on the dynamics generated by the interplay of social and hydrological processes, simplifications were made in describing climate, hydrology, hydraulic structures, as well as socio-economical motivations and strategic choices. We identified, as key variables, the number of people, their average salary and the annual rainfall: a combination of these seems to be adequate to determine (a) the fraction of exploited water resources and (b) the capital invested in water infrastructure whose timing is driven by frequency of water stress.

The proposed model was used to simulate the influence of climate and society on shaping the water supply system and at the same time was able to recognize how water supply failures influence societal-economic choices.

One of the model limitations is that feedback from water availability (i.e. water stress or abundance) to population and wealth is not considered. Of course, this modelling scheme does not permit the simulation of the temporal dynamics of the population size nor the multiplying (recessive) effect of water abundance (water stress) on population itself or wealth. At the same time, model outputs are helpful to explain how a society acts in a given climate and how it is self-organized according to its population and economic wealth.

Further efforts are needed in order to include the role of water deficit/abundance in influencing population and well-being and to throw light on the relationship between the population and the exploited area. Also, the role of desalination and water reuse must be included to analyse the socio-hydrology of highly populated dry areas.

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