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The use of a hydrological-economic model to assess sustainability in groundwater-dependent agriculture in drylands

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SUMMARY

This paper deals with the assessment of sustainability in the exploitation of groundwater by agriculture in arid and semi-arid lands. The procedure proposed is not based on an indicator made up of a few partial, static figures, but on one which requires the use of all the information collectable for the system under assessment. This information serves to calibrate a dynamic model which formalizes the main causal chains and feedbacks existing between hydrogeology and the number of farms, this being ultimately linked to farms economy. The risk of overexploitation is worked out as the percentage of model's long-term steady-states, associated to a great number of different scenarios, surpassing some chosen threshold marking out sustainability from degradation.

The procedure has been implemented for two study cases: the Eastern La Mancha aquifer (Spain), where information was abundant, and the Oued-Mird alluvial aquifer (Morocco), where quantitative information was so much scarcer. Significant risks of degradation have been found in both cases, especially in the Moroccan one.

1. Introduction

In drylands, groundwater is a crucial asset for economic development or, in some cases, just for survival. The key point to transform water into crops and profits, thereby leaving precariousness behind, is to attain the appropriate technology for reaching and pumping water reserves; sun's heat makes the rest.

According to Foster and Chilton (2003) the boom in groundwater exploitation started in 1950 and had arrived to most parts of the developing world in 1990. The question of sustainability was postponed, relying on the big size of the reserves. However, signs of overexploitation are currently reported in many different sites.

In order to assess the status of groundwater reserves, most of the hydrogeological studies are concerned in determining the groundwater net balance of inflows and outflows. The ratio between these two variables has been conventionally used as an indicator of aquifers' status, since it seems to satisfy the requirements for that: accessible field information synthesizing system's behaviour. For instance, such a ratio is one of the indicators proposed by the Spanish Plan of Action to Combat Desertification (PACD) to assess the risk of desertification in an area (MARM, 2008a).

Other indicators aiming at the same goal are also based on information about partial characteristics of the system. Some examples are the decrease in discharge-flow through springs and the increase in water mineralization (Custodio, 2005), the efficiency of the irrigation system (López-Bermúdez, 1999) or the depth of the water-table level (e.g. Sharma, 1998).

Although these indicators are undoubtedly useful, the information they yield seems insufficient in order to assess the overall process of exploitation of groundwater bodies. Indeed, is exhaustion the only possible fate of any aquifer currently showing either the ratio inflows/outflows below one, or with an inefficient irrigation system, or with its water-table being deeper than it was in the absence of pumping? Should aquifers remain pristine to avoid degradation—one of the *hydromyths* stated by Llamas and Martínez-Santos (2005a)?

Clearly, the common answer to these questions is not. Thus, according to Custodio (2002, p. 258), some fall in the water-table of unconfined aquifers is even desirable since "it often improves land drainage and maximizes groundwater recharge rates". Besides, the depth of the water-table can perfectly reach a sustainable steady-state under exploitation. And since such a depth has to

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be greater than the average depth in the absence of pumping, a number of years where outflows overcome inflows must necessarily follow the outset of exploitation. Therefore, to check that the unbalance exists at the present time is not a sufficient condition of overexploitation, unless the aquifer is already near to be exhausted (Ibáñez et al., 2008).

The key questions to solve would rather be: Is expected an eventual unbalance in flows to last for long? Or, will some negative feedbacks be triggered to favour the system reaching equilibrium? What could be the state of the aquifer at that eventual equilibrium? In other words, has the *silent revolution*—the spectacular increase in the use of groundwater resources enhanced by economic incentives such as the high value of crops, subsidies and low costs of water (Llamas and Martínez-Santos, 2005b)—regulatory mechanisms to brake itself soon enough or should such mechanisms be imposed by some external institution?

Available land for irrigation, which is not unlimited, and the costs of pumping, which go up as the depth of the water-table increases, thereby reducing farms' profitability, are examples of endogenous forces favouring system's self-regulation. Instruments triggered by Governments to control groundwater exploitation—for example, when common natural goods and services are affected, as those supplied by lakes or wetlands—exemplify exogenous feedback mechanisms.

Therefore, sustainability assessments of aquifers' exploitation somehow should probe what the state of the system could be in the long-term, when at least the main underlying, conflicting forces have come to a certain balance. The methodology proposed in this paper is precisely an attempt to tackle assessments from such a far-sighted point of view.

In order to figure out the possible long-term states of the aquifer we rely on a dynamic, holistic model. It is holistic since it represents the dynamics of both consumers and resource, that is, it formalizes the main interactions between the number of irrigation farms and groundwater in a manner that resembles a predator–prey ecological model. Next Section 2 is devoted to describe this model in detail.

In order to assess sustainability, we evaluate the model's states of equilibrium linked to a high number of different scenarios—namely 2000. An equilibrium point is defined as that whose coordinates are the long-term steady-state values of the groundwater saturated thickness and the number of farms. Both variables would arrive at equilibrium if all the model's exogenous variables were held constant throughout time at some particular set of figures. The analysis considers not only one equilibrium point but a cloud of them in order to take uncertainty into account. The indicator of overexploitation we are proposing is the percentage of points in the cloud which surpass some chosen threshold marking out sustainability from degradation. In this way, the indicator can be thought of as estimating the percentage risk of overexploitation. The procedure's details and its theoretical foundations are explained in Section 3.

Two practical applications are also described in this paper, one to the Eastern La Mancha aquifer (Spain), which has been extensively studied so that there is a good deal of information about it, and the other to the Oued-Mird alluvial aquifer (Morocco), a remote area at the border of the Sahara where data are scarcer. The overall features of these applications are described in Section 4 and the procedure's results for them are showed in Section 5.

Finally, some conclusions are drawn in Section 6.

2. A dynamic model linking hydrology and economics

The model described in this section ultimately represents the dynamics of two state variables: the height of the saturated column of water in an unconfined aquifer, HSC, and the number of agricultural farms that pump groundwater, FRM. The model has an annual basis being the equations referred to the end of the hydrological year.

Throughout the description, capital letters refers to endogenous variables and small letters denote the exogenous ones. For simplicity's sake, we do not distinguish, by the moment, between exogenous variables and parameters—after all, the latter are particular exogenous variables whose values are taken to remain unchanged in time.

2.1. Aquifer

The model represents an unconfined aquifer, i.e. one whose upper boundary is the fluctuating water-table. Groundwater storage is evaluated through the one-dimensional average thickness of the saturated column of groundwater, measured from the bottom of the aquifer to the water-table

$$\mathrm{GNB} = \mathrm{REC} - \mathrm{DIS} - \mathrm{PMP}(1 - \mathrm{rfc}) \tag{1}$$

$$\mathrm{dHSC/dt} = \mathrm{delayn(GNB)} \tag{2}$$

$$\mathrm{REC} = (\mathrm{RRC} + \mathrm{ltr})/\mathrm{sto} \tag{3}$$

$$\mathrm{RRC} = \mathrm{prc} - \mathrm{AET} \tag{4}$$

$$\mathrm{AET} = \mathrm{AET}_i - \mathrm{ehp}(1 - \mathrm{HSC/hsc} - u) \tag{5}$$

$$\mathrm{AET}_i = \mathrm{prc0.9} + [prc/(300 + 25\ \mathrm{tmp} + 0.05\ \mathrm{tmp}^2)]^{2^{-0.5}} \tag{6}$$

$$\mathrm{DST} = [(\mathrm{HSC} - \mathrm{thd})\mathrm{sto}]^{nft}/\mathrm{trt} \tag{7}$$

$$\mathrm{DSO} = (\mathrm{HSCsto})^{\mathrm{nfo}}/\mathrm{tro} \tag{8}$$

$$\mathrm{DIS} = (\mathrm{DST} + \mathrm{DSO})/\mathrm{sto} \tag{9}$$

$$\mathrm{PMP} = [(\mathrm{aaf\ FRM\ WPH/eff}) + \mathrm{urb}]/(\mathrm{sto\ aaq}) \tag{10}$$

Endogenous variables: AET = actual evapotranspiration; AET_i = initial actual evapotranspiration; DIS = total natural discharge; DSO = Other natural discharges; DST = natural discharge with threshold; FRM = number of farms; GNB = groundwater net balance in the aquifer; HSC = height of the saturated column of water in the aquifer or groundwater saturated thickness; PMP = groundwater pumping; REC = total natural recharge; RRC = recharge due to rainfall infiltration; WPH = water supplied to crops per hectare.

Exogenous variables/parameters: aaf = average area per farm; aaq = area of the aquifer; eff = average efficiency of the irrigation system; ehp = evapotranspiration-groundwater saturated thickness relation parameter; hsc_u = groundwater saturated thickness when aquifer is unexploited; ltr = lateral transferences from adjacent aquifers and /or highlands of the basin; nfo = other discharges-groundwater saturated thickness relation parameter; nft = discharge with threshold-groundwater saturated thickness relation parameter; prc = average annual precipitation; rfc = return flow coefficient; rhp = recharge-groundwater saturated thickness relation parameter; sto = aquifer storage coefficient; thd = threshold for discharge; tmp = average annual temperature; trt = groundwater residence time for discharge with threshold; tro = groundwater residence time for other discharges; urb = groundwater pumping for urban use.

The average height of the saturated column of water in the aquifer or the groundwater saturated thickness, HSC, is subject to variations over time due to: (i) the natural flows of recharge and discharge, REC and DIS, respectively; (ii) water extractions for irrigation and other uses, PMP; and (iii) the return of a fraction of the pumped groundwater, rfc. Eq. (1) expresses the net balance between these inflows and outflows, named GNB.

Some type of delay could exist between variations in flows and the fluctuations observed in the water-table level (e.g. Custodio, 2002). Eq. (2) generically expresses this by means of an indefinite operator called 'delayn'. The concrete form of this delay function would depend on the particular study case.

Two sources of natural recharge are considered: direct recharge by rainfall in the aquifer's surface, RRC, and lateral transferences from adjacent groundwater bodies and/or highlands of the basin, ltr (Eq. (3)). The latter, normally dependent on the rainfall amount in distant areas, is assumed exogenous to the model. The aquifer storage coefficient, sto, is employed in this equation to convert the total natural recharge into the average thickness it would occupy inside a saturated geological material.

Infiltration is the main source of natural recharge in many aquifers. In large basins, with moderate topographic variation, runoff can be neglected so that recharge by rainfall can be estimated as the difference between precipitation and actual evapotranspiration, AET (Eq. (4)). The latter is formalized by means of two additive terms (Eq. (5)). The first one, named initial evapotranspiration, AET_i, refers to the average annual evapotranspiration in the unexploited aquifer; its expression within the model, showed in Eq. (6), follows Turc (1961). The second term in AET serves to account for the drop in phreatophytes' transpiration as water-level descends. Note that this term cancels out when HSC equals its average value without exploitation, hsc_u.

Discharge in inland aquifers can occur in diffuse form along rivers, in localised springs or by lateral transferences to other aquifers. Several formulations express the rate of discharge as a function of groundwater storage. The most simple one is to divide the aquifer storage, HSC·sto, by an average groundwater residence time, tr. However, in numerous unconfined flow situations, a two-dimensional hydraulic analysis (Chapman, 1963) suggests that a non-linear relationship of the form $(\text{HSC sto})^{\text{nf}}/\text{tr}$ exists (Coutagne, 1948). The parameter nf would capture the effect of aquifer geometry on groundwater discharge flow paths. The potential range for nf goes from zero—representing a constrained flow concentrated in one narrow path so that discharge does not depend on HSC—to values much higher than one—a theoretical case where discharge is instantaneous (not measurable) because flow paths are infinitely disperse.

Although the value of nf uses to be around 1 in most of the common hydrogeological situations, such as alluvial aquifers, the model allows calibrating it for the two discharge functions considered (Eqs. (7) and (8)). Eq. (7) also includes a threshold value, thd, which makes the component DST of the total natural discharge, DIS (Eq. (9)), to cancel out when HSC is below it. Hence, DST would represent mainly discharges through rivers or springs.

Finally, Eq. (10) relates pumping to agricultural and urban consumptions. Note that the efficiency of the irrigation system, eff, is included in this equation to transform demands into actual consumes. The aquifer storage coefficient, sto, and the total area of the aquifer, aaq, serve to convert pumping into the height of a saturated column of groundwater.

2.2. Number of farms

The rate of variation in the number of farms is given by:

$$\text{dFRM}/\text{dt} = \text{GRF FRM}(1 - \text{FRM}/\text{PNF}) \tag{11}$$

$$\text{GRF} = \text{fr1 SPF} \tag{12}$$

$$\text{PNF} = \min\{\text{tal}/\text{aaf}, \text{fr2SPF}\} \tag{13}$$

$$\text{SPF} = \text{smoothi}\{\text{GMF}/\text{aoc}, \text{spf}_t, \text{spf}_i\} \tag{14}$$

Endogenous variables: FRM = number of farms; GMF = gross margin per farm; GRF = potential growth rate of the number of farms; PNF = potential number of farms; SPF = smoothed profitability;

Exogenous variables/parameters: aaf = average area per farm; aoc = average opportunity cost; fr1, fr2 = parameters of the growth of the number of farms; spf_t = average adjustment time for smoothing profitability; spf_i = Smoothed profitability, initial value; tal = total available land for agriculture

Eq. (11) expresses a conventional logistic function. This means that an s-shaped growth is assumed for the number of farms since the outset of pumping. Both the rate of growth of the number of farms, GRF, and its potential maximum value, PNF, are assumed to be linearly related to some smoothed profitability index, here formalized by the variable called SPF; nevertheless, PNF is constrained to the total availability of land for agriculture (Eqs. (12) and (13)).

The ratio between the gross margin per farm, GMF, and the average opportunity cost, aoc, i.e. the average alternative rent outside irrigation farming, is taken as the profitability index within the model. Any current change in the number of farms would be the result of decisions made by a number of farmers at different times and after evaluating, each one of them, the evolution of such a ratio along a chosen period of time. Hence, the current rate of variation in FRM ultimately depend on some weighted average of the current and past observed values of the profitability index, where the weights would decrease as we go back over time. An exponential distribution is concretely assumed here for those weights meaning that SPF is taken to be an exponential smooth of GMF/aoc. This is expressed by means of the operator 'smoothi' in Eq. (14).[1]

Therefore, the model reflects that when either gross margins increase or opportunity costs decrease on average along a number of years, people is attracted to the agricultural business, implying both a greater rate of growth in the number of farms and a higher potential number for them. In the opposite situation—lower gross margins per farm and/or better alternatives—people is discouraged and both GRF and PNF decrease.

2.3. Gross margin per farm

Gross margin per farm, GMF, has a crucial role in the model because both the number of farms and the water used per hectare, the two key variables involved in aquifer's exploitation, depend on it. The equations determining GMF are:

$$\text{GMF} = (\text{INH} - \text{CTH})\text{aaf} \tag{15}$$

$$\text{INH} = \text{prqYLH} + \text{sub} \tag{16}$$

$$\text{YLH} = \text{pf1}(\text{WPH} + \text{prc}) - \text{pf2}(\text{WPH} + \text{prc})^2 \tag{17}$$

$$\text{CTH} = \text{UWC WPH}/\text{eff} + \text{CEH} \tag{18}$$

$$\text{CEH} = \text{ce1} + \text{ce2WPH} \tag{19}$$

$$\text{UWC} = \text{chp}(\text{aqh} - \text{HSC})\text{pre} + \text{ocw} \tag{20}$$

Endogenous variables: CEH = exploitation costs per hectare; CTH = costs per hectare; GMF = gross margin per farm; HSC = height of the saturated column of water of the aquiferor groundwater

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[1] Specifically, if sx is an exponential smooth of *x* then $sx_t = \text{smoothi}(x, d, x_o) = (1/d)\, x_t + (1/d)\,[1 - (1/d)]\, x_{t-1} + (1/d)\,[1 - (1/d)]^2\, x_{t-2} + (1/d)\,[1 - (1/d)]^3\, x_{t-3} + \ldots$; *d* is the adjustment time: small values of d imply weights decreasing quickly, i.e. the smoothed value of *x*, *sx*, is mainly based on the most recently observed values and *vice versa*; x_o is the initial value of *sx*.

saturated thickness; INH = incomes per hectare; UWC = unitary cost of water; WPH = water supplied to crops per hectare; YLH = average yield per hectare.

Exogenous variables/parameters: aaf = average area per farm; aqh = average aquifer formation thickness, from the aquifer's bottom to land surface; ce1, ce2 = parameters of the cost of exploitation per hectare; chp = unitary cost of water-groundwater saturated thickness relation parameter; eff = efficiency of the irrigation system; pf1, pf2 = parameters of the crops production function; prq = average price perceived by farmers; prc = average annual precipitation; pre = price of energy; ocw = other unitary costs of water; sub = subsidies per hectare.

The gross margin per hectare equals the difference between incomes and costs per hectare, INH and CTH respectively (Eq. (15)). The former comes from the selling of agricultural production and from subsidies (Eq. (16)). The yield per hectare, YLH, is related to the endowment of water to crops, WPH, and precipitation, prc (Eq. (17)). This relationship includes a quadratic negative term to reflect that a threshold exists for the water supplied beyond which crop yields decrease.

The costs per hectare, CTH, are disaggregated into two terms (Eq. (18)): the cost of water and the costs of exploitation, CEH, i.e. labour force, fertilizers, seeds, pesticides and machinery. The first term equals the unitary cost of water, UWC, times the total water actually consumed per hectare, i.e. WPH over eff. CEH is assumed to be linearly related to the water supplied to crops, WPH, as a proxy of production's intensity (Eq. (19)). The unitary cost of water, UCW, depends on the depth of the water-table, the price of energy and other fixed costs (Eq. (20)).

2.4. Water to crops per hectare

The water supplied to crops per hectare is given by the following two equations:

$$\mathrm{WPH} = \min\{\mathrm{wrh}, \mathrm{WPH_o}\} \tag{21}$$

$$WPH_o = \frac{\mathrm{pf1}}{2\ \mathrm{pf2}} - \mathrm{prc} - \frac{\mathrm{ce2} + \mathrm{WC}/\mathrm{eff}}{2\ \mathrm{pf2}\ \mathrm{prq}} \tag{22}$$

Endogenous variables: UWC = unitary cost of water; WPH = water supplied to crops per hectare; $\mathrm{WPH_o}$ = Optimum water supplied to crops per hectare

Exogenous variables/parameters: ce2 = parameter of the cost of exploitation per hectare; eff = efficiency of the irrigation system; pf1, pf2 = parameters of the crops production function; prc = average annual precipitation; prq = average price perceived by farmers; wrh = water restrictions per hectare

The water supplied to crops per hectare, WPH, is the minimum of two quantities: a possible restriction, or quota, per hectare, wrh, and the optimum endowment per hectare, $\mathrm{WPH_o}$ (Eq. (21)). The latter is the amount of water that maximizes the gross margin per farm. Therefore, the model assumes that, unless constrained by quotas, farmers have an optimal economic behaviour at the time of assigning water to crops. This means that sustainability is to be assessed, later on, under the hypothesis that farmers are doing their best from a short-term economic point of view.

As can be checked, the expression of $\mathrm{WPH_o}$ (Eq. (22)) simply reflects the well-known maximum first order condition, i.e. dGMF/dWPH = 0, once it is solved for WPH. Note that, as expected, $\mathrm{WPH_o}$ is positively related to the average price of crop productions, prq, and negatively related to both the unitary cost of water, UWC, and precipitation, prc.

3. Stability analysis of the model: sustainability and degradation

A stability analysis allows figuring out the long-term equilibrium of a dynamic model for any given set of fixed values of its exogenous variables, i.e. for any scenario where all the exogenous variables behave as parameters. The system's nullclines are relevant expressions in such a task. As is well-known, these curves draw the points in the phase plane where the rates of variation of the model's state variables cancel out.

Hence, the nullcline of the groundwater saturated thickness, or HSC-nullcline, is the equation dHSC/dt = 0, i.e. that making inflows to exactly balance outflows. This equation, solved for FRM for convenience's sake, can be expressed as:

$$\mathrm{FRM^{HSC}} = \frac{\mathrm{saq}\ [\mathrm{RRC} + \mathrm{ltr} - \mathrm{DST} - \mathrm{DSO}]/(1 - \mathrm{rfc}) - \mathrm{urb}}{\mathrm{aaf\ WPH/eff}} \tag{23}$$

The super-index HSC just indicates that this expression, although solved for FRM, is the HSC-nullcline. Note that the delay function involved in eq. 2 vanishes at equilibrium. Also, since RRC only depend on exogenous variables and DST, DSO and WPH ultimately relate to HSC it follows that $\mathrm{FRM^{HSC}}$ is a function of HSC; that is, $\mathrm{FRM^{HSC}} = \varphi(\mathrm{HSC})$. Of course, a number of exogenous variables/parameters are involved in φ. Therefore, given a set of fixed values of the exogenous variables/parameters, the HSC-nullcline allows knowing the long-term equilibrium of the groundwater saturated thickness for any chosen number of farms. Indeed, if FRM is fixed to frm then HSC will evolve towards $\mathrm{hsc_{frm}} = \varphi^{-1}(\mathrm{frm})$. If $\mathrm{HSC} > \mathrm{hsc_{frm}}$ when FRM is fixed, then HSC will drop; if initially $\mathrm{HSC} < \mathrm{hsc_{frm}}$, then HSC will go up.

The FRM-nullcline, i.e. the equation dFRM/dt = 0, can be reduced to (see Eq. (11)):

$$\mathrm{FRM^{FRM}} = \min\{\mathrm{tal/aaf}, \mathrm{fr2GMF/aoc}\} \tag{24}$$

Again, the superindex FRM just indicates that this is the FRM-nullcline and the smooth function of Eq. (14) vanishes at equilibrium. As can be checked in model equations, GMF ultimately depends on HSC. Hence, the FRM-nullcline turns out to be a function of HSC as well: $\mathrm{FRM^{FRM}} = \phi(\mathrm{HSC})$. This nullcline allows knowing the equilibrium of FRM corresponding to a fixed value of HSC for any given scenario of the exogenous variables/parameters involved in ϕ. Thus, if HSC is equated to hsc at a certain time, then FRM will evolve towards $\mathrm{frm_{hsc}} = \phi(\mathrm{hsc})$ since. If $\mathrm{FRM} > \mathrm{frm_{hsc}}$ when HSC is fixed, then FRM will decrease; if initially $\mathrm{FRM} < \mathrm{frm_{hsc}}$ then the number of farms will grow.

At any intersection point of both model's nullclines neither HSC nor FRM vary. As the scenario of the exogenous variables/parameters is assumed invariant as well (yet), these intersection points define the possible long-term steady-states of the system.

Fig. 1a illustrates an instance, called case A, of the two model's nullclines for a particular scenario. It shows the phase diagram containing: (i) the FRM-nullcline (dashed line); (ii) the HSC-nullcline (solid line); (iii) the equilibrium point of the system, (hsc^*, frm^*); (iv) the directions of change corresponding to four arbitrary points, each within a different region of those delimited by the nullclines (the explanations given before regarding fixing HSC or FRM help understand these vectors); and (v) one possible complete time-trajectory of groundwater exploitation (grey dashed arrow).

Note that the point where the HSC-nullcline intersects with the horizontal axis, i.e. FRM = 0, corresponds to the value (equilibrium) of HSC when the aquifer is unexploited, $\mathrm{hsc_u}$. Note also that the intersection of the FRM-nullcline with the vertical axis, i.e. HSC = 0, is a positive value. This means that some farms would remain in the system although the aquifer is entirely exhausted.[2]

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[2] This is a feature of this particular instance of case A; other instances, under different scenarios, will result in FRM being null or even negative at the vertical axis.

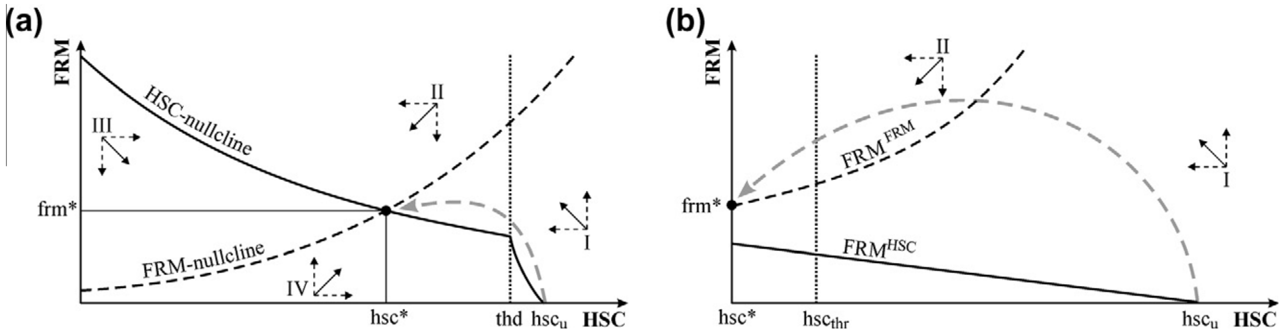

Fig. 1. Two instances of model's nullclines: (a) the sustainable "case A" and (b) the overexploited "case B" (see text).

These farms would endure either growing rainfed crops (remember that the yield per hectare, YLH, also depends on precipitation, see eq. 17) or being able to pump every annual amount of water recharging the aquifer.

Any point in the phase plane represents a possible state of the system, that is, a pair of simultaneous values of HSC and FRM. In each and every point except (hsc*, frm*), one or the two state variables are submitted to a field of forces making them to evolve through a time-trajectory, i.e. a curve within the phase plane. The solid vectors in Fig. 1a show the overall directions of such fields of forces within each phase plane's region, numbered I to IV in the figure. Since all of these vectors roughly aims at the equilibrium point (hsc*, frm*) in this case A, it follows that this is the only attractor of the system, i.e. the end of all possible time-trajectories. Such a point is then a stable long-term steady-state (for more on stability analysis in dynamic models see, for example, Clark, 1990, p. 168–196).

Indeed, suppose an initial aquifer at equilibrium without exploitation, therefore positioned at the point of coordinates (hsc$_u$, 0). In some year, a little number of farms starts pumping water. This makes the state of the system to shift upward, to some point in the phase plane's region I. In this entire region, the overall direction of change aims up-leftward meaning that the number of farms increases while the groundwater saturated thickness decreases—we know from model's description that this is ultimately caused by gross margins per farm overcoming average opportunity costs. By following the up-leftward direction the system's time-trajectory can directly reach the equilibrium, as is the case in Fig. 1a (grey dashed arrow). But anyway, had the time-trajectory crossed the FRM-nullcline and entered region II, it would be pushed to reach the same equilibrium, given that the overall direction of change in region II is down-leftward—the downward component in this region, i.e. the abandonment of farms, is explained by the fall of gross margins because of pumping has become more expensive with the reduction of HSC.

Whatever the transient time-trajectory could be, when the system arrives at the steady-state, a complete transition from the non-exploited initial situation to equilibrium under exploitation has taken place. The time employed in this transition will depend on the particular case, though it will last for a number of years in any case. Besides, the equilibrium value of HSC will always be lower than the initial hsc$_u$. And for this to be possible, outflows have to overcome inflows on average during the years of the transient period. However, this does not imply overexploitation in case A because of the unbalance in flows finally cancels out and the system settles down to a sustainable steady-state.

A second instance of model's nullclines, the case B, is shown in Fig. 1b. This is obtained with a different invariable scenario for the exogenous variables/parameters than in the case A. Here nullclines would intersect to the left of the vertical axis, i.e. at a theoretical negative value of HSC. Consequently, the feasible long-term equilibrium under this situation is placed at the intersection point of the FRM-nullcline and the vertical axis. In this case, the exploitation process leads the aquifer to be entirely exhausted. This is then a true case of overexploitation where outflows overcome inflows until the very end. Thus, what cases A and B confirm is that the ratio inflows/outflows being below one is a necessary but not a sufficient condition of overexploitation.

Of course, long-term overexploitation might have been marked, not by the extreme condition HSC = 0, but by means of another threshold for HSC, as hsc$_{thr}$ in Fig. 1b. This threshold might correspond, for example, to that needed to save some groundwater-fed wetlands. In such a case, it would suffice the long-term equilibrium to be positioned at any point to the left of hsc$_{thr}$ to indicate overexploitation.

Now we go into a crucial point. We have considered so far invariable scenarios for all of the exogenous variables, thereby treating them as parameters. But this is clearly a theoretical, unrealistic assumption. The values of many exogenous variables (e.g. annual precipitation, aquifer's lateral recharges, prices) significantly change from one year to the next. It follows that, since the model's nullclines, i.e. the functions ϕ and φ, include such variables, their shape and, consequently, the position of the long-term equilibrium, yearly shift as well. Therefore, realistic scenarios where at least some exogenous variables change annually imply that a cloud of long-term equilibriums actually exists for the system, being each equilibrium point linked to a particular year. Concretely, one equilibrium point is properly defined as the long-term steady-state the system would arrive at if the particular scenario of a certain year would be 'frozen' invariable throughout time—though, of course, it is not really.

Furthermore, this cloud of equilibrium points could include both sustainable and unsustainable equilibriums since the position of the nullclines can perfectly shift from an instance of case A to one of case B, even from one year to the next. Indeed, a rainy year where pumping is small may imply nullclines to adopt an instance of case A. But in the next year, a severe drought making pumping to increase considerably may shift the nullclines to some instance of case B.

The actual system's time-trajectory is always keeping track of the changing current-year attractor. In other words, the system is usually at disequilibrium. However, the dispersion showed by the cloud of equilibrium points plays an important role in defining system dynamics. If dispersion is high, the system's time-trajectory will wander rather erratically; if dispersion is low, the time-trajectory will be more predictable. This is illustrated in Fig. 2.

In any case, the percentage of equilibrium points which surpass the threshold delimiting degradation informs about the risk the system is taking. If most of the equilibriums do not surpass the threshold, the system's time-trajectory, even wandering around,

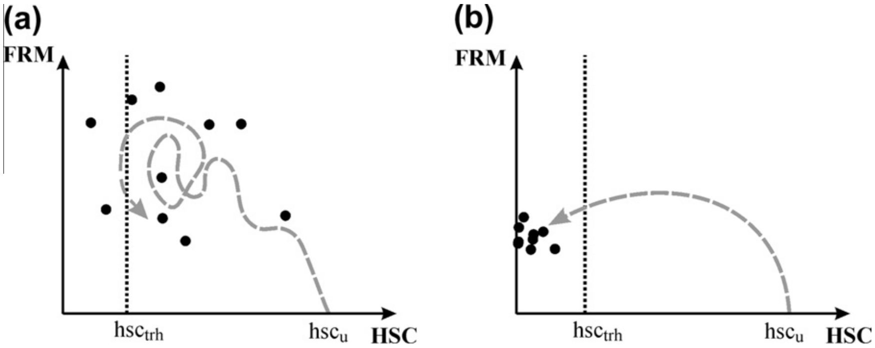

Fig. 2. The effect of dispersion in the cloud of equilibrium points on system's time-trajectory.

will seldom show the negative effects of overexploitation, so that the risk is low (Fig. 3a); if most of the equilibriums are positioned beyond the threshold, the risk is high, even if overexploitation signals are not apparent yet (Fig. 3b).

The mentioned fraction, calculated over a sample of estimated equilibrium points, is the indicator of overexploitation proposed here. Particular details regarding the procedure's application will be explained later on with references to our practical applications.

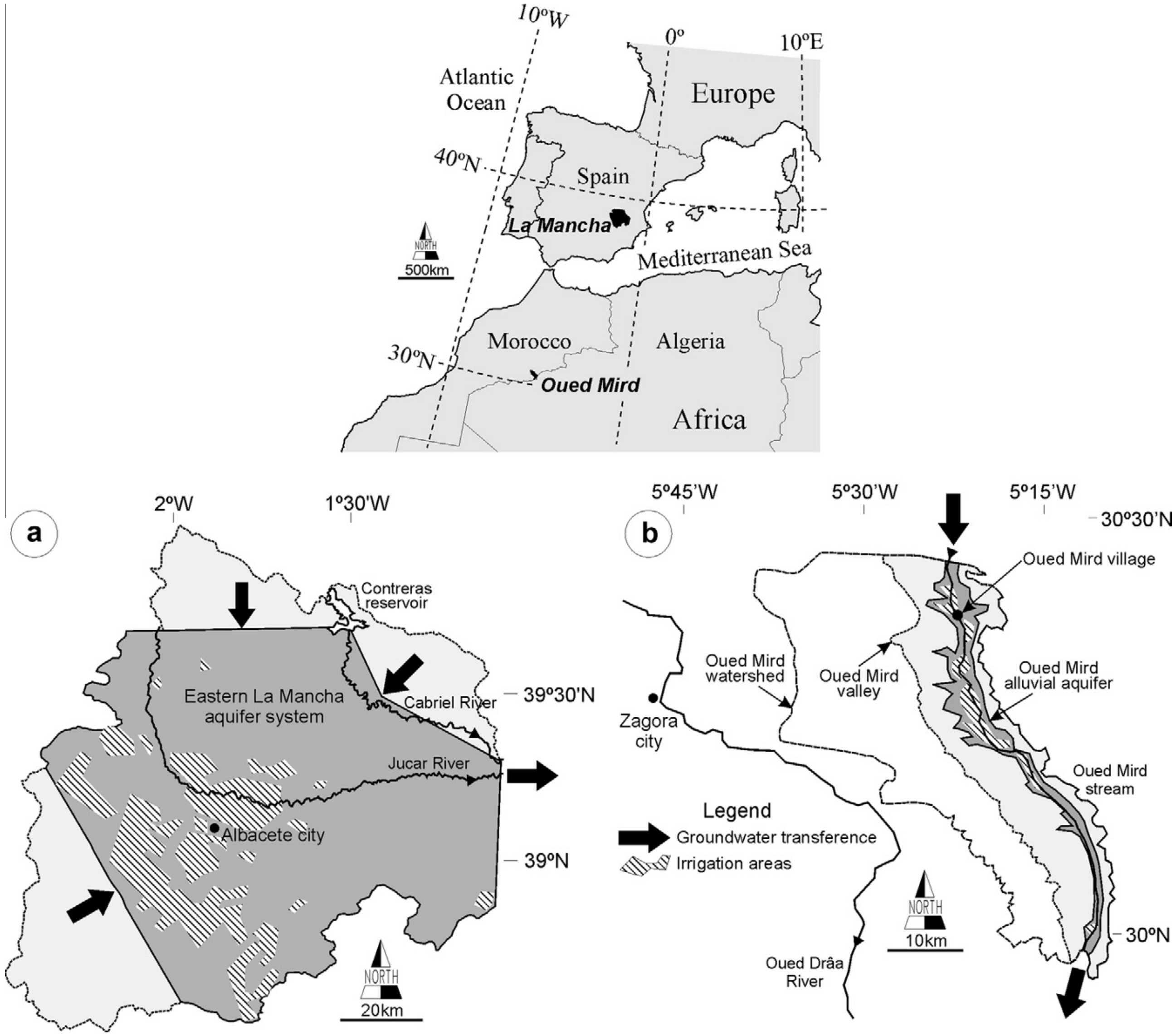

Fig. 3. Situation of the study cases. Eastern La Mancha aquifer (Spain) and Oued-Mird alluvial aquifer (Morocco).

4. Overall description of two study cases

Two study cases are presented here corresponding to unconfined aquifers in La Mancha (Spain) and Oued-Mird (Morocco) (see maps in Fig. 3). These two selected cases try to illustrate the flexibility of the methodology to be applied in a wide range of situations.

4.1. Eastern La Mancha aquifer (Spain)

The semi-arid plains of southern Castilla-La Mancha region (Spain) had been traditionally covered by rainfed crops. However in the 1970s some circumstances—affordable pumping technology and subsidies—triggered the establishment of a new irrigation culture. The 80's witnessed how maize took over the fields; this was the beginning of a succession of foreign crops to the area springing up in accordance to the market prices and subsidies policies. Even the most representative traditional crops, such as vineyards or almond trees, became irrigated. Thus, an extraordinary economic development took place on the basis of a huge aquifer system—a 7500 km^2 inland plain—placed within the Júcar River basin.

Pumping disturbed the natural regime of groundwater and concerns about the exhaustion of the aquifer were triggered, especially during and after a severe drought period in the 1990s. This led to the creation in 1995 of a Regulatory Body, one of whose purposes was to restrict the use of water by agriculture (Domínguez, 2004).

Recently profitability has fallen and it is appreciated a regression of crops surface; some farmers are returning to rainfed crops. Besides, since 2001 some amounts of water—including the entire urban water supply—are being transferred from another basin. These facts have eased the pressure on groundwater resources.

The hydrogeological characteristics of the Easter La Mancha aquifer are summarized as follows. Recharge by direct rainfall is complemented by inflows from northern, north-eastern and south-western adjacent aquifers, as shown by thick arrows in Fig. 3a. Discharge to Júcar River has been gauged and the average threshold below which it disappears estimated. Other outflows are probably directed towards aquifers in the south. Geologically, the Easter La Mancha aquifer consists on a succession of Triassic to Tertiary carbonated formations of different size, thickness and hydraulic properties, with intercalated marls that partially confine some of its central sectors. Its complex geometry, due to tectonics, induces large differences on HSC. Wells are mainly concentrated in the western and central sectors of the aquifer, the thickest ones. A 3D finite-difference groundwater numerical model exists for this aquifer; it was developed by Font (2004) using Modflow® (McDonald et al., 1992).

Table 1 summarizes the quantitative information available for this study case. It was abundant given the high number of studies existing for the system. Note specially that the number of variables with time-series data was relatively high.

4.2. Oued-Mird alluvial aquifer (Morocco)

Oued-Mird basin is located in the South East of Morocco, on the border with Algeria. The closest city is Zagora (120 km NW) and the basin is tributary of Oued Drâa River (Fig 3b). Average annual rainfall of the area is around 50 mm, with a decreasing gradient going from north to south. Heterogeneity of precipitations is quite high both temporally and spatially, with recordings ranging from 25 to 148 mm.

Table 1
Available data on Eastern La Mancha aquifer.

Parameter/variable	Source and period	Units	Average value[a]	Standard deviation
Time-series data				
aoc	INE (2008) (2000–2008)[b]	€ yr^{-1}	15,929.1	1750.4
DST	Font (2004) (1951–2002)	m yr^{-1}	0.0308	0.0183
FRM	Font (2004) (1972–75, 79, 89–90); CHJ (2004) (1983–2001); ITAP (2000–2008)[c]	farms	1108.69	474.75
ltr	Font (2004) (1951–2001)	m yr^{-1}	0.0139	0.0103
PMP	Font (2004) (1961–2000); ITAP (2008) (2000–2008)	m yr^{-1}	0.0332	0.0229
prc	INM, 2009 (1951–2009)	mm yr^{-1}	358.51	102.45
pre	CNE (2008) (1998–2008)	€ Kw h^{-1}	0.0431	0.0151
prq	MARM (2008b) (1990–2008)[d]	€ kg^{-1}	0.1802	0.0376
tmp	INM (2009) (1951–2009)	°C	13.76	0.74
urb	Font (2004) (1970, 81, 91, 98–01)	m yr^{-1}	0.0023	0.0003
WPH	López Fuster (2000) (1993–2008); ITAP (2008) (2000–2008); CHJ (2004)	m^3 ha^{-1} yr^{-1}	4574.98	887.15
Single reference values				
aaf	Ortega et al. (2004)	ha	50	
aaq	IGME (2010)	km^2	7509.94	
aqh	Font (2004), Sanz et al. (2009), IGME (2006)	m	560	
ce1	Ballesteros (2008)[d,e]	dmnl	100	
ce2	Ballesteros (2008)[d,e]	dmnl	0.33	
eff	CHJ (1998)	dmnl	0.77	
hsc$_u$	Font (2004), Sanz et al. (2009), IGME (2006)	m	480	
pf1	Ballesteros (2008)[d,e]	dmnl	3	
pf2	Ballesteros (2008)[d,e]	dmnl	3 10^{-5}	
rfc	Font (2004)	dmnl	0.2	
sto	Font (2004)	dmnl	0.0245	
sub	Bernabeu and Serna (2002)[d]	€ ha^{-1}	330.57	
tal	MARM (2008b), ITAP (2008)	ha	330,000	
thd	Font (2004), Sanz et al. (2009), IGME (2006)	m	463	
UWC	Ortega et al. (2004) and Ballesteros (2008)	€ m^{-3}	0.07–0.18	

[a] For time-series the "value" corresponds to the average over the sampled period.
[b] Average salary in Castilla-La Mancha Autonomous Community.
[c] Data refers to irrigated surface really; they were converted into farm numbers dividing by aaf.
[d] Value averaged using the areas of the main crops as weights; these areas, available for the period 2000–2008, came from ITAP (2008).
[e] Ballesteros (2008) provides regressions for yields and exploitation costs on water per hectare; average coefficients were obtained by using the areas of the main crops as weights (see note 4).

Table 2
Available data on Oued-Mird alluvial aquifer.

Parameter/variable	Source-period	Units	Value	Standard deviation
Time-series data				
FRM	Yassin et al. (2003, 2005)(1968–2003)	ha	86.58[a]	43,68
Single reference values				
aaf	Yassin et al. (2003, 2005)	ha	2.23	
aaq	Own estimation from data provided by Yassin et al. (2003, 2005)	km^2	540	
aqh	Own estimation from data provided by Yassin et al. (2008)	m	40	
aoc	Yassin et al. (2003, 2005)	MDH $farm^{-1}$ y^{-1}	20,000	
ce1	Ballesteros (2008)[b,c]	dmnl	1100	
ce2	Ballesteros (2008)[b,c]	dmnl	3	
chp·pre	Baali et al. (2002)[d]	MDH m^{-3} m^{-1}	0021	0.086
eff	FAO (2008)	dmnl	0,6	
hsc_u	Own estimation from data provided by Yassin et al. (2003, 2005)	m	30	
ltr	Own estimation from data provided by Yassin et al. (2003, 2005)[e]	m y^{-1}	0.00577	0.0026[h]
nfo	Coutagne (1948)	dmnl	1	
pf1	Ballesteros (2008), De Haas (2001), FAO (2008)[b,c]	dmnl	3	
pf2	Ballesteros (2008), De Haas (2001) FAO (2008)[b,c]	dmnl	0.00015	
prq	FAO (2008)[b]	MDH kg^{-1}	3.44	0.69[g]
rfc	CHJ, 1998	dmnl	0.2	
rrc	Own estimation from data provided by Yassin et al. (2003, 2005)[f]	m y^{-1}	0.00167	0.00077[h]
sto	Own estimation from data provided by Yassin et al. (2003, 2005)	dmnl	0044	

[a] Average historical value.

[b] Values averaged using the areas of the main crops as weights; these areas came from Yassin et al. (2003, 2005).

[c] Average coefficients were obtained by using the areas of the main crops as weights (see note 2).

[d] Mean and standard deviation for the product of chp and pre were provided by the authors.

[e] Darcy's Law was employed to estimate this value on the basis of hydraulic and piezometric data.

[f] Value worked out by using Turc's equation and daily data of Zagora weather station.

[g] Obtained by assuming the same coefficient of variation for prq than in the Spanish case.

[h] Obtained by applying the coefficient of variation of annual rainfall calculated on data provided by Yassin et al. (2003, 2005).

The alluvial aquifer consists on a Quaternary succession of sand, gravels and silt, with an average thickness of 40 m; it is positioned over a metapelitic bedrock of low permeability. Only rare, very intense rainfall events recharge the aquifer. Much more significant is lateral recharge from northern alluvial bed and piedmonts formations (Yassin et al., 2003, 2005).

In these arid conditions just nomads had survived throughout history, with their herds of camels and goats grazing the sparse vegetation of the area. But during the 1960s some nomads settled down assuring a regular provision of water by digging shallow, open wells (15–20 m). In this way nomads started to become farmers. Crops such as wheat, lucerne and different fruit trees were mostly used for self consumption; production was complemented with some commercial crops, as henna or palm trees.

Aquifer's exploitation increased since then. Agricultural production is still changing and self-consumption households are being progressively replaced by market-oriented farms which supply far markets especially with potatoes and watermelons. Now wells are mechanically drilled and equipped with motor pumps, they can explore all the aquifer's saturated thickness until the impervious base. A reticular web of parallel pipes with drips covers the fields.

Table 1 summarizes the quantitative information collected to calibrate the model for the Oued-Mird alluvial aquifer. Note that this was so much scarcer than in the Spanish case and almost it all consisted in single reference values. Only one time-series data, referred to the number of farms (FRM), was available in this case.

4.3. Calibration of the model

Any minimally detailed description of model's calibration for the two study cases would be too long to be included here. There is a working paper on the matter that the interested readers may ask for.[3] In general, either the whole model or particular sections of it were taken as a unique function including a set of unknown parameters. Calibration mainly consisted in working out figures for these parameters leading to a good fit between the recorded endogenous variables' time-trajectories and those simulated with the model or sub-models for the same variables under a scenario consisting in recorded values of the exogenous variables. In the Moroccan case, given the scarcity of time-series data, some simplifications in model equations were needed.

The calibration utility of the Vensim® software, based on a repeated-simulations procedure (Ventana Systems, Inc., 2007), was recursively used including different sub-sets of unknown parameters each time. Nevertheless, final tuning of parameter values was handmade.

Table 3 shows the list of unknown parameters and their calibrated values for the two study cases. Note that, for the Spanish case, the values of some parameters were tuned in relation to the a priori information existing on them, in order to get better fits (compare Tables 1 and 3). Fig. 4 allows seeing the observed and simulated time-trajectories of those endogenous variables with available time-series data.

5. Assessing aquifers' degradation risk

As was detailed in Section 3, the procedure to assess the risk of degradation of inland aquifers we are proposing consists on generating, by means of the model specified in Section 2, a cloud of equilibrium points associated to many different scenarios. Every scenario must be understood as a set of fixed values of the exogenous variables. These are fixed since an equilibrium point is defined as the long-term steady-state the system would arrive at if the particular figures taken by the exogenous variables in a certain year were held unchanged throughout time. Hence, any scenario within the procedure represents a set of 'frozen' exogenous values. The model is run under each scenario until equilibrium is reached and the resulting values for the height of the saturated column of groundwater (HSC) and the number of farms (FRM) are recorded and drawn, thereby getting the cloud of equilibrium points.

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[3] Contact with the corresponding author.

Table 3
Calibrated parameter values.

Eastern La Mancha aquifer						Oued-Mird alluvial aquifer		
Parameter	Value	Units	Parameter	Value	Units	Parameter	Value	Units
aqh	563	m	nft	0.93	dmnl	fr1	0.05	dmnl
chp	0.02	Kw h m^{-1} m^{-3}	ocw	0.03	€/m^{-3}	fr2	68	dmnl
eff	0.74	dmnl	rfc	0.17	dmnl	spfi	2.4	dmnl
ehp	29	dmnl	spf_i	2.2	dmnl	spft	5	year
fr1	0.07	dmnl	spf_t	5	year	tro	177.42	year
fr2	1000	dmnl	sto	0.024	dmnl			
hsc_u	487	m	tro	500	year			
nfo	0.9	dmnl	trt	11.6	year			

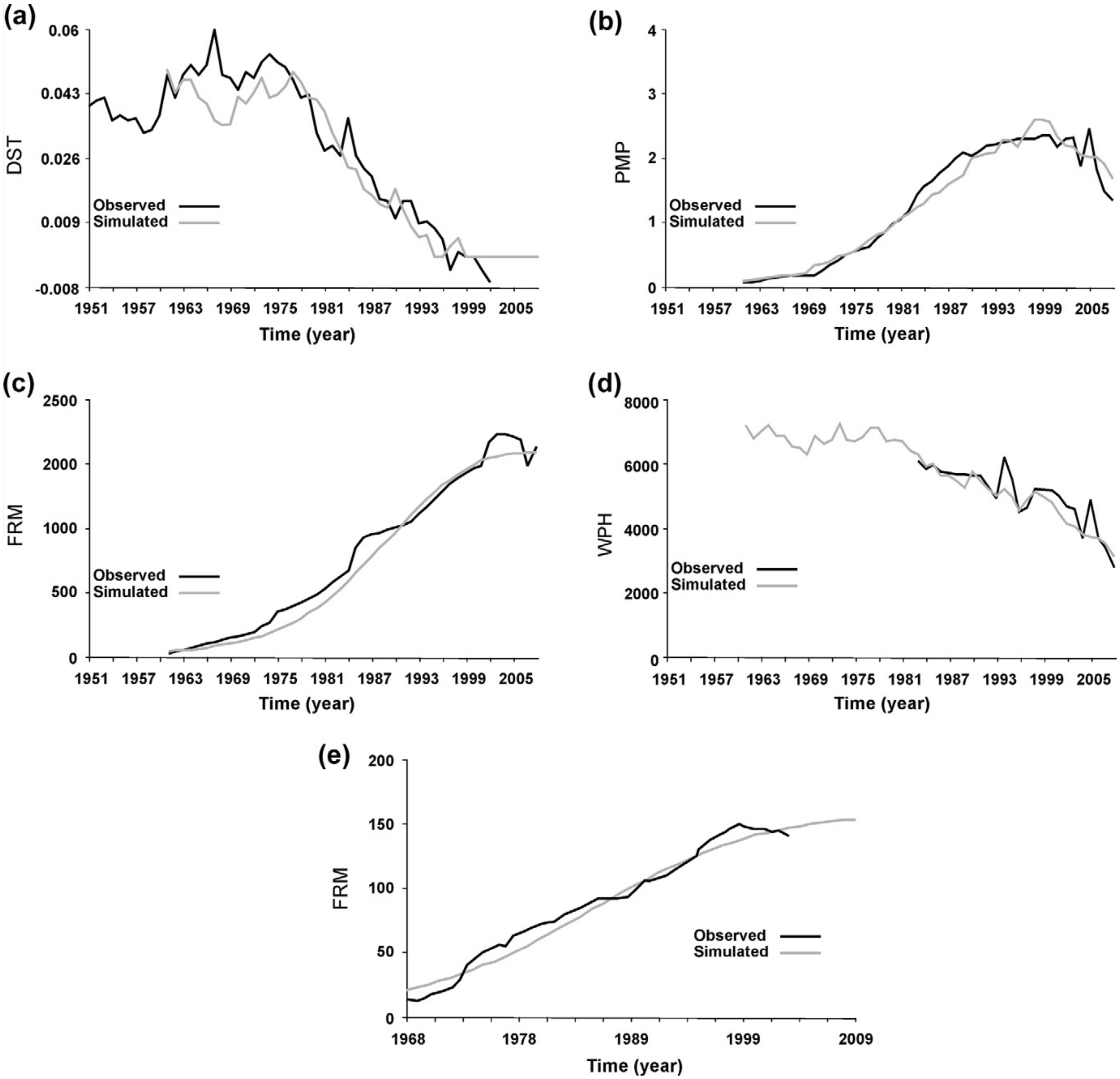

Fig. 4. Recorded and simulated time-trajectories of the endogenous variables with time-series data in the Easter La Mancha aquifer (a–d) and Oued-Mird alluvial aquifer (e).

For simplicity's sake, only a few exogenous variables were chosen to be modified between scenarios. They were those having to do with either prices or weather, which were assumed to be the two main sources of uncertainty within the system. The concrete

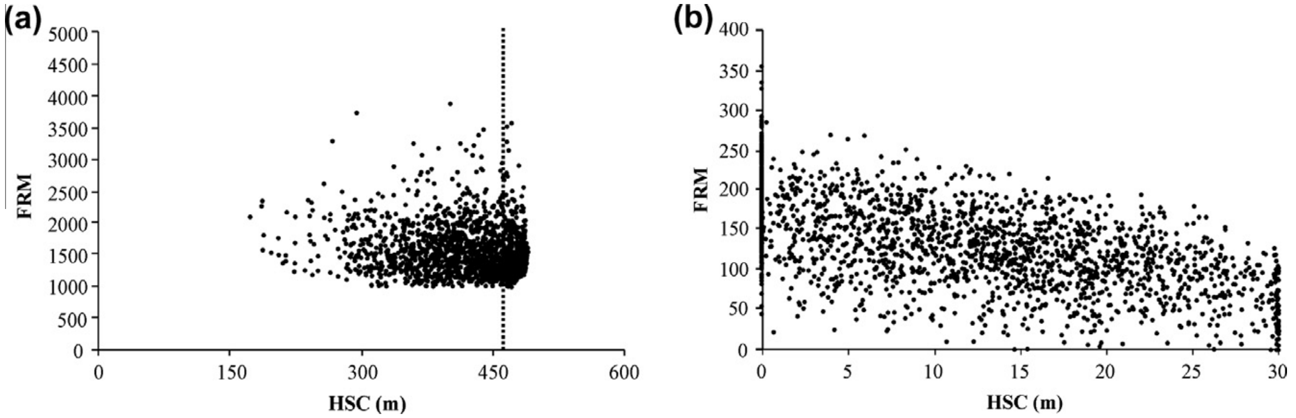

Fig. 5. Clouds of equilibrium points obtained in the benchmark analyses: (a) Easter La Mancha aquifer; (b) Oued-Mird alluvial aquifer.

sets of variables modifying their figures between scenarios were ltr, prc, tmp, prq and pre in the Spanish case and ltr, rrc, prq and the product chp·pre in the Moroccan one.

The particular number to be assigned to each of these variables within a scenario was generated through a random normal distribution whose mean and standard deviation took the corresponding figures shown in columns four and five of Tables 1 and 2. In this way 2000 different scenarios were generated for each study case. Note that the procedure implied assuming the independence between the variables randomly generated so that scenarios reflected many possible situations—high output prices, low input prices and good weather, high output prices, low input prices and bad weather, and so forth. The rest of exogenous variables did not change between scenarios and took the corresponding numbers showed in column four of the mentioned tables.

Fig. 5 shows the clouds of equilibrium points obtained in the way described so far for the Spanish and Moroccan cases. The column labelled A in Table 4 sums up the percentages of points in the clouds positioned within some ranges of HSC.

In the Spanish case, one of the thresholds delimiting the HSC-intervals of table 4 was the average groundwater thickness below which aquifer's discharge to Júcar River vanishes, i.e. thd of Eq. (7). This might be taken by many as the border delimiting degradation in the Easter La Mancha aquifer since, once surpassed, the aquifer turns from feeding the river into being fed by it, thereby reducing the supply of water downstream. HSC overcomes this threshold in 40.1% of the equilibrium points meaning that the risk of the Spanish system to withdraw resources to the river would be close to 60%. However, a small risk (4.5%) would exist of HSC to go below 300 m so that the exhaustion of the groundwater storage is not expected.

Table 4
Percentage of long-term equilibriums within ranges of HSC (in metres) in La Mancha and Oued Mird: (A) Benchmark; (B) 20% higher irrigation efficiency; (C) 20% higher efficiency + ban to increase total irrigated area over its current value; (D) Climate change (20% drops in precipitation—La Mancha—or recharges—Oued Mird—and 20% increases in their standard deviations).

HSC	A	B	C	D
La Mancha				
0–150	0.0	0.5	0.3	0.0
150–300	4.5	9.6	7.2	5.5
300 – thd	55.4	57.1	48.6	59.4
>thd	40.1	32.8	43.9	35.1
Oued Mird				
0–10	45.0	40.6	28.6	57.1
10–20	33.7	35.0	41.0	28.1
20–30	21.3	24.4	30.4	14.8

The thd-threshold did not exist in the Moroccan case, what made us to set three arbitrary 10-m-long HSC-intervals in Table 4 for it. Results show a highly dispersed cloud of equilibrium points (Fig. 5b), and a high risk of the system to evolve toward states near to aquifer's exhaustion. Indeed, although the cloud spread over the whole area of the phase plane, 45% of the points were positioned within the lowest HSC-interval. Underlying these results is the shallowness of the groundwater storage which makes inexpensive pumping even from the deepest sections of the aquifer.

It is not the goal of this paper to present a thorough sensitivity analysis of the model in any of its applications. Nevertheless, just for the sake of illustration, Table 4 allows the reader to see what happened when the analyses were repeated in the same manner described before but after changing the figures given to one or two exogenous variables.

In the B-analyses, the only difference with regard to the benchmarks, i.e. the A-analyses, was that the efficiencies of the irrigation systems (eff) were set 20% higher. Impacts of this modification differed between the Spanish and the Moroccan cases. In the former, groundwater reserve was more intensively used while in the latter the pressure on the resource was eased. Indeed, the percentage of equilibrium points positioned below thd rose to 67.3% in La Mancha and the percentage within the lowest HSC-interval dropped to 40.6% in Oued Mird. This is not weird really since equilibrium points depend on many exogenous variables whose average figures differ between both study cases. Note that by increasing the efficiency of the irrigation system conflicting forces are triggered: on the one hand, less groundwater has to be pumped to supply any given amount of water to the farms, thereby favouring sustainability; on the other, profitability is increased so that more farms enter the system, thereby favouring degradation. It turned out that the net balance of these opposite forces had different signs in La Mancha and Oued Mird due to the different surrounding conditions. What must be stressed is how we found that the long-tern effects of a presumably good measure were not what could be expected a priori. This counterintuitive effect had not been captured if the analysis lacked taking into account the feedbacks involved in farms-groundwater interactions.

The C-analyses differed from the benchmark ones in that the efficiencies of the irrigation systems were raised 20% again and, in addition, the irrigated areas were not allowed to surpass their current actual figures. Now that the improvement in efficiency is not deemed in isolation, results get better—from the sustainability's point of view—than in the benchmarks in both La Mancha and Oued Mird, although in a rather slight way in the former case.

Finally, the D-analyses explored what happened under an arbitrary climate change situation. They were implemented differently in the two study cases given the differences the model had in them.

Thus, in the Spanish case average precipitation was dropped 20% and its variability raised the same percentage with regard to the benchmark; in Oued Mird, changes were established on recharge, 20% lowering the average values of rrc and ltr and raising their standard deviations in the same percentage. As expected, results showed intensifications of aquifers' exploitation regarding the benchmarks, much greater in the Moroccan case. Note also that, although we probed a strong climate change, the negative impacts it provoked in La Mancha were smaller than those yielded by the B-analysis carried out under a supposedly beneficial measure.

6. Conclusions

Sustainability refers to the long-term so that assessing it with regard to the exploitation of any natural resource unavoidably requires deeming its possible status in the future and thus tackling many difficulties and uncertainties. Therefore, some minimum complexity seems required for any procedure aiming at such assessment to gain reliability. Non-complex procedures, as those relying on a few partial, static figures about the resource, yield insufficient assessments of sustainability. Although they are useful as preliminary evaluations about the status of the resource, and even might be thought of as following the precautionary principle, they should be complemented with other far-sighted procedures. From our point of view, these enhanced procedures should count on at least three desirable features.

Firstly and overarching, the assessment procedures ought to handle some dynamic, holistic, formal representation of the system of interest. Dynamic since, once again, sustainability refers to time. Holistic since the status of the resource in the long-term depends on mutual interactions with consumers, or in other words, because of consumers and resources co-evolve. Assessments could easily be misled if either resource or consumers are considered in isolation, taking the neglected part as exogenous. Ecologist well-known this point after studying predator–prey systems, and a hint of it was shown here when we found undesirable long-term impacts of increasing the efficiency of the irrigation system in the Easter La Mancha aquifer—in the absence of any other accompanying measure.

Second, precisely because we are facing a complex task, the assessment procedures to be undertaken should consider as much quantitative and qualitative information about the whole system as possible. This is another good reason to use dynamic, holistic models which are excellent instruments to make use, and even to make sense, of disperse available knowledge and data.

Third, some measure of uncertainty should be somehow explicitly included within the procedures given that the long-term is unavoidably uncertain. In this regard possibilities are numerous, but it should never be forgotten that, if a model is used, an efficient, non-exclusive way to tackle uncertainty is to update model equations, parameters calibration and results from time to time, as more data on the system get available.

Regarding model's dimension and complexity, it seems desirable to find a compromise between completeness, avoiding any important variable or relationship to be lacked, and simplicity, allowing the model to be fed with the most basic raw data. A big, detailed model could not be applied to study cases where the availability of information is low and would make difficult to frequently update parameter values and assessments. Thus, for the task of concern, we clearly bet for exploratory models rather than predictive ones, following the classification made by Perry and Millington (2008). After all, the goal is in no way to accurately forecast figures for any aquifer's variable, but to explore, at any present time, what is the range of possible outcomes of the dynamic forces interacting within the system.

Of course, although the procedure described in this paper incorporates all the mentioned desirable properties, success can not be presumed at all. In addition to the flaws that might be found in both the model and the procedure, it is the crude fact that uncertainty never entirely vanishes, no matter how realistic the formal representation used to probe the long-term could become. But the need for assessing sustainability in the exploitation of natural resources is undeniable too, as is our commitment to keep searching for better insights on the matter.

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