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# A methodology to diagnose the effect of climate change and to identify adaptive strategies to reduce its impacts in conjunctive-use systems at basin scale

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SUMMARY

A methodology to analyze impact, vulnerability and adaptation to climate change in conjunctive-use systems at basin scale is presented. Based on the value obtained for various indices under possible future scenarios (indices obtained from the results of a system management model), a systematic procedure is presented to identify problems and solutions to adapt to climate change effects. The future hydrological scenarios to be analyzed can be approached by starting from the historical series available for the system and taking into account the changes expected in the key statistics of the series. A method to predict the expected changes in the key statistics using the results of previous climate change studies in the area has been developed. A "downscaling" procedure is proposed to translate the climatic variations into results on a basin scale. The methodology has been applied to the case study of the Serpis River Basin (Eastern Spain).



## 1. Introduction

The majority of climate change studies in the published literature have focused on the impacts of climate change on surface water resources (Lautenbach et al., 2009; Bell et al., 2007). Meanwhile, only a few studies have looked at groundwater hydrology to determine the sensitivity of groundwater systems and river–aquifer relationships to climate change (e.g., Scibek et al., 2007; Roosmalen et al., 2007). However, the predicted changes in temperature and precipitation could produce significant alterations to the recharge of aquifers (Jyrkama and Sykesa, 2007) which will bring concomitant variations in the phreatic level, and therefore, in the availability of resources, river–aquifer relationship, pumping costs and groundwater pollution.

Water resources system models can be useful tools to study the effects of climate change and to identify adaptation strategies in the water sector. In this sense, conjunctive-use management optimization and simulation models can help to analyze impact, vulnerability and adaptation to climate change scenarios considering simultaneously surface and groundwater resources and the interaction between them (Marino, 2001). The literature contains only a few research studies where these models are employed to analyze climate change impacts in water resources system planning and management. California has been featured in pioneering studies of the influence of climate change on water resources systems, and it is the region where most studies of this type have been done. Lettenmaier and Sheer (1991) and Sandberg and Manza (1991) examined the implications of climate change scenarios on the State Water Project and Central Valley Project, using simulation models. The majority of later studies on the impact of climate change in California were also based on simulation models (e.g., Knowles and Cayan, 2004). An exception to this simulation approach is the statewide work presented by Tanaka et al. (2006) using the CALVIN optimization model developed by Lund et al. (2003). Fowler et al. (2007a,b) employed a conjunctive-use management simulation model to study the effect of climate change in

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north-west England. Sulis et al. (2009) presented an example of conjunctive use of a distributed simulation model and a multicriteria Decision Support System (DSS) to analyze different adaptation strategies to mitigate climate change impacts on a catchment in southern Portugal.

In order to help in the evaluation of system performance and in the planning and management decision process, several authors have proposed different indices to condense the results of water resources system management models. For example, Hashimoto et al. (1982a,b) defined some indices to describe how likely a system is to fail (reliability), how quickly it recovers from failure (resilience), how severe the consequences of failure may be (vulnerability), and how robust a system is. More recent research, such as the work published by El-Baroudy and Simonovic (2004) exploring the utility of fuzzy criteria, also includes different ways of defining indices of reliability, vulnerability, robustness and resilience. Martin-Carrasco and Garrote (2007) proposed a method to calculate a number of indices to study water scarcity in water resources systems using the results of a management optimization model. Some indices may also be useful to analyze the effects of climate change. In this paper we develop a systematic methodology to analyze the impact, vulnerability and adaptation to climate change in conjunctive-use systems. The methodology is based on the calculation of various indices that employ the results of a system management model under expected future scenarios.

Starting from an available water resources scenario of the system (a historical data series) a procedure is proposed to compute possible future hydrological scenarios approaching the variation produced by climate change in the monthly mean and variance of the series. Changes in these statistics can be estimated (for basins located in Europe) using climate change scenarios (forecast for the period 2071–2100) and control scenarios (30-year scenarios that correspond to the hydrological situation for the period 1961–1990) derived from the Prudence Project (2004). In that project a series of high-resolution climate change scenarios for the period 2071–2100 were obtained for Europe. These scenarios were generated using eight different Regional Climate Models (RCMs). The results obtained from each of these RCMs, which were defined over different grids (meshes with different origin and cell size, which, depending on the model, varied from 50 km to 22 km), are public and available on the web page http://prudence.dmi.dk/.

The aim is to incorporate this information into the definition of future hydrological scenarios of the systems under study. Therefore, a downscaling technique must be applied. Over the last few decades, scientists have developed techniques of regionalization or "downscaling" (dynamic and statistical) in order to translate the climatic variations into results on a regional scale (Khan et al., 2006; Wilby et al., 2004; Vrac et al., 2007; Díez et al., 2009; Brekke et al., 2008). Though there is extensive literature on the strengths and weaknesses of the methods of downscaling climatic variables to smaller cells, less attention has been paid to downscaling to examine the impacts of climate change on water resources systems in terms of runoff or groundwater recharge (Fowler et al., 2007b; Cayan et al., 2008). Some research (ej. Zhu et al., 2005) employed hydrologic response ratios to translate historical streamflow in a system to streamflow under climate change conditions. These hydrological response ratios are derived from available information about climate change effects in an area. This technique allows the generation of future scenarios by modifying the monthly means of the historical series in accordance with an estimation of the increment or decrement produced by climate change in these parameters (monthly means). In some systems (for example systems with low storage capacity and/or significant streamflow or reservoir losses due to infiltration or evaporation) where climate change could significantly modify not only the mean, but also the standard deviation of streamflow, this change in variability could have an influence on future management problems and possible solutions to them. For this reason, we propose a series of transformations as a downscaling method to generate future series for a basin incorporating not only available predictions of changes in the monthly means produced by climate change in the area (as the hydrologic response ratios technique does) but also in the monthly standard deviations.

Once the future hydrology and the urban, industrial and environmental water demands expected in the system for the period 2071–2101 are estimated, a conjunctive-use management simulation model can be employed to analyze the system behavior under future scenarios.

## 2. Definition of future scenarios. downscaling method proposed

In order to study the effect of climate change on a water resources system, we need to characterize the hydrology and demands of historical and future scenarios to be analyzed with the management model. Management models usually work on a monthly time scale and can be defined with different spatial detail. The spatial and temporal scales selected for the management model determine the detail required to characterize the scenarios to be analyzed.

In this section we propose a downscaling method to make use of the results of the climatic change scenarios generated for Europe in the Prudence Project in order to analyze changes in the hydrology of a specific water resources system. For each RCM employed in the Prudence Project we obtained (http://prudence.dmi.dk/) monthly series (for climatic and hydrological variables) corresponding to the control scenario (defined over a 30-year period [1961–1990] of historical situation) and climate change scenario (simulated future series under climate change conditions). The future scenarios correspond to the results derived from the RCM simulations for the period 2071–2100 under different greenhouse-gas emission scenarios. The spatial resolution of the series varies from 50 km to 22 km depending on the RCM, 50 km being the most common. This spatial resolution may be too coarse to study the management of a given basin. Logically, when studying the management of a water resources system, the historical hydrological situation must be characterized using a level of spatial detail that is in accordance with the case study and the available data. The hydrological state of the system is reproduced with more spatial detail and greater accuracy using the historical series obtained to build the management model (from this point on, the "original streamflow series") than if it were directly derived from the Prudence Project data (control scenarios available on the Prudence Project web page).

For this reason, in order to analyze the effect of climate change on a system we propose to perturb the "original streamflow series" (we selected the historical series for the period 1967–1990, for which data were available) by modifying the key statistics (monthly relative change in mean and standard deviation) as deduced from the Prudence Project data series for the area where the system is located. Therefore, we only use the relative change of hydrological variables (we assume that this relative changes can be properly captured from the RCM simulations) predicted by the RCM in the area but not the absolute value provided by them. The following steps show how the future system streamflow series can be defined:

(1) Aggregation of the original streamflow series of the system to define a single global series $y^{x,j}(O)$, where $x$ varies from 0 to $X-1$ ($X$ being the number of years in the series) and $j$ varies from 1 to 12, representing the 12 months of the year.

Thus, the product $x \cdot j$ represents the number of months in the series. ($O$) is employed to indicate that we refer to the original streamflow series.

(2) Identification of the cell of the Prudence Project grid where the system is located to obtain the monthly mean ($\mu^j$) and standard deviation ($\sigma^j$) values of the Prudence Project series $y^{x,j}(s)$ (where $s$ can adopt one of two values, 1 for a control scenario and 2 for a future scenario).

(3) Normalization of the control and future streamflow series $y^{x,j}(s)$ using $\mu^j(s)$ and $\sigma^j(s)$. The normalized series will be:

$$y_N^{x,j}(s) = \left[y^{x,j}(s) - \mu^j(s)\right]/\sigma^j(s) \quad (1)$$

(4) Change in the mean and the standard deviation, respectively, will be given by:

$$\Delta\mu^j = \left[\mu^j(2) - \mu^j(1)\right]/\mu^j \text{ and } \Delta\sigma^j = \left[\sigma^j(2) - \sigma^j(1)\right]/\sigma^j(1) \quad (2)$$

(5) The single global series modified to take into account the effect of climate change ($y^{x,j}(C)$, where ($C$) is employed to indicate that we refer to the climate change streamflow series) will be:

$$y^{x,j}(C) = \sigma^j(C) \cdot y_N^{x,j}(O) + \mu^j(C) \quad (3)$$

where $\sigma^j(C) = \sigma^j(O) \cdot (1 + \Delta\sigma^j)$ and $\mu^j(C) = \mu^j(O) \cdot (1 + \Delta\mu^j)$, being ($O$) employed to indicate that we refer to the original streamflow series.

(6) Finally, the global series can be distributed between the multiple streamflow series originally considered in the water resources management model, maintaining the percentage of change with respect to the aggregated series identified in the historical scenario.

This downscaling methodology has been developed and described for small river basins located in a cell of a RCM grid. But it could be also extended to large river basins incorporating the spatial variation of climate change impacts with the spatial resolution employed by the RCM. In these cases, the procedure we have just described should be repeated for each of the system portion located in different RCM cells. Therefore, an aggregation of the original hydrological series should be performed for each basin portion located in different RCM cells and each aggregated series would be perturbed using the relative changes in monthly means and standard deviations deduced from the RCM model in its corresponding cell.

The described methodology allows to use directly the available series of streamflow data (control and future scenarios) to estimate the impact of climate change on this variable. But, actually, the mostly widely used approach of analyzing climate change impacts on river flow (e.g. in regional climate change impact assessments) is to simulate river flow response to changed climate input using hydrological models (Hernández-Barrios, 2007).

Another hydrological estimate required to analyze future hydrological scenarios with the conjunctive-use model is the mean groundwater recharge for each aquifer in the system. An estimate of the historical mean recharge value of the main aquifers in Spain was completed by the "Instituto Tecnológico Geominero de España" (ITGE, 1999). More recently, Alcalá (2006) estimated the recharge from rainfall to Spanish aquifers using the chloride mass balance in the soil, and these values have been used in the current study. Since there are no aquifer recharge series available in the Prudence Project, we have assumed the recharge to be proportional (relationship that was checked for the historical period) to the difference between precipitation and evaporation, (series available in the Prudence Project) in order to obtain an approximate value of the effect produced by climate change on aquifer recharge using Prudence series. Thus, the change in recharge to the aquifers due to climate change has been estimated by analyzing the Prudence Project control and future series (defined as the difference between rainfall and evaporation in the area where the aquifers are located). We have estimated a coefficient defined as the mean of the series (defined as the difference between precipitation and evaporation) for the future scenario divided by the mean for the control scenario and we have applied it to perturb the original mean recharge data for each aquifer in the system.

A demonstration of this methodology is presented in Section 4, where it has been applied to a case study, the Serpis River basin.

One of the objectives of this research is to study if current agricultural demands could be satisfactorily met under possible future scenarios, and the exploration of the impact of changing the availability of water for agricultural use in the system. In order to analyze this with a conjunctive-use management model, we first need to estimate urban, industrial, and environmental water demands expected in the system during the future scenario (period 2071–2101). In the case study analyzed in this paper, the urban and industrial demands are assumed to account for a small percentage (24%) of the total water demand of the system. Data of current demand and forecasts were provided by the Spanish Environmental Ministry for 2015. Using these data and considering that the trend observed between 2005 and 2015 could be maintained in the future, we applied a linear regression to estimate the mean urban and industrial demand in the future. More research about industrial and urban water demand forecast is required for Spanish basins (Pedregal, 2004), but this aspect does not form part of the objective of the current study. Rather, we focus on the development of a methodology to generate future hydrological scenarios (using a downscaling technique) and to condense results of conjunctive-use management under hypothetical future scenarios in order to diagnose the effect of climate change and to identify possible adaptive strategies to reduce its impacts.

## 3. Analysis of the system planning and management

The planning and management of the water resources system under different scenarios (as described in the previous section) was simulated using SIMGES, a management simulation model of the generalized tool AQUATOOL (Andreu et al., 1996). AQUATOOL is a user-friendly Decision Support System (DSS) widely employed in Spain and other countries (e.g., Italy, Mexico, Morocco). This DSS facilitates the definition of monthly conjunctive-use management models at basin scale, simulating surface and groundwater flow components simultaneously, as well as their interaction.

On the monthly time scale used by this management model, the surface system can be simulated by a simple flow-balance in a flow network. The simulation of groundwater flow and surface–groundwater interactions in SIMGES can be performed using different kinds of computationally-efficient groundwater flow models that allow for the simulation of management alternatives of complex large-scale systems over long time horizons (with many competing demands, several reservoirs and aquifers, and a high interconnection among these elements). The simplest approach for groundwater flow simulation and stream aquifer interaction is defined using linear reservoirs (see Pulido-Velazquez et al., 2005), but it also allows distributed approaches derived using eigenvalue techniques (see Pulido-Velazquez et al., 2007).

The results obtained with the conjunctive-use model for the generated future scenario were employed to study whether current agricultural demand could be satisfactorily supplied and what the effect of increasing or reducing this demand would be. These results can also be used to derive a series of indices that we propose to diagnose the effect of climate change on a system and to deduce possible adaptive strategies (planning strategies) to reduce its impacts.

Some of the indices ($I_s$ and $I_r$) we propose are similar to the ones selected by Martin-Carrasco and Garrote (2007) to study systems supplied exclusively from surface water sources, but adapted to cases with conjunctive-use management. Two indices ($I_s$ and $I_r$) have been selected to identify what kinds of problems could arise under the estimated future scenarios:

– *Demand satisfaction index ($I_s$)*: Represents the system's volumetric supply reliability. It can be computed with the equation:

$$I_s = \frac{S}{D} \tag{4}$$

where $S$ represents the total amount of water supplied (including surface and groundwater) to the system demands and $D$ is the total water demand. It gives an idea of the magnitude of the failures in attempting to supply the demands. Small values of this index indicate a greater vulnerability to reduction of natural resources produced by climate change.

– *Demand reliability index ($I_R$)*: Represents the total supply given to meet the demand under a condition of no failure ($S_r$) divided by the total water demand of the system ($D$).

$$I_r = \frac{S_r}{D} \tag{5}$$

where $S_r$ is the sum of the supply for all the demands and months in which no failure appears. We consider failure to meet demand for a specific month to be when the supply is less than a certain percentage of the water demand. It gives an idea of the demand supply reliability in the system. A small value of this index means the system cannot reliably satisfy its demands and is prone to water scarcity, even for droughts of moderate intensity.

Two other indices ($I_w$, index proposed in this work which is totally new, and $I_u$ introduced with a definition different to the related index presented by Martin-Carrasco and Garrote, 2007) are proposed to identify the origin or cause of problems and possible adaptive strategies to follow:

– *Withdrawal index*: Defined to evaluate the percentage of water resources abstracted in the system ($Y$) with respect to the total water demand ($D$). It can be computed as:

$$I_w = \frac{Y}{D} \tag{6}$$

where $Y$ is the conjunctive-use yield in the system, that would represent the total amount of water leaving the system if there were not surface infrastructure to store streamflow. It is estimated as the summation for all the stress periods of surface water inflows plus pumping, minus the stream-depletion produced by pumping. Therefore, the yield ($Y$) depends on the total amount of pumping. A small value of this index in systems with supply problems means that water demand exceeds withdrawal. In these cases, complementary resources would be required (additional pumping, water transfers, water reuse, etc.).

Withdrawal use index: Defined to evaluate the percentage of water resources withdrawn in the system to supply demand. It can be computed as:

$$I_u = \frac{S}{Y} \tag{7}$$

where $S$ represents the total water supply to meet the system demand and $Y$, the conjunctive-use yield. Small values of this index in a system with supply problems (low demand satisfaction index ($I_s$) and/or low demand reliability index ($I_R$)) reflect a reduced use of withdrawaled water, and the need for greater system regulation. This increment in the regulation can be achieved by improving the management of the available infrastructures or, in cases in which they are properly managed, adding more infrastructures (for example, surface structural works, infrastructure for developing artificial recharge, infrastructure for water reuse, etc.). A resources use index was proposed also by Martin-Carrasco and Garrote (2007), but in that work it was defined for yields under natural conditions and systems supplied exclusively from surface water sources.

As can be deduced from the definition of the indices $I_s$, $I_w$ and $I_u$, they are related by the mathematical expression:

$$I_s = I_w \cdot I_u \tag{8}$$

This equation shows that the system vulnerability index is defined as the product of the water resource scarcity index and the system regulation/infrastructure deficiency index, implying that the capability of a system to meet water demand depends on both the availability of surface and groundwater resources and the infrastructure to make water readily available for human use.

Different hypotheses about the pumping limit imposed could be analyzed, corresponding to particular levels of reduction in the system storage. The conjunctive-use management will be constrained by these pumping thresholds and the results (the values of the indices) will depend on them. For example, in terms of pumping restrictions, we could compute different yields. If we prohibit pumped abstractions from the system (in absence of groundwater supply and therefore without the chance of conjunctive-use management), the yield at any moment will depend only on the management of the surface water inflow and there would not be any reduction in the aquifer's natural storage. We could also define pumping limits as functions of the aquifer recharge in order to maintain a certain level of sustainability. The indices could also be obtained by imposing the condition that pumping does not exceed the historical pumping minus the recharge reduction estimated for the aquifer in this area. This last hypothesis could allow analysis of cases where the historic impact on the aquifer storage evolution is not increased.

Different climate change indices can be derived from the results of the conjunctive-use management model under future scenarios of climate change. Depending on the value of the indices, a diagnosis of the problem and different adaptive strategies are proposed. Both the problems and solutions proposed are summarized in Table 1:

Note that climate change is an evolving process and (large) uncertainties still exist in climate change projections. Therefore, climate change impacts and adaptation strategies are scenario dependent.

Three different intensity levels from a qualitative perspective (high, intermediate and low) were considered for the indices $I_r$ and $I_s$ (see Table 1). In terms of the indices $I_r$ and $I_s$, two types of supply problems have been considered: vulnerability [problem 1: water scarcity may produce significant economic (when urban, industrial and agricultural demands are far to be satisfied) and/or environmental (when environmental demands are far to be satisfied) damage], whose intensity increases when $I_s$ is smaller, and unreliability [problem 2: low intensity droughts may lead to water scarcity], whose intensity increases when $I_r$ is smaller.

When the combination of indices $I_r$ and $I_s$ indicate that there are problems (cases in which $I_r$ and $I_s$ are both not high), $I_w$ and $I_u$ can be used to identify the origin or cause of the problems and to select the appropriate adaptive strategies. Two different intensity levels (high and low) have been considered for indices $I_w$ and $I_u$. Small values of $I_w$ (noted as $I_w^-$ in Table 1) are associated with a demand that exceeds withdrawal (problem 3 in Table 1), and where, therefore, complementary resources are needed (solution B in Table 1). In accordance with the mathematical relationship described between $I_s$, $I_w$ and $I_u$ ($I_w = \frac{I_s}{I_u}$), the intensity of problem 3 (high, intermediate and low) and of the related adaptive strategy B (high, intermediate and low) is inversely proportional to the value taken by $I_s$ (low, intermediate and high respectively). The expression also shows that some combinations of $I_s$, $I_w$ and $I_u$ cannot occur. For

**Table 1**
Problems and solutions based on the values of the indices.

| | Withdrawal use ($I_w$) | Withdrawal ($I_u$) | Demand reliability ($I_r$) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | High ($I_s^+$) | | Intermediate ($I_s^=$) | | Low ($I_s^-$) | |
| | | | Problems | Solutions | Problems | Solutions | Problems | Solutions |
| *Demand satisfaction ($I_s$)* | | | | | | | | |
| High ($I_s^+$) | High ($I_w^+$) | High ($I_u^+$) | | | $2^{=}$ | $A^{-}$ | $2^{+}$ | $A^{-}$ |
| | | Low ($I_u^-$) | | | $2^{=}–4^{-}$ | $A^{-}–C^{-}$ | $2^{+}–4^{-}$ | $A^{-}–C^{-}$ |
| | Low ($I_w^-$) | High ($I_u^+$) | | | $2^{=}–3^{-}$ | $A^{-}–B^{-}$ | $2^{+}–3^{-}$ | $A^{-}–B^{-}$ |
| Intermidiate ($I_s^=$) | High ($I_w^+$) | Low ($I_u^-$) | $1^{=}–4^{=}$ | $A^{=}–C^{=}$ | $1^{=}–2^{=}–4^{=}$ | $A^{=}–C^{=}$ | $1^{=}–2^{+}–4^{=}$ | $A^{=}–C^{=}$ |
| | Low ($I_w^-$) | High ($I_u^+$) | $1^{=}–3^{=}$ | $A^{=}–B^{=}$ | $1^{=}–2^{=}–3^{=}$ | $A^{=}–B^{=}$ | $1^{=}–2^{+}–3^{=}$ | $A^{=}–B^{=}$ |
| Low ($I_s^-$) | High ($I_w^+$) | Low ($I_u^-$) | $1^{+}–4^{+}$ | $A^{+}–C^{+}$ | $1^{+}–2^{=}–4^{+}$ | $A^{+}–C^{+}$ | $1^{+}–2^{+}–4^{+}$ | $A^{+}–C^{+}$ |
| | Low ($I_w^-$) | High ($I_u^+$) | $1^{+}–3^{+}$ | $A^{+}–B^{+}$ | $1^{+}–2^{=}–3^{+}$ | $A^{+}–B^{+}$ | $1^{+}–2^{+}–3^{+}$ | $A^{+}–B^{+}$ |
| | | Low ($I_u^-$) | $1^{+}–3^{+}–4^{+}$ | $A^{+}–B^{+}–C^{+}$ | $1^{+}–2^{=}–3^{+}–4^{+}$ | $A^{+}–B^{+}–C^{+}$ | $1^{+}–2^{+}–3^{+}–4^{+}$ | $A^{+}–B^{+}–C^{+}$ |

+ High = Intermediate – Low
Problem:
1. Vulnerable: water scarcity may produce significant damages.
2. Unreliable: low intensity droughts may lead to water scarcity.
3. Excess of demand with respect to withdrawal (pumping + natural inflows-depletions produced by pumping).
4. Reduced use of withdrawal.
Solution:
A. Demand management.
B. Complementary resources are needed (additional pumping, water transfer, water reuse, etc.).
C. Increase regulation of the system withdrawal (surface structural works, artificial recharge, water reuse, etc.).

example, if $I_w$ and $I_u$ are low ($I_w^-$ and $I_u^-$) $I_s$ cannot be high ($I_s^+$), and if $I_w$ and $I_u$ are high ($I_w^+$ and $I_u^+$) $I_s$ cannot be low ($I_s^-$).A small value of $I_u^-$ shows reduced withdrawal (problem 4) where increased regulation of the system withdrawal will be required (solution C). A similar analysis to the one described in the previous paragraph could be applied to problem 4 and solution C. The intensity of problem 4 (high, intermediate and low) and the related adaptive strategy C (high, intermediate and low) is inversely proportional to the value taken by $I_s$ (low, intermediate and high, respectively).

Finally, solution A (demand management) can be an adaptive strategy to reduce or solve any of the supply problems resulting from climate change (see Table 1). The intensity of the solution required depends on the magnitude of the problems identified.

## 4. Case study: Serpis system

The Serpis water resource system, located in the Jucar River Basin in Eastern Mediterranean Spain (see Fig. 1), has been selected as a case study.

The Serpis River system has a surface area of 990 km$^2$. Average rainfall in the basin is around 630 mm, and the mean temperature is 16.3 °C. Mean yearly natural surface inflow is 96 Mm$^3$/year. The current population in the basin is 205,414 people, but during the summer tourism increases this number by around 50%. Most of the urban demand is supplied from pumped aquifer abstractions. Agricultural demand is 103 Mm$^3$/year, which accounts for 76% of the water demand of the system (135.5 Mm$^3$/year). This demand is more intensive during the summer (15% in autumn, 13% in winter, 27% in Spring and 45% in summer). Agricultural land covers 37,401 Hm$^2$, of which 41 % (15,169 Hm$^2$) is irrigated.

A schematic of the Serpis River system is shown in Fig. 2. It includes one reservoir (Beniarrés Reservoir, capacity 29.5 Mm$^3$), 5 aquifers, 37 conduits, 23 inflows and 18 demand centres (7 of them agrarian). A management model of the current situation can be observed in the next figure.

We are not going to describe the different components of this management model in detail because its construction is not the objective of this paper. The main interest of this section is to show how the methodology developed can be applied to any system to generate new scenarios and how the systematic procedure proposed (using indices calculated from a management model) can be applied to identify problems, as well as their solutions to reduce climate change impacts.

### 4.1. Future scenarios

Different scenarios for the Serpis River system have been generated combining different hypothesis about demands and pumping thresholds with one expected future hydrology (generated with the proposed procedure) as described in Section 2.

#### 4.1.1. Hydrological future scenario

The control and future scenarios provided by the Prudence Project using the GKSS regional model for the area studied were employed to generate a climate-change hydrological scenario of the system, following the steps described in Section 2.

This section summarizes each of the steps to estimate a future inflow scenario due to climate change. The monthly mean ($\mu^j$) and standard deviation ($\sigma^j$) of the GKSS run-off series (both control [1961–1990] and future series [2071–2100]) are represented in Fig. 3, together with their confidence intervals. These values were employed to generate the normalized run-off series $y^{x,j}(s)$.

The relative differences between these variables (mean and standard deviation) for the control and future scenarios are given in Table 2.

The aggregated streamflow series was modified to take into account the effect of climate change (changes in mean and standard deviation) following the steps described in Section 2.1. The original and derived series are represented at monthly and yearly scale in Fig. 4. We have also represented in Fig. 4 the results derived applying a monthly constant ratio to the original series in order to compare results with those obtained from the proposed procedure. As can be observed in Fig. 4, the generation of streamflow series for this case study is sensitive to changes in the downscaling method.

The global series was disaggregated into the multiple streamflow series originally considered within the management model, maintaining their percentage with respect to the aggregated series in the historical scenario.

The average monthly inflows over the period selected have been also represented in Fig. 5 in order to show how the trend would change in an average year.

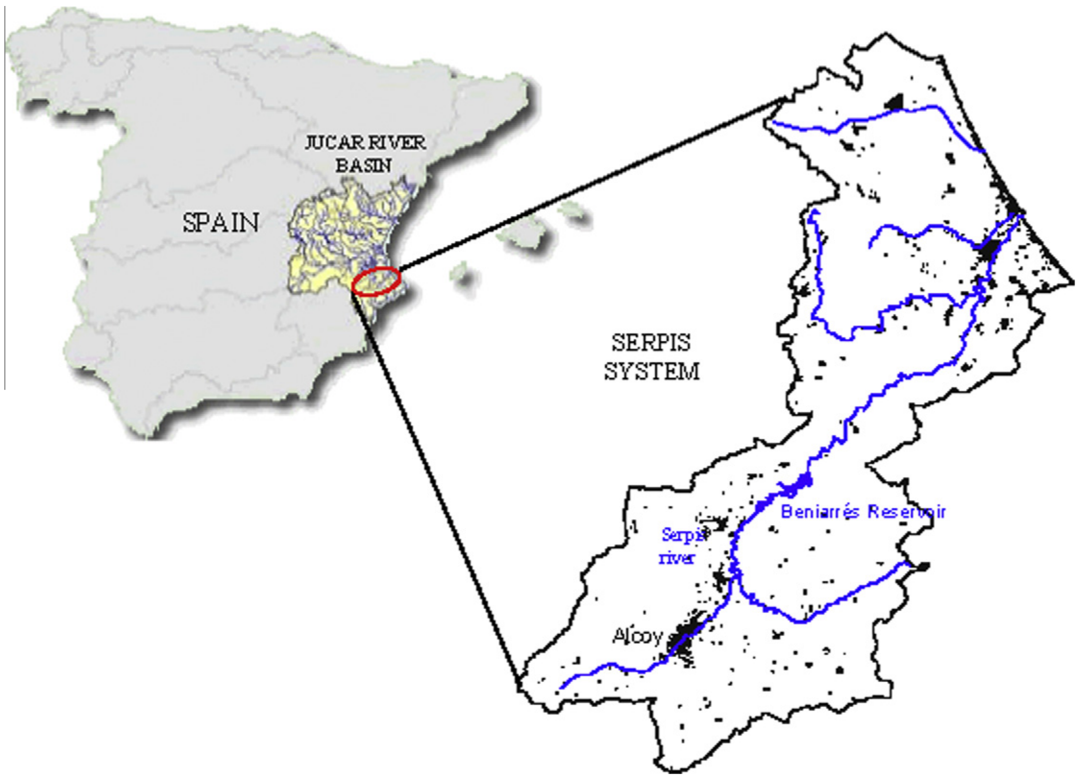


**Fig. 1.** Location of the Serpis River system.

As can be observed in Table 2 and Fig. 5, the maximum reduction in mean monthly streamflow due to climate change will appear during August, month in which the historical streamflow is at its minimum and the agricultural demand at its maximum. The maximum change in standard deviation would appear also during August. In accordance with the changes predicted, climate change would contribute to make this month the most critical in the management of the system (significantly more than in the current situation).

#### 4.1.2. Future scenarios defined with one estimated future hydrology and different policy scenarios

As stated in Section 2, one of the objectives of this research is to study if current agricultural demands could be satisfactorily supplied with the expected future hydrology considering that the effect of slightly increasing or decreasing water for agricultural use in the system. In order to achieve this objective, we decided to analyze future scenarios defined under the following hypotheses about agricultural demands: to maintain the current agricultural demand, or to increase or decrease it by 10% (which allows us to carry out a sensitivity analysis to small changes in the agricultural demand). These scenarios have been analyzed under different hypotheses about sustainable use of the aquifers in the basins, which have been defined as limiting the pumping from each aquifer to certain percentages of the recharge considered reasonable from an environmental perspective. In order to analyze the sensitivity of the method to pumping hypothesis we have considered different percentages of the estimated future aquifer recharge (0%, 25%, 75% and 100%) to define the pumping constraints. We also considered a case defined as maintaining the current net aquifer recharge (difference between pumping and recharge) in order to approach a scenario where the influence over aquifer storage is not increased. Combining all these aspects we have finally defined 18 policy scenarios, which are shown in Table 3.

### 4.2. Results obtained: diagnosis of problems expected and planning and management strategies to reduce them

The management model was employed to calculate the indices described in Section 3, under one historical scenario and the 18 future scenarios described in the previous section (defined by combining one estimated future hydrology and different hypotheses about agricultural demands as well as pumping constraints). The indices obtained for these scenarios under different pumping limit hypotheses fixed as percentages of aquifer recharge are presented in Fig. 5 and their numerical values are shown in Table 4. Thus, for a fixed pumping constraint (set to maintain a certain sustainability level), the values taken by the selected indices under different agricultural demands can be seen. We could also deduce the agricultural demand that could be supplied by maintaining a certain range of the selected indices (in order to avoid supply problems) under a pumping constraint hypothesis.

In terms of the values taken by the indices we classified each into three categories of high, intermediate and low. The numerical threshold that defines these categories should take into account historical water management in the basin (indices obtained for the scenario that represents the current situation, see Section 4.2.1). In order to analyze (in this case study) if the indices are sensitive to the downscaling method we have compared the value obtained for them in scenario S1 (see Table 3) with those obtained using as future streamflow series the one generated by employing hydrologic response ratios.

#### 4.2.1. Current scenario

We computed the proposed indices for this system under the scenario that represents the current situation (current hydrology, demands and operations in the system). The values obtained are: $I_s = 0.96$, $I_r = 0.94$, $I_w = 0.88$ and $I_u = 1.09$.These high values of the indices correspond to excellent supply conditions from a

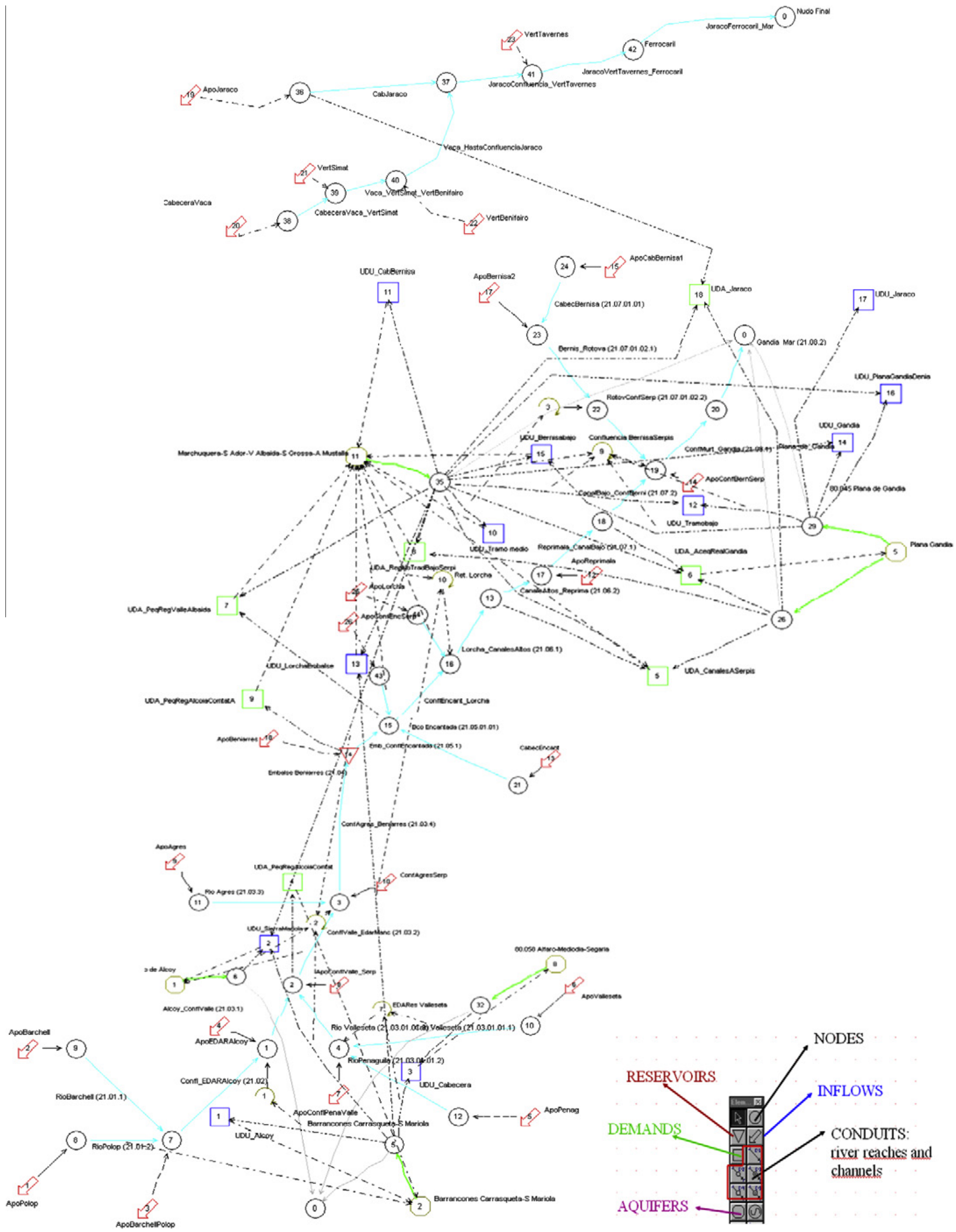


**Fig. 2.** Schematic of the Serpis River system.

quantitative perspective, which agrees with the general feeling of the stakeholders and the water agency. The high value of $I_u$, (1.09), even higher than 1, is due to the high level of water reuse in the basin. The pumping in the basin is around 40% of the total net recharge in the aquifers of the system.

*4.2.2. Future scenarios*

In this subsection we analyze the results obtained under different pumping constraints defined as certain percentages of the aquifer recharge for the future scenario generated with the proposed procedure. The values obtained for the indices are represented in Fig. 6 and listed in Table 4. They have been estimated for three different hypotheses about agricultural demands (current demands, current +10%, and current −10%).

As can be observed for all the values of $I_u$ represented in Fig. 5 and shown in Table 4, the $I_u$ values computed for the future scenarios are slightly higher than those for the current situation (1.09). This would be due to the increased urban water demands, which would produce more returns (if the percentage of returns with respect to the demand is maintained), and, therefore, an increase in abstractions.

Fig. 5 also shows how the values of $I_s$ and $I_r$ rise as pumping increases. When we increase the flexibility in the conjunctive-use management (relaxing the pumping constraint) the demand will be supplied with less problems (see supply problems characterized by indices $I_s$ and $I_r$ in Section 3). Therefore, a compromise solution must be adopted between minimizing demand deficits and fulfilling certain environmental constraints on pumpings in the aquifers. Fixing the pumping limit as a percentage

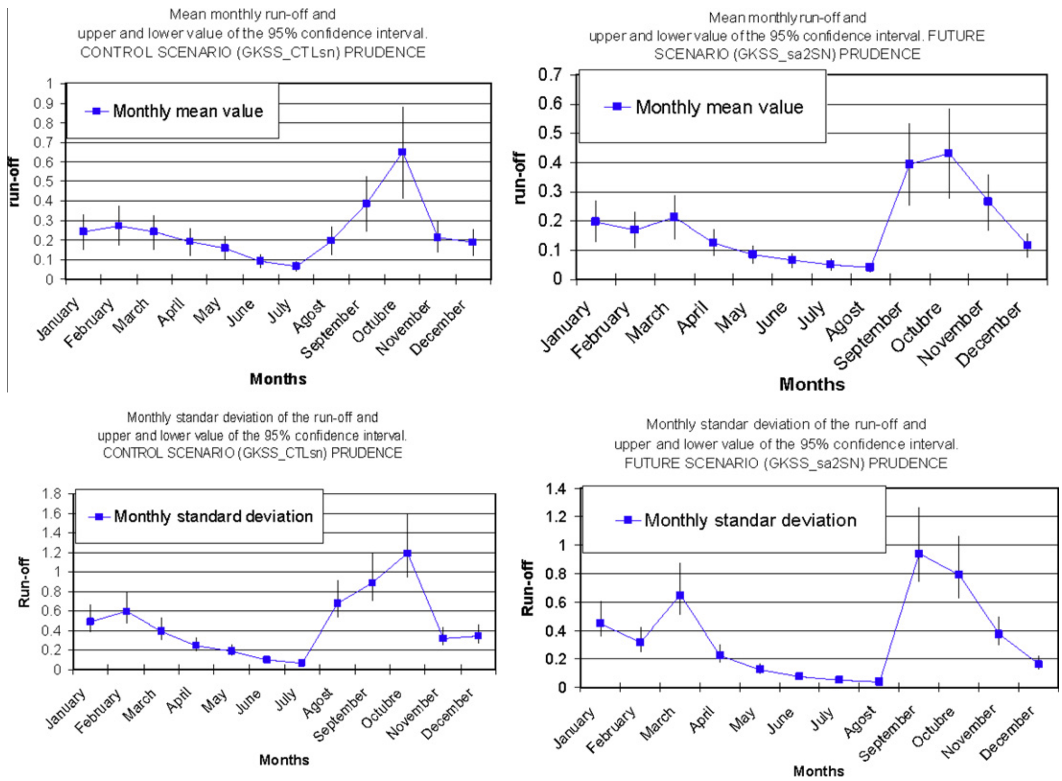


**Fig. 3.** Monthly means ($\mu^j$) and standard deviations ($\sigma^j$) of the GKSS run-off series with their confidence interval.

**Table 2**
Relative differences between monthly means and standard deviations obtained for the control and future scenarios defined by the GKSS model.

| Months | Realative differences(Eq. (2)) | |
|---|---|---|
| | Mean ($\Delta\nu^j$) | Standard deviation ($\Delta\nu^j$) |
| January | −0.19 | −0.08 |
| February | −0.38 | −0.46 |
| March | −0.12 | 0.65 |
| April | −0.34 | −0.08 |
| May | −0.47 | −0.35 |
| June | −0.29 | −0.21 |
| July | -0.23 | −0.19 |
| August | −0.80 | −0.95 |
| September | 0.02 | 0.06 |
| October | −0.33 | −0.34 |
| November | 0.23 | 0.16 |
| December | −0.39 | −0.52 |

of the mean recharge (percentage that should be derived from environmental criteria), the values of $I_s$ and $I_r$ under different hypothesis of agricultural demands can be deduced (see Fig. 5). If the thresholds that define the qualitative range for each index (high, intermediate and low) were fixed, the values represented could be used to identify problems and possible solutions (Table 1).

For example, in this system it was decided to adopt the following restrictive criteria (in accordance with the results obtained for the current situation and the general feeling of the stakeholders) to define high, intermediate and low levels of the indices Table 5:

One extreme case is where pumping is 0%, a hypothesis that does not change natural surface flow in the system. The reuse under these conditions (no pumping and current surface infrastructure) would be significant as shown by the high values of the index $I_u$ for the three hypotheses of agricultural demands considered: $I_u = 1.18$ maintaining the agricultural demand volume, $I_u = 1.29$ reducing it by 10%, and $I_u = 1.22$ increasing the agricultural demand by 10%. Despite the significance of the reuse, low values of the other indices will be obtained for the three demand hypotheses in this case ($I_s = 0.30$ and $I_r = 0.19$ maintaining the agricultural demand volume, $I_s = 0.38$ and $I_r = 0.38$ reducing the agricultural demand by 10%, $I_s = 0.28$ and $I_r = 0.18$ increasing the agricultural demand by 10%). We would also have a low system yield in this scenario with respect to the demand (which is also reflected in $I_w$ values: $I_w = 0.26$ maintaining the agricultural demand volume, $I_w = 0.29$ reducing it by 10%, and $I_w = 0.23$ increasing it by 10%). Therefore, in accordance with Tables 3 and 1, the problems identified in the system are: high vulnerability, high unreliability and high excess of demand with respect to withdrawal. Solutions (see also Table 1) could be found through alternative demand management strategies or by introducing complementary resources (additional pumping, water transfers, etc.). An increment in the maximum pumping limit would allow greater flexibility in the conjunctive-use management. We have also solved this management scenario (without pumping) for the current agricultural demand with the future streamflow series generated by modifying the monthly means of the original series. The values obtained for the indices ($I_s = 0.32$, $I_r = 0.19$, $I_w = 0.25$ and $I_u = 1.28$) show, as for this case study, that they are slightly sensitive to the downscaling method employed (the indices obtained with the future streamflow series that takes into account also the expected change in the standard deviation were $I_s = 0.30$, $I_r = 0.19$, $I_w = 0.26$ and $I_u = 1.18$).

The other extreme value of pumping constraints represented in Fig. 5 corresponds to the case in which pumping is limited to the estimated mean recharge. Under this hypothesis, stream depletion will reduce the base flow but will not produce a long

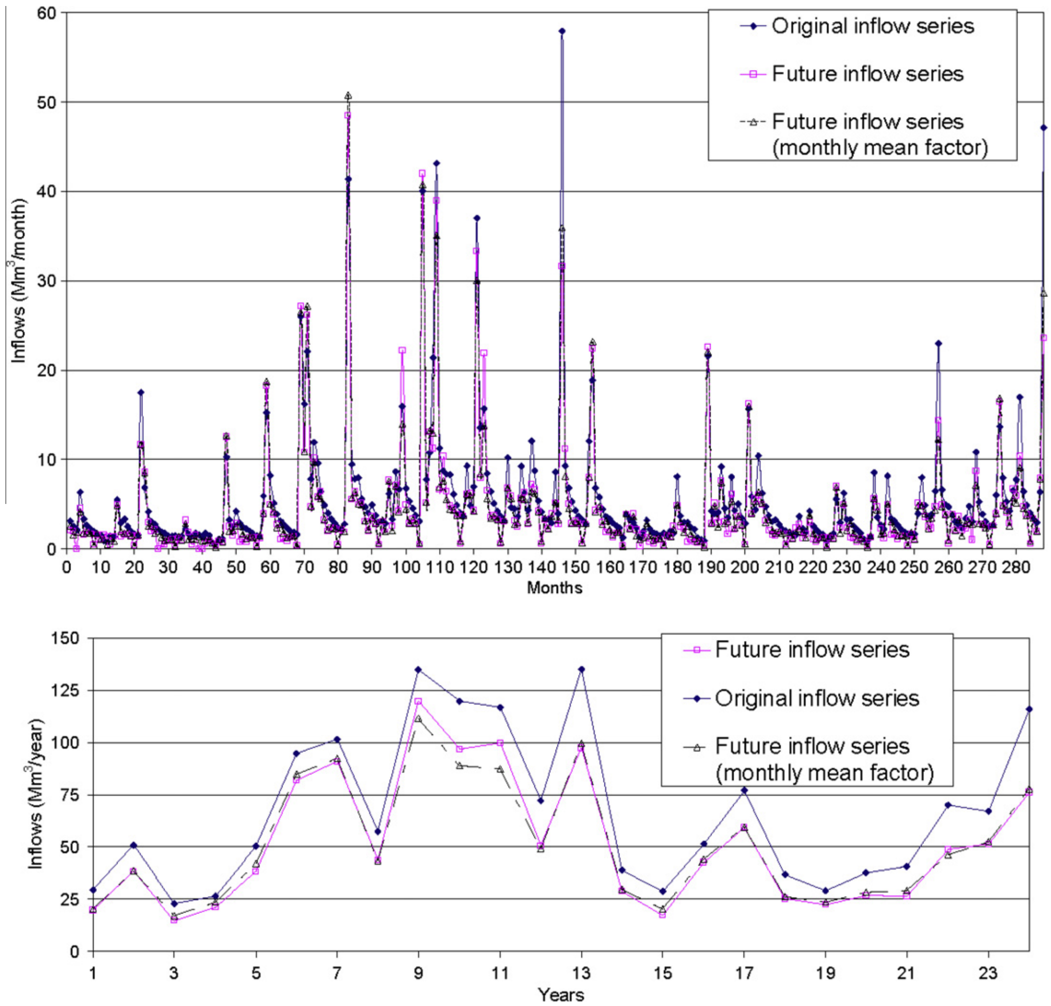


**Fig. 4.** Aggregated original inflow series of the system and estimated future one.

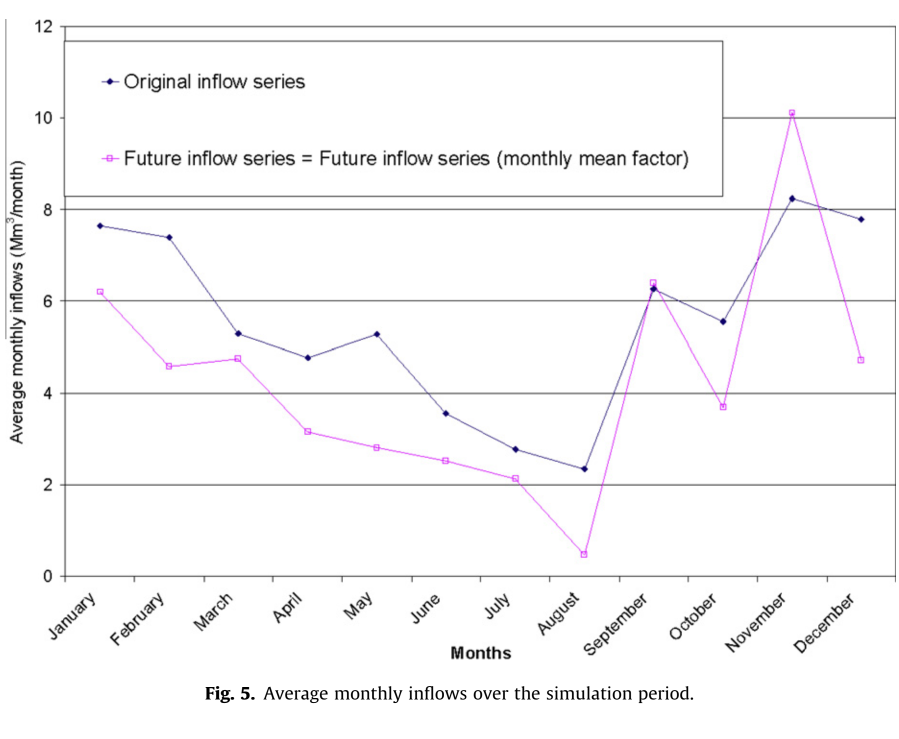


**Fig. 5.** Average monthly inflows over the simulation period.

**Table 3**
Future policy scenarios considered in the analysis.

| Pumping constraint | Agricultural demands | | |
|---|---|---|---|
| | Current demand | Reducing 10% | Increasing 10% |
| *Future hydrological scenario* | | | |
| 0% of the recharge | S1 | S6 | S11 |
| 25% of the recharge | S2 | S7 | S12 |
| 50% of the recharge | S3 | S8 | S13 |
| 75% of the recharge | S4 | S9 | S14 |
| 100% of the recharge | S5 | S10 | S15 |
| Maintaining the net recharge | S16 | S17 | S18 |

term net-flow from the stream to the aquifer. The values of the indices for this pumping constraint are $I_s = 0.96$, $I_r = 0.92$, $I_w = 0.82$ and $I_u = 1.17$ maintaining the agricultural demand volume, $I_s = 0.96$, $I_r = 0.92$, $I_w = 0.83$ and $I_u = 1.16$ reducing it by 10%, and $I_s = 0.94$, $I_r = 0.84$, $I_w = 0.78$ and $I_u = 1.21$ increasing agricultural demand by 10%. Therefore, in accordance with Tables 1 and 3, under this hypothesis, the system could be managed without any supply problem if agricultural demands are equal or smaller than the current one, but not when they increase by 10% or more. A 10% increase in agricultural demand would produce intermediate values of $I_s$ and $I_r$ ($I_s^=$ and $I_r^=$) and a low $I_w$ index ($I_w$). Therefore, in accordance with Table 1, problems of intermediate intensity would arise: vulnerability, unreliability and a demand that exceeds withdrawal. The solutions (see also Table 1) to these problems could be found through demand management alternatives or by introducing complementary resources that could come from a water transfer scheme. In this case, there is no option of increasing pumping (limited to the 100% of the aquifer recharge) without inducing environmental problems. The level of water reuse is also significant in the basin ($I_u = 1.21$) and it would therefore be difficult to increase.

However, if environmental considerations led to pumping being limited to less than 50%, there would be supply problems (even if the agricultural demand were reduced by 10%). In accordance with Table 1, the problems identified in the system would be: vulnerability, unreliability and a demand that exceeds withdrawal, but not as severe as in the previous case (pumping limit is smaller or null). Solutions to these problems (see also Table 1) could include demand management alternatives or the introduction of complementary resources (additional pumping or water transfer). The actions required in this case are not as intensive as when the pumping is limited to smaller values.

### 4.2.3. Future scenario considering pumping abstractions limited to the current pumping minus the estimated reduction in aquifer recharge

We also wanted to study the effect of maintaining the current net aquifer recharge (difference between pumping and recharge) in order to approach a scenario where the influence over aquifer storage is not increased. This analysis was performed by limiting the monthly pumping to the mean historical pumping, minus the estimated reduction in aquifer recharge. The indices calculated under this hypothesis are intermediate between the one obtained limiting the pumping to 50% and 75% of aquifer recharge ($I_s = .82, I_r = 0.69$, $I_w = 0.73$ and $I_u = 1.18$ maintaining the agricultural demand, $I_s = 0.88$, $I_r = 0.71$, $I_w = 0.72$ and $I_u = 1.20$ reducing it by 10%, and $I_s = 0.84$, $I_r = 0.60$, $I_w = 0.72$ and $I_u = 1.20$ increasing it by 10%). Intermediate values of $I_s$ and $I_r$ are obtained (if the agricultural demand is increased by 10% $I_r$ would be on the limit for a low value ($I_r = 0.60$)), jointly with small $I_w$ values. Therefore, the problems identified in the system (Table 1) are: vulnerability, unreliability and demand in excess of withdrawal. The solutions (see also Table 1) to these problems could be found through demand management alternatives or by introducing complementary resources from water transfers or additional pumping in cases where they are compatible with the environmental constraints.

## 5. Limitations

The future streamflow scenario is generated from a historical series with a procedure to modify some statistics (monthly mean and variance) of the original series in accordance with the change estimated in the area for them due to climate change. The downscaling methodology has been developed assuming that, although RCMs do not provide accurate absolute value of hydrological variables for a system, a good approximation of the relative change (due to climate change) on the main statistics (monthly mean and variance) of the hydrological variables can be derived from them. We have not incorporated the change expected for statistics of higher order (only for the mean and variance). This research studies if current agricultural demands could be satisfactorily supplied under possible future policy scenarios and explores the effect of slightly (10%) increasing or reducing water for agricultural use in the system (a sensitivity analysis). It does not intend to forecast and analyze future agricultural demand scenarios.

Irrigation water demand scenarios are determined by changes in the physical variables of the scenario (precipitation and temperature), changes in socio-economic conditions (management at the farm level, markets and trade, and policy), and changes in technology (agricultural and hydraulic). When policy and technology re-

**Table 4**
Values of the indices estimated for the 18 scenarios considered.

| Pumping constraint | Agricultural demands | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Current demand | | | | Reducing 10% | | | | Increasing 10% | | | |
| | $I_s$ | $I_r$ | $I_w$ | $I_u$ | $I_s$ | $I_r$ | $I_w$ | $I_u$ | $I_s$ | $I_r$ | $I_w$ | $I_u$ |
| *Future hydrological scenario* | | | | | | | | | | | | |
| 0% of the recharge | 0.30 | 0.19 | 0.26 | 1.18 | 0.38 | 0.38 | 0.29 | 1.29 | 0.28 | 0.18 | 0.23 | 1.22 |
| 25% of the recharge | 0.59 | 0.41 | 0.53 | 1.12 | 0.63 | 0.44 | 0.54 | 1.17 | 0.58 | 0.36 | 0.50 | 1.17 |
| 50% of the recharge | 0.82 | 0.61 | 0.69 | 1.18 | 0.83 | 0.63 | 0.70 | 1.19 | 0.79 | 0.56 | 0.66 | 1.20 |
| 75% of the recharge | 0.91 | 0.71 | 0.77 | 1.18 | 0.92 | 0.73 | 0.78 | 1.18 | 0.89 | 0.64 | 0.74 | 1.20 |
| 100% of the recharge | 0.96 | 0.92 | 0.82 | 1.17 | 0.96 | 0.92 | 0.83 | 1.16 | 0.94 | 0.84 | 0.78 | 1.21 |
| Maintaining the net recharge | 0.82 | 0.73 | 0.73 | 1.18 | 0.88 | 0.71 | 0.72 | 1.20 | 0.84 | 0.60 | 0.72 | 1.20 |

$I_s$ = DEMAND SATIFICATION.
$I_r$ = DEMAND RELIAVILITY.
$I_w$ = WITHDRAWL.
$I_u$ = WITHDRAWL USE.

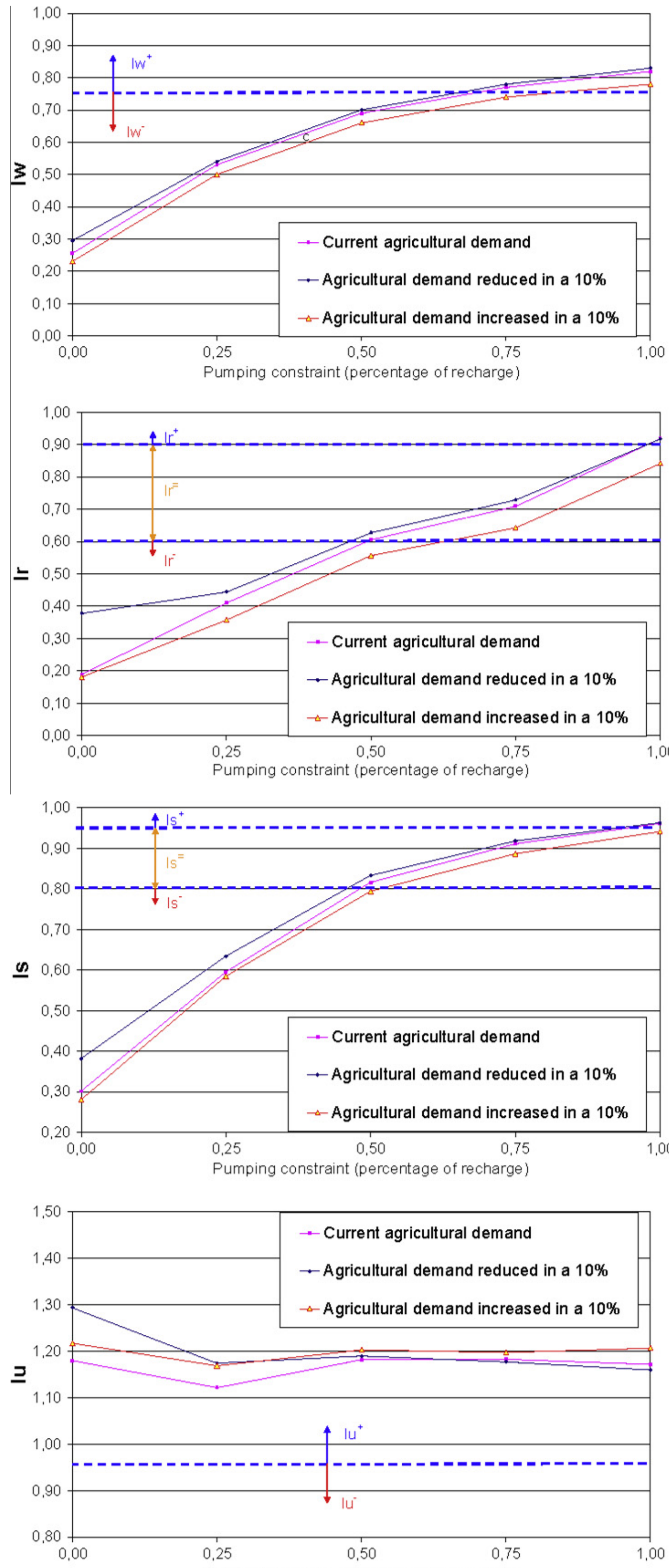


Fig. 6. Index values for different pumping and agricultural demands.

main constant, it has been shown that agricultural water demand increases in all scenarios in the region (Iglesias et al., 2007). The main drivers of this irrigation demand increase are the decrease in effective rainfall and increase in potential evapotranspiration (due to higher temperature and changes of other meteorological variables). It is reasonable to assume that, without changes in

**Table 5**
Index thresholds used to define the qualitative categories.

| Indexes | High value | Inter mediate value | Low value |
|---|---|---|---|
| DEMAND SATIFICATION ($I_s$) | >0.95 | [0.95–0.80] | <0.80 |
| DEMAND RELIAVILITY($I_r$) | >0.90 | [0.90–0.60] | <0.60 |
| WITHDRAWAL ($I_w$) | >0.75 | – | <0.75 |
| WITHDRAWL USE($I_u$) | >0.95 | – | <0.95 |

policy, land use or technology, projected irrigation demand in the basin will be higher than present irrigation demand even if farmers apply efficient management practices and adjust cropping systems to the new climate. Nevertheless, land use and water policies, and technology, are key determinants of future projections (Iglesias, 2009). It is accepted without any doubt that future agricultural and water policy in the region will have a profound effect in lowering the demand of irrigation water. Policies include water pricing, and the complying with environmental regulations. It is also reasonable to assume technology will make water use more effective. Therefore, future irrigation demand may increase or decrease depending on the relative importance of these two sets of determinants, but the magnitude of the changes is probably low also as result of these two sets of determinants. To characterize this uncertain future, we have selected a sensitivity analysis of plus and minus 10% irrigation demand, to represent a pessimistic scenario dominated by physical changes, and an optimistic scenario driven by policy adjustments that respond to the societal demand of increasing environmental services of water.

Scenarios of urban water demand are driven by changes in population and lifestyles. Population is expected to increase slightly (reference of the population database of www.ciesin.org or the population projections of the basin plan), projections of increased GDP result in lifestyle changes that demand more urban water (from collective living to single home living). No major urban development is projected in the basin. Therefore, if current land use policy remains or environmental regulations are intensified, the urban demand projections will only increase as in recent years. Industrial water demand has followed the same trend over the last four decades; the small increases also take into account the supplied demand guarantee.

The selected case study corresponds to a small system located in a cell of the RCM grid, but as commented in Section 2, it could also be extended to large river basins taking into account the spatial variation of climate change impacts with the spatial resolution considered in the RCM model. Finally, although a systematic procedure is described to estimate the indices proposed to identify problems and solutions to adapt to climate change, good knowledge of the current water management and the general feeling of the stakeholders and the water agency are required to establish the numerical thresholds of these indices.

## 6. Conclusions

Several general conclusions are supported by this study:

– A series of transformations (a downscaling method) can be employed to define future hydrological scenarios of a system modifying the historical hydrological series in accordance with information available in the area about the increase or decrease of monthly means and standard deviations produced by climate change in these variables.
– A systematic methodology, based on the values obtained for a series of indices (indices obtained from the results of a system management model) under different future scenarios, can be applied to identify problems and solutions to adapt to climate change effects in a water resource system.

The application to the Serpis River Basin has allowed us to reach the following conclusions:

– The generation of streamflow series for this case study is sensitive to changes in the downscaling method (different results have been obtained applying the technique of hydrologic response ratios and the transformation proposed in this paper).
– The maximum reduction in mean monthly streamflow due to climate change would appear in August, month in which the historical streamflow is minimum and the agricultural demand maximum. The maximum change in standard deviation would appear also in this month. Therefore, climate change would contribute to make August the most critical month in the management of the system (significantly more than in the current situation).
– The application of the indices methodology for different future scenarios has shown that, if the current agricultural demands are maintained or slightly modified (increasing or decreasing them by 10%) and the pumping is limited to values smaller than the aquifer recharge, the following problems would appear in the system: vulnerability, unreliability and a demand that exceeds withdrawal, (whose severity increases when pumping in the aquifers is reduced). Solutions to these problems could include demand management alternatives or the introduction of complementary resources (additional pumping or water transfer).
– The values obtained for the indices show, for this case study, a slight sensitivity to the downscaling method employed.

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