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Operational resilience of reservoirs to climate change, agricultural demand, and tourism: A case study from Sardinia

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HIGHLIGHTS

- A comprehensive reservoir resilience model is presented.
- Operational resilience under multiple scenarios is assessed.
- Climate change is less of a factor than development scenarios.
- Pedra e' Othoni reservoir is resilient under all likely future scenarios.
- Other Sardinian reservoirs may not be as resilient.

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ABSTRACT

Many (semi-) arid locations globally, and particularly islands, rely heavily on reservoirs for water supply. Some reservoirs are particularly vulnerable to climate and development changes (e.g. population change, tourist growth, hydropower demands). Irregularities and uncertainties in the fluvial regime associated with climate change and the continuous increase in water demand by different sectors will add new challenges to the management and to the resilience of these reservoirs. The resilience of vulnerable reservoirs must be studied in detail to prepare for and mitigate potential impacts of these changes. In this paper, a reservoir balance model is developed and presented for the Pedra e' Othoni reservoir in Sardinia, Italy, to assess resilience to climate and development changes. The model was first calibrated and validated, then forced with extensive ensemble climate data for representative concentration pathways (RCPs) 4.5 and 8.5, agricultural data, and with four socio-economic development scenarios. Future projections show a reduction in annual reservoir inflow and an increase in demand, mainly in the agricultural sector. Under no scenario is reservoir resilience significantly affected, the reservoir always achieves refill. However, this occurs at the partial expenses of hydropower production with implications for the production of renewable energy. There is also the possibility of conflict between the agricultural sector and hydropower sector for diminishing water supply. Pedra e' Othoni reservoir shows good resilience to future change mostly because of the disproportionately large basin feeding it. However this is not the case of other Sardinian reservoirs and hence a detailed resilience assessment of all reservoirs is needed, where development plans should carefully account for the trade-offs and potential conflicts among sectors. For Sardinia, the option of physical connection between reservoirs is available, as are alternative water supply measures. Those reservoirs at risk to future change should be identified, and mitigating measures investigated.
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1. Introduction

Reservoirs are generally built to augment water supply, for hydropower generation (World Watch Institute, 2012) and to attenuate flash flood flows. They alter hydrological regimes by attenuating flood

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flows and releasing accumulated volume in the summer to cope with dry season demand. In regions where water resources are scarce and summer demand is high, reservoirs play a crucial role in securing water for irrigation and domestic use. Many areas worldwide are wholly or largely reliant on reservoirs for water supply. This is particularly true for many locations in the Mediterranean where (ground) water resources are limited and inter-annual climatic variability is high. Strong dependence on reservoirs as the main water source may lead to major pressures from future changes, requiring a balance between climate change and its effects on water availability, and the development of water demand. Future pressures on reservoir operation can include: i) climate change, which can modify rainfall totals, increase evaporation losses and/or unfavourably alter the variability of supply and the hydrological regime (Arnell, 2004; Beniston et al., 2007; Christensen and Christensen, 2007; Hall et al., 2014) with implications for water resources; ii) population growth and urbanization. Water demand increases imposed by socio-economic changes are likely to pose a significant challenge. Urbanization, population growth and life style change mean that more water is needed to satisfy the domestic needs (e.g., Vandecasteele et al., 2013; Harrison et al., 2014; McDonald et al., 2014); iii) changes to agricultural regimes, influenced by changes in climate, diets and other market forces (e.g., biofuels), often leading to increasing water demand (Gerbens-Leenes et al., 2009; Munir et al., 2010; Babel et al., 2011; Elliott et al., 2014); and iv) changes to tourism. In locations where water is scarce and with a growing trend in tourism (e.g. the Mediterranean and Sardinia (see Section 3)), strong seasonal stresses in supply may be found in places with single-source water supply, increasing vulnerability to prolonged dry climatic periods. Also, in regions largely relying on summer tourism for their economy, strong seasonal stresses to water supply and distribution networks may occur (e.g. Vandecasteele et al., 2013; Harrison et al., 2014; McDonald et al., 2014).

Understanding how the resilience of reservoir-dominated systems may change in response to future changes is critical for improved mid- to long-term decision making regarding water management in these regions, especially to safeguard domestic, urban and agriculture supply. If alternative water sources (i.e., groundwater, water treatment, desalination) are not physically available or economically viable, water has to be efficiently used and intelligently allocated between sectors. This requires improved understanding of the potential changes that various forcing mechanisms, such as those described above, might have on the water balance of reservoirs.

In this paper, the resilience of a reservoir-dominated supply system (Pedra e' Othoni) located on the eastern edge of Sardinia (Italy) was assessed under current and future changes (climate, population, tourism). The reservoir (Section 3) supplies water for the tourism industry, domestic demand, agricultural sector and hydropower generation. We introduce the general modelling approach used to simulate the potential impact of changes on a reservoir-dominated supply system also accounting for some of the uncertainty surrounding various projections (i.e., climate change, population growth, tourism). The aim is to understand how potential future changes might alter long-term water supply and which of these changes have the greatest impact on the reservoir operation. Results are presented, followed by a discussion about the potential implications for operational reservoir resilience in Sardinia and the concomitant impacts on water security and competition. This work, while focussed on a specific study site, is framed within a wider agenda to secure and use more effectively existing and future water supplies, to serve a growing population in a changing world. The work is novel for the use of multiple climate and water-demand forecasting models, coupled with a system dynamics framework in which to assess potential future reservoir resilience to a wide range of threats to water security.

2. Reservoir resilience modelling approach

System Dynamics Modelling (SDM; Forrester, 1961; Ford, 1999) was exploited in order to assess the state of the reservoir water balance and resilience in Sardinia from a range of potential future threats (see Section 4 for details on the model structure). SDM was developed to study feedback problems in industry, however it has been successfully applied widely across a number of fields (Khan et al., 2009; Rehan et al., 2011; Sušnik et al., 2013; Sahin et al., 2014). SDM is used to study the behavior of complex systems which may be forced by multiple, disparate external factors and where stocks and flows lie at the heart of the system. Such systems tend to be dominated by feedback and/or delay processes. During iterative development (Ford, 1999), the model structure is constantly checked in order to verify that it still performs the desired function for which it was initially set (e.g., in this case assessing long term reservoir water balance).

SDMs comprise three main elements: stocks (e.g., water in a reservoir); flows (e.g., river inflows or evaporation) and converters which control flow rates (e.g., evaporation rates). If the inflows and outflows to/from a stock balance or are set to zero, then the value of the stock remains constant. Converters link the system elements and create feedback loops. Each expression between elements is evaluated at every modelling time-step (Ford, 1999).

For this study, the reservoir resilience model was built using STELLA (www.iseesystems.com), specific software for SD modelling. SDM has many advantages over more conventional modelling approaches. One may model many disparate sub-systems within the same simulation (e.g., water, agriculture and tourism). This was exploited here by combining elements from hydrology, irrigation, tourism, climate change and hydropower. SDM allows for the splitting of a large system into many dynamically interacting sub-systems. The models are necessarily not as realistic as dedicated spatially explicit physical models (e.g., GIS-based catchment hydrologic models). However, being able to 'mix' metrics and include socio-economic factors such as the tourism climate index, split the system into simpler pieces and incorporate relevant feedbacks, are the main reasons for choosing SDM for this study. Detailed information about climate model inputs, agricultural model inputs, tourist water demand estimation and the development scenarios used in this work is presented in Section 4.

3. Study site

We use a case study on Sardinia (Fig. 1) with which to assess reservoir resilience to future changes in climate, agriculture expansion and tourism. Specifically, the focus is on the Pedra e' Othoni reservoir (Fig. 2). Sardinia relies largely on surface water, and a large proportion of supply is stored for summer use in reservoirs across the island.

Pedra e' Othoni reservoir (Fig. 2), located in the eastern part of Sardinia, was selected to assess reservoir resilience to future changes in climate, agriculture expansion and tourism — an important economic sector for Sardinia. The reservoir is located in a water stressed region and provides water for irrigation, urban areas, tourist facilities, and hydropower generation. The reservoir also mitigates flash flooding in the catchment. Therefore the reservoir needs to be resilient to many future changes and challenges.

The Pedra e' Othoni reservoir was created by constructing a dam across the Cedrino Valley. It was completed in 1994, and has an absolute capacity of 117 Mm^3, although the utilised volume is 16–20 Mm^3. This difference can be explained by the flash-flood mitigation function. This part of Sardinia is prone to extremely intense rainfall (rainfall events have exceed 400 mm per day in the past), and the reservoir was partially designed to mitigate the resulting flood events, hence the large storage volume. It serves nine villages and one small city (Nuoro). The basin feeding the reservoir is 628 km^2 (Fig. 2). The average annual basin runoff coefficient (the proportion of upstream precipitation that ends up as surface runoff to the reservoir) was estimated by the regional water authority (ENAS) at 0.4. The reservoir receives on average 169 ± 34 Mm^3 yr^{-1}, but may peak to 240 Mm^3 yr^{-1} in rainy years. 92% of the annual inflow is received in autumn, winter and spring. The inner territories of the basin contain old growth forest and

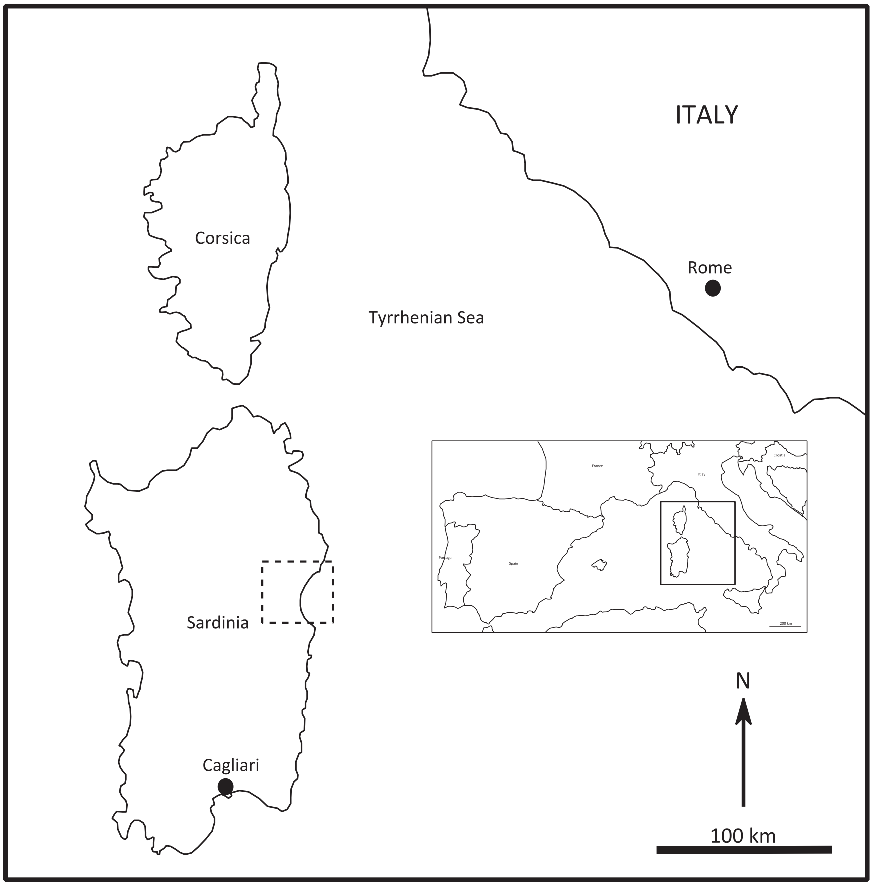

Fig. 1. The Sardinia study area. Inset: location of Sardinia in the Mediterranean (outlined by the box). Main map: dashed box indicates area shown in Fig. 2.

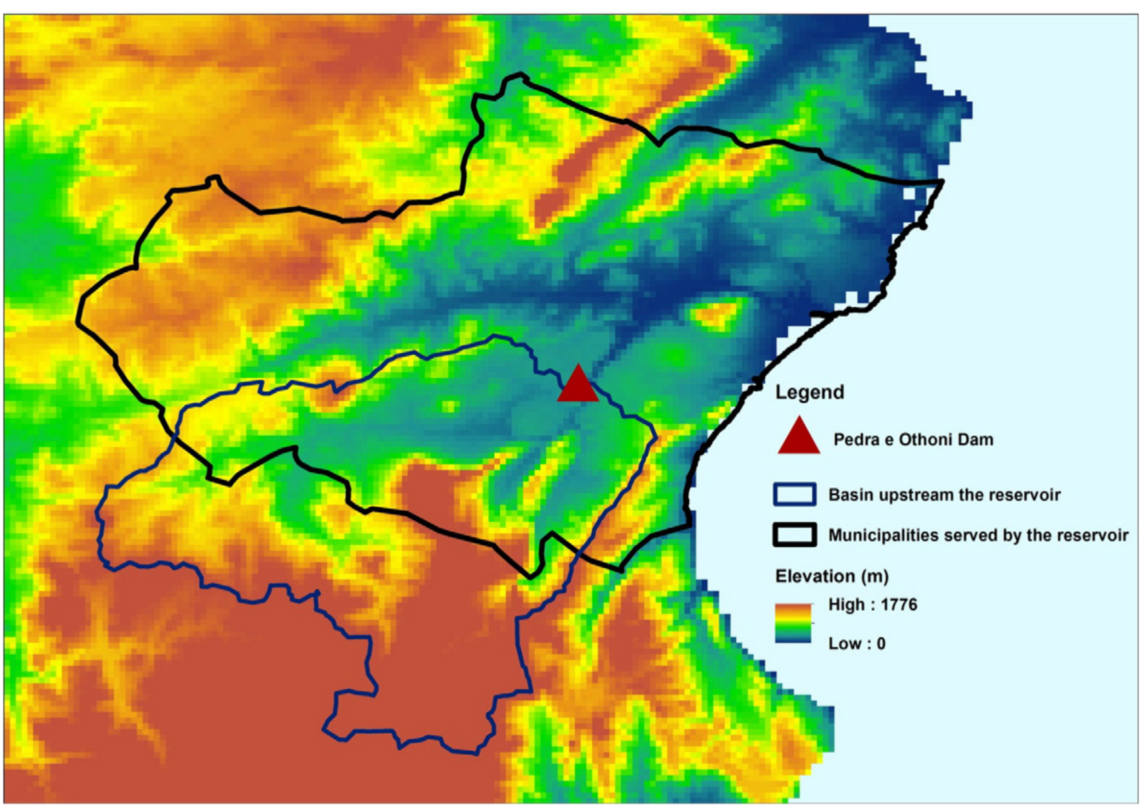

Fig. 2. The Pedra e' Othoni study basin, Sardinia.

archaeological sites important for tourism. These characteristics attract visitors throughout the year but mostly in spring and autumn, while a summer peak characterises coastal tourism. The high prevalence of forest and the low population in the upstream basin lead to high quality water with low quantities of pollutants and nutrients entering the reservoir. Therefore, the upper catchment can be considered well managed. Occasionally during flash floods, large volumes of sediment may be mobilised to reservoir. Sediment control through management is offered mainly during 'normal' discharges. However, these catchment management services are compensated neither by consistent shares of reservoir water distribution or subsidies (i.e. there is no incentive to carry on managing the upper catchment appropriately), implying that the maintenance of positive hydrological functions may be at risk in the future if the upstream population is not included in a proactive compensation/incentive scheme. The municipalities served by the reservoir produce several traditional products, but the economy of the coastal municipalities strongly relies on tourism.

4. Data, scenarios, and model development

Several climate datasets were utilised to: 1) calibrate and validate the SD model against existing dam discharge observations (2009–2011); 2) assess the dam discharge for the present climate conditions (baseline, average over the 1960–2000 period) and; 3) assess the dam discharge for an ensemble of future climate projections (2050, average over 2035–2065). Climate datasets are available on a monthly scale, the same as for the reservoir water balance model.

The reservoir model (Section 4.3) was calibrated and validated for three consecutive years from 2009 to 2011 using the CRU dataset (CRU, 2013), while monthly water outflows for agriculture, urban use and hydroelectricity production data provided by the regional water management body (Ente Acque della Sardegna). This means we use globally recognised climate data coupled to regionally accurate demand and use data for model calibration and validation.

Afterwards a baseline scenario was run using the WorldClim dataset (the model was run for 48 months to test the stability of the average annual water storage over four years). The future water balance scenarios were simulated for an ensemble of CIMP5 Earth System Models (ESMs) for two RCP scenarios (19 ESMs for RCP 4.5 and 17 ESMs for RCP 8.5). Thus, we use the latest climate projection datasets available and coherent development scenarios commonly used from the literature.

4.1. Model calibration data

The reservoir water balance model was calibrated and validated against three years (2009–2011) of monthly discharge observations. Local meteorological data were only available from a single station located over the dam and thus do not represent the spatial variability between the reservoir basin and the area served by it. For that reason, weather parameters (2009–2011) were extracted from two adjacent pixels of the CRU TS 3.1 dataset (CRU, 2013) in order to characterize with comparable scale and adequately overlap the respective climate conditions over the basin and agricultural land served by the reservoir.

The CRU TS 3.1 dataset (CRU, 2013) is a global gridded monthly time series (1900–2012) based on the interpolation of station observations for several climate variables at half degree resolution. Variables extracted and used in this study are diurnal temperature range, precipitation, daily mean temperature, monthly average daily maximum and minimum temperature, and potential evapotranspiration.

4.2. Current and future climate data

Current and ensembles of future (2050) climate projections were extracted from the WorldClim dataset (Hijmans et al., 2005) which defines a high resolution (30 arc sec) interpolation of monthly climate station observations (monthly average over 1960–2000) of temperature (Tmin, Tmax and Tav) and precipitation.

A combination of Earth System Models (ESMs) of future climate provided by Phase 5 of the Coupled Model Intercomparison Project (CMIP5; Meehl and Bony, 2011) and representative concentration pathways (RCPs; Vuuren et al., 2011) have been previously downscaled (Ramirez and Jarvis, 2010), spatially resolving monthly GCM climate anomalies with the same resolution as the WorldClim data. Ensembles of downscaled GCM models and RCP scenarios include multiple climate anomaly projections for 2050 (monthly averages 2035–2065) over WorldClim (i.e., climate model bias is excluded). It is assumed that the change in climate is similar over the catchment.

The perturbed monthly mean, minimum and maximum temperatures were used to calculate reference evapotranspiration (ET_o) using the empirical formula given in Hargreaves and Samani (1985).

4.3. Reservoir storage balance model

The simulation of the reservoir water balance functioning, integrating several relevant water flows, was developed and run in STELLA (Section 2). A schematic of the developed model structure is shown in Fig. 3. The model simulates the volume of water stored in the Pedra e' Othoni reservoir over time. The volume is controlled by one inflow and five outflows. The inflow to the reservoir is effective runoff from the upstream basin area. The outflows are: i) evaporation from the surface of the reservoir; ii) domestic water use; iii) water for irrigation; iv) spillway overflow that occurs when the water level exceeds the maximum storage capacity of the reservoir; and v) water discharged to maintain the environmental flow, ensure storage space to mitigate flooding and to ensure the operation of the hydropower turbines. The maximum throughput at the hydropower plant is 22 Mm^3 $month^{-1}$. The water level in the reservoir is maintained between the maximum storage capacity of the reservoir and the minimal critical water level, in accordance with current operating rules. The simulations account for the two RCP scenarios each in combination with four development scenarios which are described in the sections below.

The following climate data were used to simulate the inflow and outflow components of the water balance and resilience model for actual conditions (WorldClim 1960–2000) and for the ensemble of projected future conditions:

- Average monthly precipitation over the basin upstream of the reservoir;
- Average monthly open water evaporation over the reservoir;
- Average monthly mean temperature and precipitation over the distribution area served by the reservoir to calculate the Tourism Climate Index (TCI, Mieczkowski, 1985), which was used to estimate water demand for tourism;
- Average monthly precipitation and ET_o which are used to account for the irrigation requirements of the existing crop types over the distribution area served by the reservoir.

4.4. Open water evaporation

Evaporation from open water bodies, to calculate losses by evaporation from the reservoir, is approximated by multiplying reference ET_o by a coefficient of 1.1, which is an average between values reported in literature ranging between 1.05 and 1.15 (Allen et al., 1998; Jensen, 2010; Finch and Calver, 2008).

4.5. Domestic water requirements and the Tourism Climate Index (TCI)

Monthly water requirements for domestic use were calculated assuming 170 l $person^{-1}$ day^{-1} by the resident population (ISTAT, 2012). While this appears high, it includes all domestic water uses

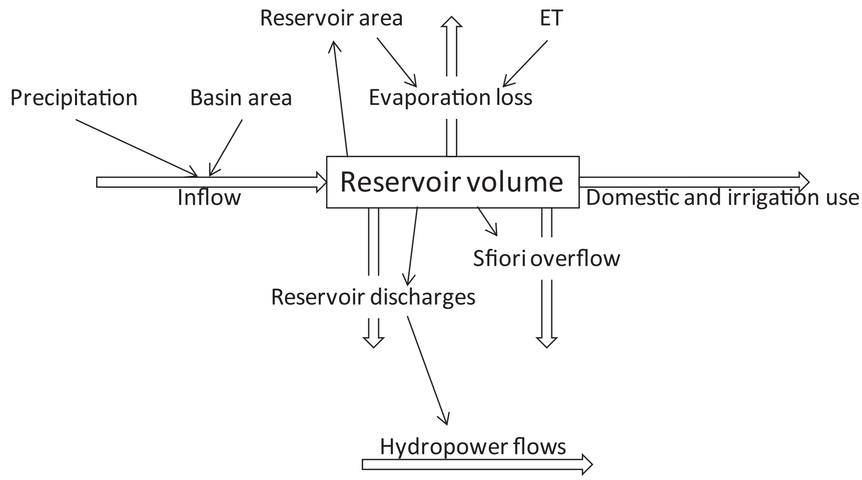

Fig. 3. Schematic overview of the systems model for calculation of the reservoir water balance. ET is evapotranspiration. Sfiori is the Italian name for a reservoir overflow structure that is used to control water releases and erosion during flooding events.

(e.g. car-washing and gardening). Large seasonal changes in water demand are assumed to be caused by tourist flows. Monthly data of overnight stays in the study area for the period 2009–2011 were provided from the Regional Statistics Office (Regione Autonoma della Sardegna). Average water consumption per tourist in hotels in Italy is about 40% greater than in camping accommodation (Gössling et al., 2012). The water consumption was set at 400 l person^{-1} day^{-1} for hotels and at 250 l person^{-1} day^{-1} for other facilities (camping, B&B, agri-tourism).

The TCI is an indicator for describing the comfort sensation of tourists for outdoor activities. It has been widely used to assess the attractiveness of a destination, and through its correlation to tourism-related data, such as arrivals and overnight stays, it can be used to estimate the impact of long-term climatic changes on tourist preferences. The TCI was developed by Mieczkowski (1985), with the objective of measuring the climatic well-being of tourists.

The maximum value of the TCI is 100, with values over 80 denoting "excellent" conditions for summer tourism. The effects of climate change on the TCI were estimated to account only for the monthly temperature and precipitation anomalies. While this measure is relatively simple, it provides a reasonable proxy for tourist comfort, and has

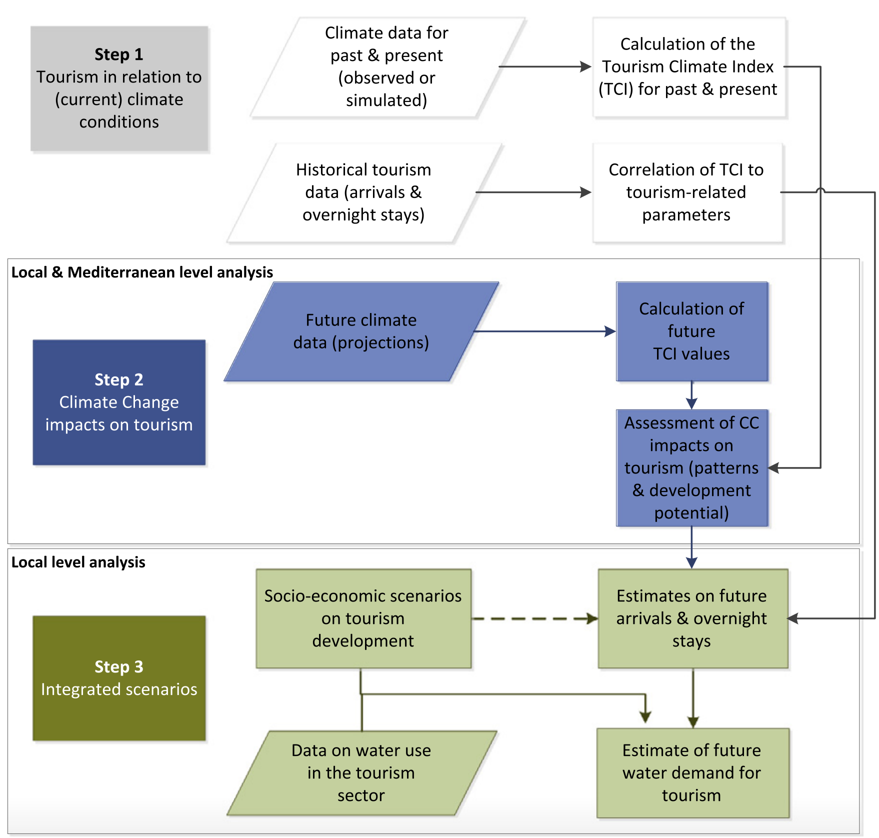

Fig. 4. Schematic showing the calculation steps involved in the TCI scenarios.

been used previously to estimate tourist fluxes (Kampregou et al., 2012).

The methodology to project future tourist water demands follows three steps (Fig. 4):

- Step 1: "Tourism in relation to current climate conditions" involves the analysis of the interrelation between climate and tourism using historical data. TCI was correlated with tourism-related parameters (monthly overnight stays over 2009–2011) using an exponential curve ($R^2 = 0.92$) in order to verify that TCI can be used to predict future tourism patterns.
- Step 2: "Climate change impacts on tourism" assessed the impacts of future climate change on tourism. On the basis of climate projections, future TCI values are calculated and used to estimate changes in tourism-related parameters for local-level analysis.
- Step 3: "Integrated scenarios" focuses on future water demand for tourism and combines analysis of both climate change impacts and socio-economic scenarios with regard to tourism development and water demand.

For this work, the TCI calculated using the CRU dataset was calibrated against overnight stay statistics. After transforming tourist flows into water demand, the simulated demand was validated against measured demand for domestic use. For Step 2, the effects of climate change on overnight stays were calculated for present and future climate scenarios. The preferences of tourists for cultural, natural and other attractions were assumed not to change. No changes due to development in tourist facilities were considered. For Step 3, four socio-economic scenarios were developed for the case study:

1. "Business As Usual (BAU) Scenario". This applies the average value of annual variations of tourist flux calculated for the reference period 2009–2011 to the period 2010–2050; an annual increment in flux of 0.75% was used.
2. "Intensive Tourism Growth (INT) Scenario". Uses the average value of annual variations observed over the period 2005–2010 chosen as a reference period with a strong expansion of the tourist sector; an annual increment of 2.1% was used.
3. "Strictly Controlled Sustainable Tourism (SOST) Scenario". An unchanged accommodation capacity has been assumed until 2050. Overnight stays are predicted to change to reach present average gross occupancy rates and the 'tourist flow patterns' are assumed to match patterns observed in 2010 in the national context for heritage destinations (namely cultural, hill and mountain locations); an annual increment of 1.2% was used.
4. "Balanced Competitive and Sustainable Growth (BAL) Scenario". It simulates progressive diversification in tourism facilities, attractions and products. A reduction in average annual growth rates has been assumed on the accommodation supply side. On the demand side, overnight stays are predicted to change in order to reach present average gross occupancy rates for coastal and mountainous locations. An annual increment of 1% was used.

The resulting overnight stays (OS_{SE}) were assumed to be equal for all months. To account for the effects of climate change, the monthly rates were corrected by the ratio of estimated overnights due to climate change (OS_{CC}) against the average value of overnight stays for the reference period 1981–2010 (OS_{RefPer}). The final estimate of future overnight stays (OS_{sc}) is calculated using:

$$OS_{SC} = OS_{SE} \cdot \frac{OS_{CC}}{OS_{RefPer}} \cdot \quad (1)$$

Results are subsequently used to assess future domestic and tourism water demand.

4.6. Irrigation requirements

The irrigation demand was estimated using a one-dimensional GIS-based soil water balance model that integrates monthly gridded climate data (CRU, 2013), soil, land cover maps and crop surface statistics at municipal level (ISTAT, 2012).

Monthly water needs (I) for each polygon were calculated using:

$$I_{i=} ETc_i - P_i + RO_i - \delta w_i - G_i \quad (4)$$

where P_i is the precipitation in month i (mm); RO is the surface runoff (mm); ETc is the crop evapotranspiration (mm), and δw is the soil moisture content in the root zone (mm). Due to the deep aquifers in the region, water capillary rise term (G) was neglected.

The fraction of effective rainfall (*Peff*) available to each crop was estimated using the empirical formulae of the USDA Soil Conservation Service (USDA, 1967). This excludes the volume of water lost by runoff or intercepted by plants.

$$Peff_{(i)} = \left(\frac{P_{(i)}}{125}\right) * \left(125 - 0.2P_{(i)}\right) \quad \text{for} \quad P_{(i)} < 250 \ \text{mm} \quad (5)$$

$$Peff_{(i)} = 125 + 0.1P_{(i)} \quad \text{for} \quad P_{(i)} > 250 \ \text{mm} \quad (6)$$

Crop evapotranspiration (ET_c) was calculated by adjusting the reference evapotranspiration using the well-known crop coefficient (K_c) method described by Allen et al. (1998). This method assumes that plants are growing under optimal nutrient and water conditions. This does not necessarily reflect the actual farming practices where plants are deliberately (i.e., for quality reasons) or unintentionally (i.e. bad irrigation management) exposed to water stress or over-irrigation.

In this work, the total volumetric irrigation need was calibrated with the measured volume for irrigation over the period 2009–2011. The water balance model was then applied for the baseline and 2050 period using the following four crop development scenarios (Table 1):

1. Business-As-Usual (BAU): irrigated areas are unchanged.
2. Intensive growth scenario (INT): 40% expansion of irrigated areas only for high value, water demanding crops.
3. Strictly controlled sustainable growth scenario (SOST): irrigated areas increase for fruit trees, vegetables and traditional crops but not for high demanding crops (e.g. maize and pasture).
4. Balanced Competitive and Sustainable Growth (BAL) Scenario: Irrigated areas increase for all crops but proportionally less for high water demanding crops.

These scenarios are used together with the TCI scenarios described above to alter water demands in the reservoir balance model.

Table 1
Actual irrigated agricultural area (hectare per crop type) for the study area, and their assumed development under the four crop development scenarios.

	Actual	BAU	IGS	SOST	BAL
Fruit trees	46	46	65	60	65
Vineyards	185	185	259	241	241
Arable	12	12	17	17	16
Vegetables	75	75	105	105	105
Citrus	76	76	107	91	91
Pasture	1349	1349	1889	1349	1484
Olive	282	282	395	338	338
Oat	19	19	27	19	21
Barley	19	19	27	19	21
Maize	53	53	74	0	37
Total	2117	2117	2964	2241	2420

4.7. Hydropower generation

Hydropower generation follows a complex seasonal pattern which depends on power demand and the amount of water stored in the reservoir which must always guarantee water for irrigation and domestic use. The hydropower plant produces approximately 0.09 kWh m^{-3} of water, and annually produces about 8 GWh (ENEL, 2013).

5. Results

5.1. Changes to temperature and precipitation

Climate scenarios for the basin predict average change in annual precipitation ranging from −173 to +31 mm compared to 1960–2000. However, increases in precipitation are unlikely to occur, and average values indicate decreases of 40 [−66/−8] and 56 [−111/−2] mm for RCPs 4.5 and 8.5 respectively (values in square brackets represent the 15th and 85th percentiles respectively and do so through the rest of the paper). Assuming no change in the basin runoff coefficient these reductions correspond to average change of inflow in the reservoir of −10 and −14 Mm^3, respectively. ESM models show much less uncertainty for annual mean temperatures which increase on average by 1.96 [1.3/2.6] and 2.46 [1.7/3.1] °C for the 4.5 and 8.5 RCPs respectively (Fig. 5). The absolute values and the effects of climate change on the direct evaporation from the reservoir surface are minor.

5.2. Model validation

The models for irrigation and domestic water demand were fairly accurate with a normalized root mean squared error (RMSE) of 0.13 and 0.14 respectively (Fig. 6). Both models capture both the intra- and the inter-annual variability observed in the period 2009–2011. The model outputs for hydropower production are not as satisfactory (RMSE = 0.28). This poor correlation is due to the complexity of the human decisions and of the power grid performance (power demand) that is not accounted for in the model. Annual modelled fluxes for the three sectors are in good agreement with measured volumes. The modelled reservoir volume follows the measured annual fluctuations but with some delays or anticipations due to the uncertainty of timing for the hydropower energy production (RMSE = 0.22).

5.3. Changes to water demands and reservoir water balance under future scenarios

Irrigation under the BAU scenario implemented no change in crop distribution, therefore climate change alone determines the slight increase in crop water requirements of 1.35 [0.9/1.8] and 1.63 [1.1/2.1] Mm^3 under the RCP 4.5 and RCP 8.5 respectively due to the combined effect of higher temperature and lower precipitation (Fig. 7). The SOST and Bal scenarios have water demand slightly higher than BAU since both avoid or limit the expansion of irrigated area for high water demanding crops. The irrigation requirements for the intensive growth scenario, with a 40% expansion of irrigated area, increase by 5.22 Mm^3 [4.6/5.9] in the RCP 4.5 and by 5.6 [4.9/6.3] under the RCP 8.5 scenario.

Changes in domestic use (Fig. 8) are minor compared to other uses in terms of water volume. However, the distribution of this water is expensive due to the requisite infrastructure. This cost was not modelled for this work, but presents an opportunity for future research. Both the RCP 4.5 and 8.5 scenarios predict an increase in TCI in April/May and October/November that is reflected in an increase in domestic water requirement during these months. In the summer months, TCI either remains the same or it decreases slightly. High temperatures will negatively affect tourism during this period of time, therefore the increase in domestic water requirements in these months is mostly due to the development scenarios.

Note that the INT scenarios predict the highest increase in water requirements. However, this scenario addresses mostly coastal tourism with a high water demand per person and also requires the construction of an extensive distribution network. The SOST and BAL scenarios address internal (mainland) tourism with a lower water requirement per person and minor changes to the distribution network.

The Pedra e' Othoni reservoir was built to secure downstream areas from floods. The dam collects water from a large basin but continuously discharges the large quantities of water collected in order to preserve storage volume and buffer flash floods. It is not surprising that despite the increase in water requirements for irrigation and domestic use, under all scenarios, the initial water volume is always restored by the end of the year (Fig. 9). That is, under no scenario is long-term, chronic depletion of the reservoir water resource expected. However, under the intensive (INT) growth scenario, the reservoir undergoes higher fluctuations in summer compared to the other development scenarios, with potential implications for water quality and competition between sectors. Additionally, the increased demand for water by the agricultural sector and the decreased precipitation (i.e., reduction in reservoir inflow) are largely compensated by a decrease in the available annual water for energy production in the range of −14.5 [−22.4/−6.3] Mm^3 in the best case scenario (BAU RCP 4.5) up to −21 [−31/−11.4] Mm^3 in the INT and RCP 8.5 case (i.e., reduction in hydropower generation).

In order to examine what increases in demand would be required to seriously deplete the reservoir, a series of additional simulations were carried out. In these extreme scenarios, domestic and irrigation demand were increased by simple multiples relative to the current situation. Under a doubling of current demands, there is no substantial loss of storage capacity, and the reservoir can essentially function as normal, although hydropower production would be constrained for slightly longer periods of time through a typical year. Under a five-fold demand increase, the stored volume would not be nearly sufficient to meet summer requirements and the hydropower releases are significantly curtailed. This would have clear implications for Sardinian energy generation. Under an extreme 10-fold demand increase, the reservoir system essentially collapses. Refill is no longer possible and the reservoir is completely empty for much of the simulation. While catastrophic, a 10-fold increase to irrigation and domestic demands is considered extremely unlikely. It was used here to demonstrate the conditions required in order to inhibit refilling of the reservoir.

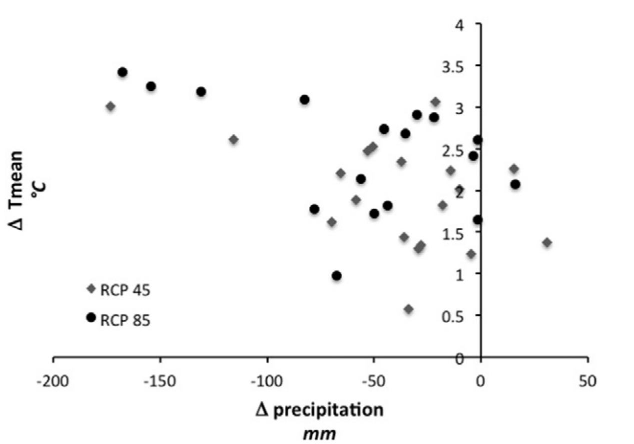

Fig. 5. Change in annual mean temperature and precipitation projected by different ESM models for RCPs 4.5 and 8.5 and downscaled for the area served by the reservoir.

6. Discussion

The principle role of the reservoir of Pedra e' Othoni is to secure water supply for multiple users, to generate electricity and to protect downstream areas from flash floods similar to those that have occurred in the past. In the past 20 years, rain events up to 400 mm in less than

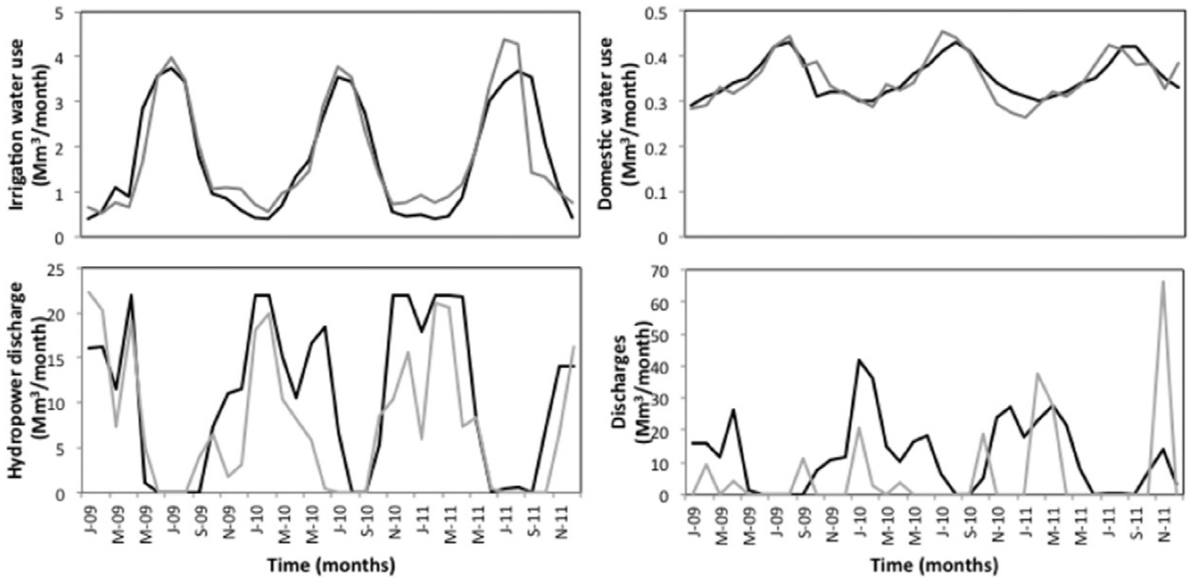

Fig. 6. Measured (grey line) and modelled (black line) water flows for the Pedra e' Othoni Reservoir from 2009 to 2011. Irrigation: r = 0.91, RMSE = 0.52. Domestic use: r = 0.85, RMSE = 0.027. Hydropower: r = 0.77, RMSE = 6.3. Discharges: r = 0.27, RMSE = 15.9. The inaccuracy in modelling hydropower production and discharges is largely due to the difficulty in predicting human decisions.

12 h have occurred and with climate change these events are likely to become frequent and intense in the future. Given its main purpose and excess storage, the dam is capable of supplying water for irrigation and domestic use under all scenarios (Section 5). Under all other climate change and development scenarios, the reservoir functioning was not considerably affected, suggesting that it is highly resilient under a range of projected climate, tourist and agricultural scenarios that might occur over the next 50 years in Sardinia. Only under unrealistic increases in demand might reservoir system failure occur. However, it is worth considering that agricultural and hydropower users may come into competition regarding the water resource for certain parts of the year. It is suggested that interactions between local and regional stakeholders are studied in an integrated assessment of Sardinian reservoir resilience, and that the effectiveness of adaptation strategies to mitigate competition for resources is assessed. The basins of other reservoirs in the island are not as disproportionately sized as that of Pedra e' Othoni, and those may have much lower resilience under similar changes in inflows (−7%) and water demands for irrigation (+8%) only due to climate change. Thus, development scenarios should be thought through carefully before being implemented in other areas, and competition and certainty of supply must be carefully studied. It should be considered that the studied reservoir could be physically connected to other reservoirs or used to serve additional areas where present water resources are stressed or insufficient to meet the demand.

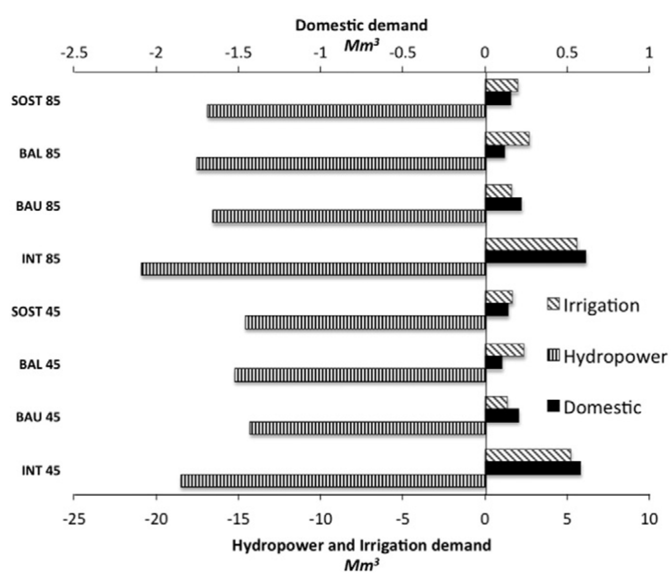

Fig. 7. Changes in water volumes in each economic sector relative to the baseline (1960–2000). Note the order-of-magnitude difference in the two x-axis scales. Positive change means an increase in water demand relative to today. Negative change means a decrease. The decrease for hydropower is due to the increases in domestic and irrigation demands. Therefore, there may be water-energy conflicts.

At the studied reservoir, the water required for the additional demands for domestic and irrigation use may be taken from the hydropower sector, thus losing some potential for the production of renewable energy. This reservoir only accounts for about 2% of the hydropower generation of the island, however if similar changes would take place across the whole island this could result in a potential loss of generation of about 10% under the BAU scenario. Since the domestic use only requires a minor portion of the water resource, potential competition may be between the agricultural and energy sectors. The industrial sector has declined recently and is projected to decline further. Thus, the request for energy and water from industry may be reduced, leaving some 'slack' for agricultural expansion. Clean energy facilities (wind turbines and solar power) have been implemented in Sardinia in the past ten years. On the other hand, land abandonment is increasing dramatically in Sardinia suggesting a possible reduction in irrigation requirements and also having possible implications for hydrological risks. Land abandonment and urbanization are considered the two major causes of the flood related damages that occurred in 2013. The agricultural sector has partially failed to compete effectively in the market with little implementation of new technologies (e.g., irrigation scheduling, sub-surface drip irrigation). However, crops for high quality products (wine and olive oil) have been maintained, while interest for environmentally friendly production systems (e.g., organic, permaculture, recovery of genetic biodiversity) is increasing. More efficient agriculture means that demand from the reservoir may be reduced, freeing up additional water for other users in the basin.

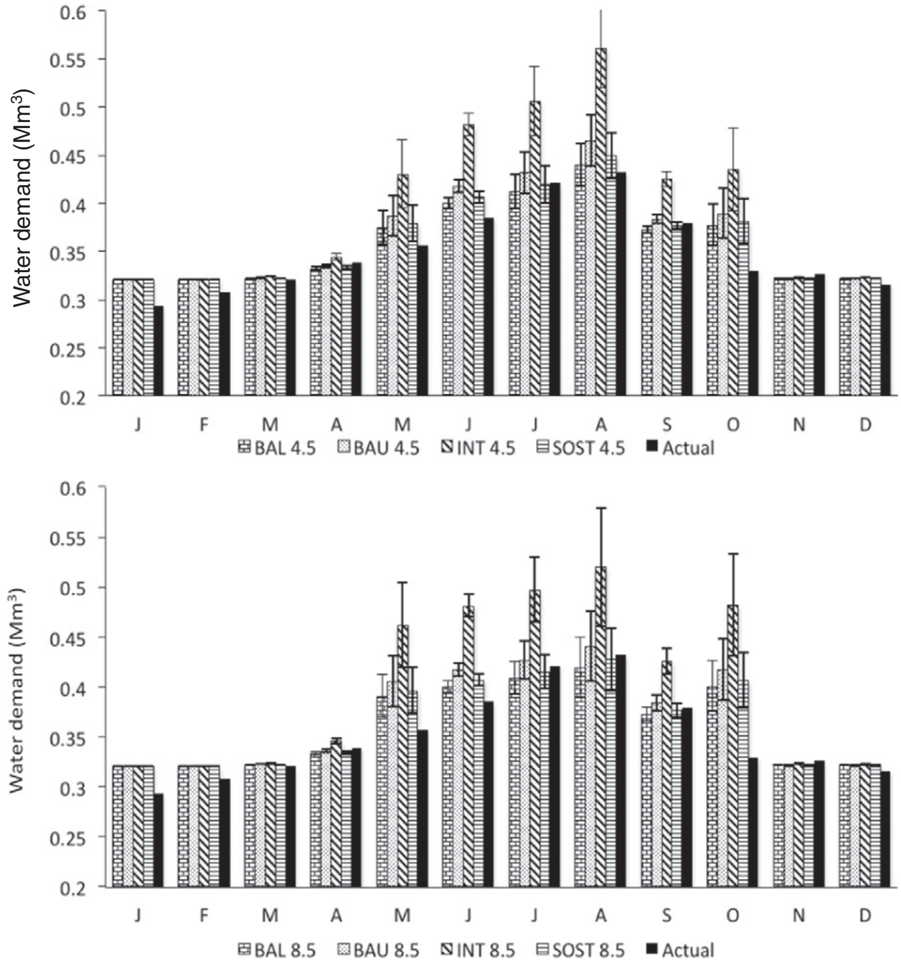

Fig. 8. Monthly water demand for domestic use under the actual conditions (solid black bar) and for the four development scenarios. Error bars represent the standard deviation among model runs with different ESM inputs. Upper panel RCP 4.5, lower panel RCP 8.5.

The increased demand for water by the domestic sector is not quantitatively important for the water budget in terms of volume. However it should be noted that the model made no assumptions on the population growth rates under the different development scenarios. It is likely that under the INT scenario, the population will grow in the coastal municipalities, albeit seasonally, while in the SOST scenario population could remain stable or even increase in the inner land municipalities where the population is presently declining. Additionally, the INT has a high financial cost in infrastructure for urban water distribution networks not accounted for in this analysis. Because mass tourism is mostly oriented to summer, the hotel sector has been experiencing a growing spread among supply and demand growth rates. This results, on one side, in large facilities near the coast mostly managed by major national and international operators and, on the other, in small size family-run hotels (with 24 rooms or less) concerned by strategic and operational isolation and, therefore, a low propensity for integrated solutions.

While our work is focussed on Sardinia, many Mediterranean locations face similar issues (climate change impacts, agricultural expansion, tourist demand fluctuations, and changes to the water balance). Islands in particular tend to rely on few water sources for supply, increasing their vulnerability to change. Although our case example is fairly robust to change, other reservoirs on Sardinia and throughout the Mediterranean may not be. It is suggested that if other reservoirs on Sardinia and throughout the Mediterranean experience change in inflows and outflows as those simulated in this work, their resilience would not be guaranteed. This may have implications for water supply for a range of sectors, and on energy generation, with knock-on impacts for economic development. Countries should carefully assess the resilience of reservoir operations to a wide variety of change factors in order to assess the future direction of water resources management in these critical locations.

7. Conclusions

We developed and presented a simulation model for Pedra e' Othoni reservoir in Sardinia, Italy. The model was forced with extensive ensemble climate data for RCPs 4.5 and 8.5, crop and agricultural data, along with four socio-economic development scenarios in order to assess the resilience of the reservoir to a wide range of realistic future changes in the region. The impacts to hydropower generation were considered, and the impacts to local climatic conditions were assessed.

It is expected from the climate data that the regional climate will on average get slightly drier and warmer. If nothing else changes, this would lead to probable decreases in annual reservoir inflow, while demands would be increased mainly in the agricultural sector as a result of increased crop water requirements. On top of climate change, multiple development futures in line with RCP storylines were assessed. Modelling showed that under no scenario is reservoir resilience significantly affected. That is, the reservoir always achieves complete refill. However, this occurs at the partial expenses of hydropower generation with implications for the production of clean energy.

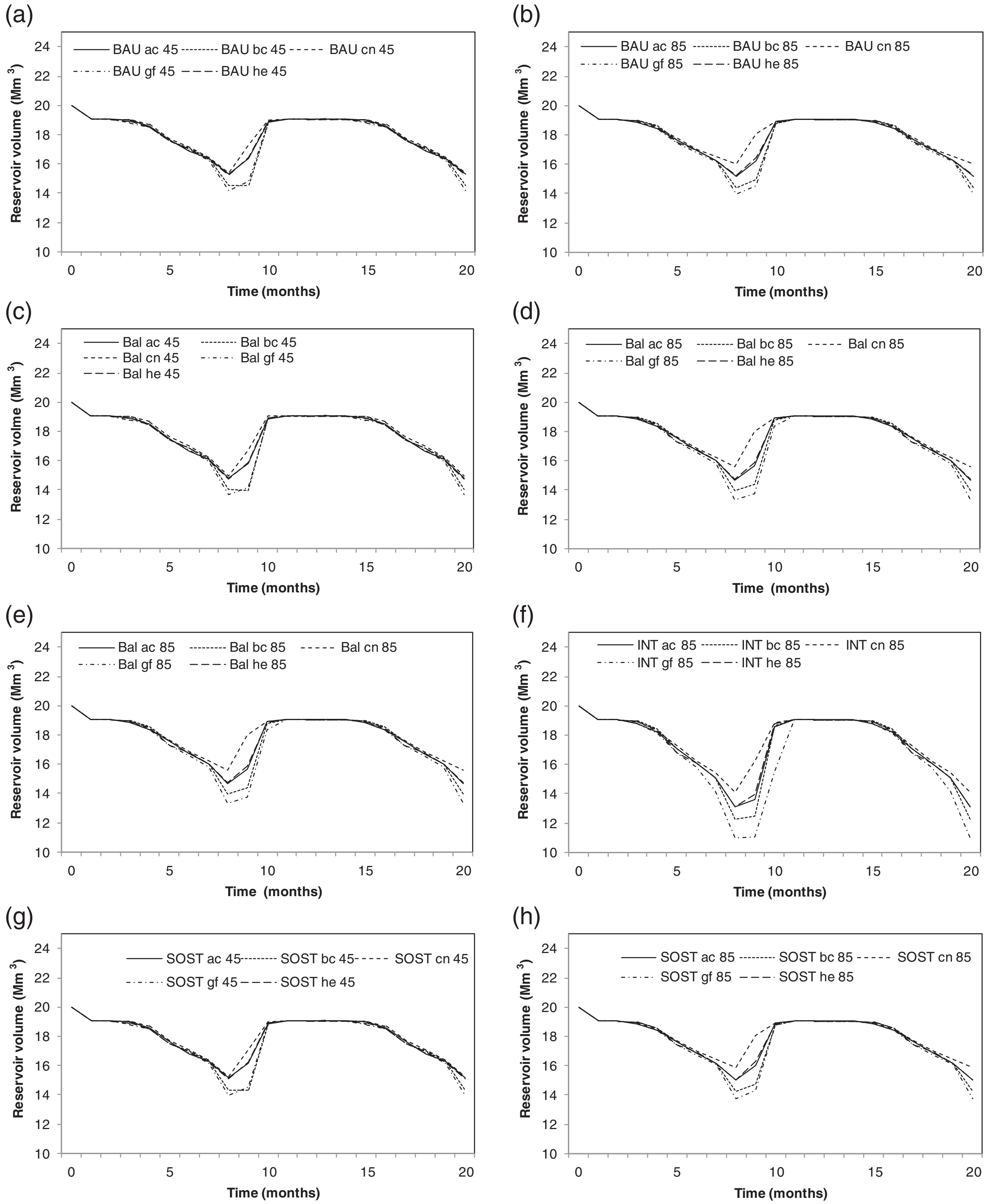

Fig. 9. Reservoir stored volume of Pedra e' Othoni reservoir using (a) BAU RCP 4.5 scenario; (b) BAU RCP 8.5 scenario; (c) Bal RCP 4.5 scenario; (d) Bal RCP 8.5 scenario; (e) INT RCP 4.5 scenario; (f) INT RCP 8.5 scenario; (g) SOST RCP 4.5 scenario and; (h) SOST RCP 8.5 scenario. Ac; bc; cn; gf, and he are the different ESM models. See Section 4 for description of development scenarios. We show 20 months of simulation out of 60 in order to highlight details between earth system models and scenarios. The cycles shown here repeat with low variation for the rest of the simulations and are representative.

This reservoir shows resilience to future change mostly because of the large basin feeding it. It can therefore be used to augment lower resilience reservoirs on Sardinia in times of stress. However, other reservoirs and reservoir systems on Sardinia and throughout the Mediterranean may not be so robust. Under these circumstances, regional development plans should carefully account for the trade-offs and potential conflicts among sectors. It is recommended that detailed resilience assessment, as presented here, is carried out. Those reservoirs at risk to future change should be identified, and mitigating measures should be considered.

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References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements. Irrigation and Drainage Paper No. 56. United Nations Food and Agriculture Organization, Rome, Italy (300 pp.).

Arnell, N.W., 2004. Climate change and global water resources: SRES emissions and socio-economic scenarios. Glob. Environ. Chang. 14, 31–52. http://dx.doi.org/10.1016/j.gloenvcha.2003.10.006.

Babel, M.S., Shrestha, B., Perret, S.R., 2011. Hydrological impact of biofuel production: a case study of the Khlong Phlo Watershed in Thailand. Agric. Water Manag. 101, 8–26. http://dx.doi.org/10.1016/j.agwat.2011.08.019.

Beniston, M., Stephenson, D.B., Christensen, O.B., Ferro, C.A.T., Frei, C., Goyette, S., Halsnaes, K., Holt, T., Jylha, K., Koffi, B., Palutikof, J., Scholl, R., Semmler, T., Woth, K., 2007. Future extreme events in European climate: exploration of regional climate model projections. Clim. Chang. 81, 71–95. http://dx.doi.org/10.1007/s10584-006-9226-z.

Christensen, J.H., Christensen, O.B., 2007. A summary of PRUDENCE model projections of changes in European climate by the end of this century. Clim. Chang. 81, 7–30. http://dx.doi.org/10.1007/s10584-006-9210-7.

Climatic Research Unit (CRU), 2013. [Phil Jones; Ian Harris]. CRU TS3.21: Climatic Research Unit (CRU) Time-Series (TS) Version 3.21 of High Resolution Gridded Data of Month-by-month Variation in Climate (Jan. 1901–Dec. 2012). NCAS British Atmospheric Data Centre (24th, September).

Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., Glotter, M., Flörke, M., Wada, Y., Best, N., Eisner, S., Fekete, B.M., Folberth, C., Foster, I., Gosling, S.N., Haddeland, I., Khabarov, N., Ludwig, F., Masaki, Y., Olin, S., Rosenzweig, C., Ruane, A.C., Satoh, Y., Schmid, E., Stacke, T., Tang, Q., Wisser, D., 2014. Constraints and potentials of future irrigation water availability on agricultural production under climate change. PNAS 111 (9), 3239–3244.

ENEL, 2013. Dichiarazione Ambientale 2013: Impianti idroelettrici Flumendosa, Coghinas e Taloro. EMAS ITALIA, certificate: IT-V-0001 (in Italian).

Finch, J., Calver, A., 2008. Methods for the Quantification of Evaporation From Lakes. NERC/Centre for Ecology & Hydrology, Wallingford, UK (47 pp.).

Ford, A., 1999. Modelling the Environment: An Introduction to System Dynamics Modeling of Environmental Systems. Island Press, Washington, D.C., U.S.A.

Forrester, J., 1961. Industrial Dynamics. Pegasus Communications, Waltham, MA, U.S.A.

Gerbens-Leenes, W., Hoekstra, A.Y., van der Meer, T.H., 2009. The water footprint of bioenergy. PNAS 106 (25), 10219–10223. http://dx.doi.org/10.1073/pnas.0812619106.

Gössling, S., Peetersc, P., Halld, M., Cerone, J., Duboisf, G., Lehmanng, L.V., Scotth, D., 2012. Tourism and water use: supply, demand, and security. An international review. Tour. Manag. 33 (1), 1–15.

Hall, J.W., Grey, D., Garrick, D., Fung, F., Brown, C., Dadson, S.J., Sadoff, C.W., 2014. Coping with the curse of freshwater variability. Science 346, 429–430. http://dx.doi.org/10.1126/science.1257890.

Hargreaves, G.H., Samani, Z.A., 1985. Reference crop evapotranspiration from temperature. Trans. ASAE 1 (2), 96–99.

Harrison, P.A., Dunford, R., Savin, C., Rounsevell, M.D.A., Holman, I.P., Kebede, A.S., Stuch, B., 2014. Cross-sectoral impacts of climate change and socio-economic change for multiple, European land- and water-based sectors. Clim. Chang. http://dx.doi.org/10.1007/s10584-014-1239-4.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. Int. J. Climatol. 25, 1965–1978.

ISTAT, 2012. 6th Italian Agriculture Census. http://www.istat.it/it/censimento-agricoltura/agricoltura-2010 (accessed on July 2014).

Jensen, M.E., 2010. Estimating evaporation from water surfaces. Presented at the CSU/ARS Evapotranspiration Workshop, Fort Collins, CO, 15-Mar–2010, second edition. Parts of Several Sections Were Extracted From Chapter 6, ASCE Manual 70 (Jul-08 draft).

Kampregou, E., Lekkas, D., Mereu, S., Assimacopoulos, D., 2012. Analysis of climate change impacts on tourism at the case study level and relevant water demand projections. WASSERMed Deliverable 4.3.2.

Khan, S., Yufeng, L., Ahmad, A., 2009. Analysing complex behaviour of hydrological systems through a system dynamics approach. Environ. Model. Softw. 24, 1363–1372.

McDonald, R.I., Weber, K., Padowski, J., Florke, M., Schneider, C., Green, P.A., Gleeson, T., Eckmann, S., Lehner, B., Balk, D., Boucher, T., Grill, G., Montgomery, M., 2014. Water on an urban planet: urbanization and the reach of urban water infrastructure. Glob. Environ. Chang. 27, 96–105. http://dx.doi.org/10.1016/j.gloenvcha.2014.04.022.

Meehl, G.A., Bony, S., 2011. Introduction to CMIP5. Clivar Exch. 16, 2–5.

Mieczkowski, Z., 1985. The tourism climatic index: a method of evaluating world climates for tourism. Can. Geogr. 29, 220–233.

Munir, A., Hanjra, M., Qureshi, E., 2010. Global water crisis and future food security in an era of climate change. Food Policy 35 (5), 365–377. http://dx.doi.org/10.1016/j.foodpol.2010.05.006.

Ramirez, J., Jarvis, A., 2010. Downscaling Global Circulation Model Outputs. CIAT, Cali, Colombia.

Rehan, R., Knight, M.A., Haas, C.T., Unger, A.J.A., 2011. Application of system dynamics for developing financially self-sustaining management policies for water and wastewater systems. Water Resour. 45, 4737–4750.

Sahin, O., Siems, R.S., Stewart, R.A., Porter, M.G., 2014. Paradigm shift to enhanced water supply planning through augmented grids, scarcity pricing and adaptive factory water: a system dynamics approach. Environ. Model. Softw. http://dx.doi.org/10.1016/j.envsoft.2014.05.018.

Sušnik, J., Vamvakeridou-Lyroudia, L.S., Savić, D.A., Kapelan, Z., 2013. Integrated modelling of a coupled water-agricultural system using system dynamics. J. Water Clim. Chang. 4 (3), 209–231. http://dx.doi.org/10.2166/wcc.2013.069.

USDA, 1967. Irrigation Water Requirements. Tech. Release No. 21. United States Department of Agriculture Soil Conservation Service (USDA-SCS), Washington, DC.

Vandecasteele, I., Bianchi, A., Batista e Silva, F., Lavalle, C., Batelaan, O., 2013. Mapping current and future European public water withdrawals and consumption. Hydrol. Earth Syst. Sci. Discuss. 10, 9889–9914. http://dx.doi.org/10.5194/hessd-10-9889-2013.

Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., 2011. The representative concentration pathways: an overview. Clim. Chang. 109, 5–31. http://dx.doi.org/10.1007/s10584-011-0148-z.

Worldwatch Institute, 2012. Use and capacity of global hydropower increases. Available at:, http://www.worldwatch.org/node/9527 (accessed on March 2015).