

1 **Operational resilience of reservoirs to climate change, agricultural demand, and tourism: a**  
2 **case study from Sardinia**

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18 **Abstract**

19 Many (semi-) arid locations globally, and particularly islands, rely heavily on reservoirs for  
20 water supply. Some reservoirs are particularly vulnerable to climate and development

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

## 43 **1. Introduction**

44 Reservoirs are generally built to augment water supply, for hydropower generation (World  
45 Watch Institute, 2012) and to attenuate flash flood flows. They alter hydrological regimes by  
46 attenuating flood flows and releasing accumulated volume in the summer to cope with dry  
47 season demand. In regions where water resources are scarce and summer demand is high,  
48 reservoirs play a crucial role in securing water for irrigation and domestic use. Many areas  
49 worldwide are wholly or largely reliant on reservoirs for water supply. This is particularly  
50 true for many locations in the Mediterranean where (ground) water resources are limited  
51 and inter-annual climatic variability is high. Strong dependence on reservoirs as the main  
52 water source may lead to major pressures from future changes, requiring a balance between  
53 climate change and its effects on water availability, and the development of water demand.  
54 Future pressures on reservoir operation can include: i) climate change, which can modify  
55 rainfall totals, increase evaporation losses and/or unfavourably alter the variability of supply  
56 and the hydrological regime (Arnell, 2004; Beniston et al., 2007; Christensen and  
57 Christensen, 2007; Hall et al., 2014) with implications for water resources; ii) population  
58 growth and urbanisation. Water demand increases imposed by socio-economic changes is  
59 likely to pose a significant challenge. Urbanization, population growth and life style change  
60 mean more water is needed to satisfy the domestic needs (e.g., Vandecasteele et al., 2013;  
61 Harrison et al., 2014; McDonald et al., 2014); iii) changes to agricultural regimes, influenced  
62 by changes in climate, diets and other market forces (e.g., biofuels), often leading to  
63 increasing water demand (Gerbens-Leenes et al., 2009; Munir et al., 2010; Babel et al., 2011;  
64 Elliott et al., 2014); and iv) changes to tourism. In locations where water is scarce and with a  
65 growing trend in tourism (e.g. the Mediterranean and Sardinia (see Section 3)), strong  
66 seasonal stresses in supply may be found in places with single-source water supply,  
67 increasing vulnerability to prolonged dry climatic periods. Also, in regions largely relying on

68 summer tourism for their economy, strong seasonal stresses to water supply and  
69 distribution networks may occur (e.g. Vandecasteele et al., 2013; Harrison et al., 2014;  
70 McDonald et al., 2014).

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

79 In this paper, the resilience of a reservoir-dominated supply system (Pedra e' Othoni) located  
80 on the eastern edge of Sardinia (Italy) was assessed under current and future changes  
81 (climate, population, tourism). The reservoir (Section 3) supplies water for the tourism  
82 industry, domestic demand, agricultural sector and for hydropower generation. We  
83 introduce the general modelling approach used to simulate the potential impact of changes  
84 on a reservoir-dominated supply system also accounting for some of the uncertainty  
85 surrounding various projections (i.e., climate change, population growth, tourism). The aim  
86 is to understand how potential future changes might alter long-term water supply and which  
87 of these changes have the greatest impact on the reservoir operation. Results are presented,  
88 followed by a discussion about the potential implications for operational reservoir resilience  
89 in Sardinia and the concomitant impacts on water security and competition. This work, while  
90 focussed on a specific study site, is framed within a wider agenda to secure and use more

91 effectively existing and future water supplies, to serve a growing population in a changing  
92 world. The work is novel for the use of multiple climate and water-demand forecasting  
93 models, coupled with a system dynamics framework in which to assess potential future  
94 reservoir resilience to a wide range of threats to water security.

## 95 **2. Reservoir resilience modelling approach**

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

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

112 | For this study, the reservoir resilience model was built using STELLA ([www.iseesystems.com](http://www.iseesystems.com)),  
113 specific software for SD modelling. SDM has many advantages over more conventional

114 modelling approaches. One may model many disparate sub-systems within the same  
115 simulation (e.g., water, agriculture and tourism). This was exploited here by combining  
116 elements from hydrology, irrigation, tourism, climate change and hydropower. SDM allows  
117 for the splitting of a large system into many dynamically interacting sub-systems. The models  
118 are necessarily not as realistic as dedicated spatially explicit physical models (e.g., GIS-based  
119 catchment hydrologic models). However, being able to 'mix' metrics and include socio-  
120 economic factors such as the tourism climate index, split the system into simpler pieces and  
121 incorporate relevant feedbacks, are the main reasons for choosing SDM for this study.  
122 Detailed information about climate model inputs, agricultural model inputs, tourist water  
123 demand estimation and the development scenarios used in this work is presented in Section  
124 4.

### 125 **3. Study site**

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

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

136 The Pedra e' Othoni reservoir was created by constructing a dam across in the Cedrino  
137 Valley. It was completed in 1994, and has an absolute capacity of 117 Mm<sup>3</sup>, although the  
138 utilised volume is 16-20 Mm<sup>3</sup>. This difference can be explained by the flash-flood mitigation  
139 function. This part of Sardinia is prone to extremely intense rainfall (rainfall events have  
140 exceed 400 mm per day in the past), and the reservoir was partially designed to mitigate the  
141 resulting flood events, hence the large storage volume. It serves nine villages and one small  
142 city (Nuoro). The basin feeding the reservoir is 628 km<sup>2</sup> (Figure 2).The average annual basin  
143 runoff coefficient (the proportion of upstream precipitation that ends up as surface runoff to  
144 the reservoir) was estimated by the regional water authority (ENAS) at 0.4. The reservoir  
145 receives on average  $169 \pm 34 \text{ Mm}^3 \text{ yr}^{-1}$ , but may peak to  $240 \text{ Mm}^3 \text{ yr}^{-1}$  in rainy years. 92% of  
146 the annual inflow is received in autumn, winter and spring. The inner territories of the basin  
147 contain old growth forest and archaeological sites important for tourism. These  
148 characteristics attract visitors throughout the year but mostly in spring and autumn, while a  
149 summer peak characterises coastal tourism. The high prevalence of forest and the low  
150 population in the upstream basin lead to high quality water with low quantities of pollutants  
151 and nutrients entering the reservoir. Therefore, the upper catchment can be considered well  
152 managed. Occasionally during flash floods, large volumes of sediment may be mobilised to  
153 reservoir. Sediment control through management is offered mainly during 'normal'  
154 discharges. However, these catchment management services are compensated neither by  
155 consistent shares of reservoir water distribution or subsidies (i.e. there is no incentive to  
156 carry on managing the upper catchment appropriately), implying that the maintenance of  
157 positive hydrological functions may be at risk in the future if the upstream population is not  
158 included in a proactive compensation/incentive scheme. The municipalities served by the

159 reservoir produce several traditional products, but the economy of the coastal municipalities  
160 strongly relies on tourism.

#### 161 **4. Data, scenarios, and model development**

162 Several climate datasets were utilised to: 1) calibrate and validate the SD model against  
163 existing dam discharge observations (2009-2011); 2) assess the dam discharge for the  
164 present climate conditions (baseline, average over the 1960-2000 period) and; 3) assess the  
165 dam discharge for an ensemble of future climate projections (2050, average over 2035-  
166 2065). Climate datasets are available on a monthly scale, the same as for the reservoir water  
167 balance model.

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

174 Afterwards a baseline scenario was run using the WorldClim dataset (the model was run for  
175 48 months to test the stability of the average annual water storage over four years). The  
176 future water balance scenarios were simulated for an ensemble of CIMP5 Earth System  
177 Models (ESMs) for two RCP scenarios (19 ESMs for RCP4.5 and 17 ESMs for RCP8.5). Thus,  
178 we use the latest climate projection data sets available and coherent development scenarios  
179 commonly used from the literature.

##### 180 *4.1 Model calibration data*

181 The reservoir water balance model was calibrated and validated against three years (2009-  
182 2011) of monthly discharge observations. Local meteorological data were only available  
183 from a single station located over the dam and thus do not represent the spatial variability  
184 between the reservoir basin and the area served by it. For that reason, weather parameters  
185 (2009-2011) were extracted from two adjacent pixels of the CRU TS 3.1 dataset (CRU, 2013)  
186 in order to characterize with comparable scale and adequate overlap the respective climate  
187 conditions over the basin and agricultural land served by the reservoir.

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

#### 193 *4.2 Current and future climate data*

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

198 A combination of Earth System Models (ESMs) of future climate provided by Phase 5 of the  
199 Coupled Model Intercomparison Project (CMIP5; Meehl and Bony, 2011) and representative  
200 concentration pathways (RCPs; Vuuren et al., 2011) have been previously downscaled  
201 (Ramirez and Jarvis, 2010), spatially resolving monthly GCM climate anomalies with the same  
202 resolution as the WorldClim data. Ensembles of downscaled GCM models and RCP scenarios  
203 include multiple climate anomaly projections for 2050 (monthly averages 2035-2065) over

204 WorldClim (i.e., climate model bias is excluded). It is assumed that the change in climate is  
205 similar over the catchment.

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

#### 209 *4.3 Reservoir storage balance model*

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

224 The following climate data were used to simulate the inflows and outflows components of  
225 the water balance and resilience model for actual conditions (WorldClim 1960-2000) and for  
226 the ensemble of projected future conditions:

- 227 - Average monthly precipitation over the basin upstream of the reservoir;
- 228 - Average monthly open water evaporation over the reservoir;
- 229 - Average monthly mean temperature and precipitation over the distribution area  
230 served by the reservoir to calculate the Tourism Climate Index (TCI, Mieczkowski, 1985),  
231 which was used to estimate water demand for tourism;
- 232 - Average monthly precipitation and  $ET_0$  which are used to account for the irrigation  
233 requirements of the existing crop types over the distribution area served by the reservoir.

#### 234 *4.4 Open water evaporation*

235 Evaporation from open water bodies, to calculate losses by evaporation from the reservoir,  
236 is approximated by multiplying reference  $ET_0$  by a coefficient of 1.1, which is an average  
237 between values reported in literature ranging between 1.05 and 1.15 (Allen et al. 1998;  
238 Jensen, 2010; Finch and Calver, 2008).

#### 239 *4.5 Domestic water requirements and the Tourism Climate Index (TCI)*

240 Monthly water requirements for domestic use were calculated assuming  $170 \text{ l person}^{-1} \text{ day}^{-1}$   
241 by the resident population (ISTAT, 2012). While this appears high, it includes all domestic  
242 water use (e.g. car-washing, gardening, etc.). Large seasonal changes in water demand are  
243 assumed to be caused by tourist flows. Monthly data of overnight stays in the study area for  
244 the period 2009-2011 were provided from the Regional Statistics Office (Regione Autonoma  
245 della Sardegna). Average water consumption per tourist in hotels in Italy is about 40%  
246 greater than in camping accommodation (Gössling et al., 2012). The water consumption was  
247 set at  $400 \text{ l person}^{-1} \text{ day}^{-1}$  for hotels and at  $250 \text{ l person}^{-1} \text{ day}^{-1}$  for other facilities (camping,  
248 B&B, agri-tourism).

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

255 The maximum value of the TCI is 100, with values over 80 denoting “excellent” conditions for  
256 summer tourism. Effects of climate change on the TCI were estimated to account only for  
257 the monthly temperature and precipitation anomalies. While this measure is relatively  
258 simple, it provides a reasonable proxy for tourist comfort, and has been used previously to  
259 estimate tourist fluxes (Kampragou et al. 2012).

260 The methodology to project future tourist water demands follows three steps (Figure 4):

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

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

278 1. “Business As Usual (BAU) Scenario”. This applies the average value of annual  
279 variations of tourist flux calculated for the reference period 2009-2011 to the period 2010-  
280 2050; an annual increment in flux of 0.75% was used.

281 2. “Intensive Tourism Growth (INT) Scenario”. Uses the average value of annual  
282 variations observed over the period 2005-2010 chosen as a reference period with a strong  
283 expansion of the tourist sector; an annual increment of 2.1% was used.

284 3. “Strictly Controlled Sustainable Tourism (SOST) Scenario”. An unchanged  
285 accommodation capacity has been assumed until 2050. Overnight stays are predicted to  
286 change to reach present average gross occupancy rates and the 'tourist flow patterns' are  
287 assumed to match patterns observed in 2010 in the national context for heritage  
288 destinations (namely cultural, hill and mountain locations); an annual increment of 1.2% was  
289 used.

290 4. “Balanced Competitive and Sustainable Growth (BAL) Scenario”. It simulates  
291 progressive diversification in tourism facilities, attractions and products. A reduction in  
292 average annual growth rates has been assumed on the accommodation supply side. On the  
293 demand side, overnight stays are predicted to change in order to reach present average

294 gross occupancy rates for coastal and mountainous locations. An annual increment of 1%  
295 was used.

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

$$301 \quad OS_{sc} = OS_{SE} \cdot \frac{OS_{CC}}{OS_{RefPer}} \quad (1)$$

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

#### 303 *4.6 Irrigation requirements*

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

307 Monthly water needs ( $I$ ) for each polygon was calculated using:

$$308 \quad I_i = ETc_i - P_i + RO_i - \delta w_i - G_i \quad (4)$$

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

312 The fraction of effective rainfall ( $P_{eff}$ ) available to each crop was estimated using the  
313 empirical formulae of the USDA Soil Conservation Service (USDA, 1967). This excludes the  
314 volume of water lost by runoff or intercepted by plants.

$$315 \quad P_{eff(i)} = \left( \frac{P_{(i)}}{125} \right) * (125 - 0.2 P_{(i)}) \quad \text{for} \quad P_{(i)} < 250 \text{ mm} \quad (5)$$

$$316 \quad P_{eff(i)} = 125 + 0.1 P_{(i)} \quad \text{for} \quad P_{(i)} > 250 \text{ mm} \quad (6)$$

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

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

- 326 1. Business-As-Usual (BAU): irrigated areas are unchanged.
- 327 2. Intensive growth scenario (INT): 40% expansion of irrigated areas only for high value,  
328 water demanding crops.
- 329 3. Strictly controlled sustainable growth scenario (SOST): irrigated areas increase for  
330 fruit trees, vegetables and traditional crops but not for high demanding crops (e.g. maize and  
331 pasture).

332 4. Balanced Competitive and Sustainable Growth (BAL) Scenario: Irrigated areas  
333 increase for all crops but proportionally less for high water demanding crops.

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

#### 336 *4.7 Hydropower generation*

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

### 341 **5. Results**

#### 342 *5.1 Changes to temperature and precipitation*

343 Climate scenarios for the basin predict average change in annual precipitation ranging from -  
344 173 to +31 mm compared to 1960-2000. However, increases in precipitation are unlikely to  
345 occur, and average values indicate decreases of 40 [-66/-8] and 56 [-111/-2] mm for RCP 4.5  
346 and 8.5 respectively (values in square brackets represent the 15<sup>th</sup> and 85<sup>th</sup> percentile  
347 respectively and do so through the rest of the paper). Assuming no change in the basin  
348 runoff coefficient these reductions correspond to average change of inflow in the reservoir  
349 of -10 and -14 Mm<sup>3</sup>, respectively. ESM models show much less uncertainty for annual mean  
350 temperatures which increase on average by 1.96 [1.3/2.6] and 2.46 [1.7/3.1] °C for the 4.5  
351 and 8.5 RCPs respectively (Figure 5). The absolute values and the effects of climate change  
352 on the direct evaporation from the reservoir surface are minor.

#### 353 *5.2 Model validation*

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

### 364 *5.3 Changes to water demands and reservoir water balance under future scenarios*

365 Irrigation under the BAU scenario implemented no change in crop distribution, therefore  
366 climate change alone determines the slight increase in crop water requirements of 1.35  
367 [0.9/1.8] and 1.63 [1.1/2.1] Mm<sup>3</sup> under the RCP 4.5 and RCP 8.5 respectively due to the  
368 combined effect of higher temperature and lower precipitation (Figure 7). The SOST and Bal  
369 scenarios have water demand slightly higher than BAU since both avoid or limit the  
370 expansion of irrigated area for high water demanding crops. The irrigation requirements for  
371 the intensive growth scenario, with a 40% expansion of irrigated area, increase by 5.22 Mm<sup>3</sup>  
372 [4.6/5.9] in the RCP 4.5 and by 5.6 [4.9/6.3] under the RCP 8.5 scenario.

373 Changes in domestic use (Figure 8) are minor compared to other uses in terms of water  
374 volume. However, the distribution of this water is expensive due to the requisite  
375 infrastructure. This cost was not modelled for this work, but presents an opportunity for  
376 future research. Both the RCP 4.5 and 8.5 scenarios predict an increase in TCI in April/May

377 and October/November that is reflected in an increase in domestic water requirement  
378 during these months. In the summer months, TCI either remains the same or it decreases  
379 slightly. High temperatures will negatively affect tourism during this period of time,  
380 therefore the increase in domestic water requirements in these months is mostly due to the  
381 development scenarios.

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

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

399 4.5) up to -21 [-31/-11.4] Mm<sup>3</sup> in the INT and RCP 8.5 case (i.e., reduction in hydropower  
400 generation).

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

## 414 **6. Discussion**

415 The principle role of the reservoir of Pedra e' Othoni is to secure water supply for multiple  
416 users, to generate electricity and to protect downstream areas from flash floods similar to  
417 those that have occurred in the past. In the past 20 years, rain events up to 400 mm in less  
418 than 12 hours have occurred and with climate change these events are likely to become  
419 frequent and intense in the future. Given its main purpose and excess storage, the dam is  
420 capable of supplying water for irrigation and domestic use under all scenarios (Section 5).  
421 Under all other climate change and development scenarios, the reservoir functioning was

422 not considerably affected, suggesting that it is highly resilient under a range of projected  
423 climate, tourist and agricultural scenarios that might occur over the next 50 years in Sardinia.  
424 Only under unrealistic increases in demand might reservoir system failure occur. However, it  
425 is worth considering that agricultural and hydropower users may come into competition  
426 regarding the water resource for certain parts of the year. It is suggested that interactions  
427 between local and regional stakeholders are studied in an integrated assessment of  
428 Sardinian reservoir resilience, and that the effectiveness of adaptation strategies to mitigate  
429 competition for resources are assessed. The basins of other reservoirs in the island are not  
430 as disproportionately sized as that of Pedra e' Othoni, and those may have much lower  
431 resilience under similar changes in inflows (-7%) and water demands for irrigation (+8%) only  
432 due to climate change. Thus, development scenarios should be thought through carefully  
433 before being implemented in other areas, and competition and certainty of supply must be  
434 carefully studied. It should be considered that the studied reservoir could be physically  
435 connected to other reservoirs or used to serve additional areas where present water  
436 resources are stressed or insufficient to meet the demand.

437 At the studied reservoir, the water required for the additional demands for domestic and  
438 irrigation use may be taken from the hydropower sector, thus losing some potential for the  
439 production of renewable energy. This reservoir only accounts for about 2% of the  
440 hydropower generation of the island, however if similar changes would take place across the  
441 whole island this could result in a potential loss of generation of about 10% under the BAU  
442 scenario. Since the domestic use only requires a minor portion of the water resource,  
443 potential competition may be between the agricultural and energy sectors. The industrial  
444 sector has declined recently and is projected to decline further. Thus, the request for energy  
445 and water from industry may be reduced, leaving some 'slack' for agricultural expansion.

446 Clean energy facilities (wind turbines and solar power) have been implemented in Sardinia in  
447 the past ten years. On the other hand, land abandonment is increasing dramatically in  
448 Sardinia suggesting a possible reduction in irrigation requirements and also having possible  
449 implications for hydrological risks. Land abandonment and urbanization are considered the  
450 two major causes of the flood related damages that occurred in 2013. The agricultural sector  
451 has partially failed to compete effectively in the market with little implementation of new  
452 technologies (e.g., irrigation scheduling, sub-surface drip irrigation). However, crops for high  
453 quality products (wine and olive oil) have been maintained, while interest for  
454 environmentally friendly production systems (e.g., organic, permaculture, recovery of  
455 genetic biodiversity) is increasing. More efficient agriculture means that demand from the  
456 reservoir may be reduced, freeing up additional water for other users in the basin.

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

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

## 482 **7. Conclusions**

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

489 It is expected from the climate data that the regional climate will on average get slightly  
490 drier and warmer. If nothing else changes, this would lead to probable decreases in annual  
491 reservoir inflow, while demands would be increased mainly in the agricultural sector as a  
492 result of increased crop water requirements. On top of climate change, multiple

493 development futures in line with RCP storylines were assessed. Modelling showed that  
494 under no scenario is reservoir resilience significantly affected. That is, the reservoir always  
495 achieves complete refill. However, this occurs at the partial expenses of hydropower  
496 generation with implications for the production of clean energy.

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

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