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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.

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 $\pm$ 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