A multi-compartment modeling framework to study the impacts of climate change on the Lisbon water supplies

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ABSTRACT

The Lisbon water supply is mostly originated from the Tagus river basin, a large transnational watershed with complex land-uses and geology. Project ADAPTACLIMA-EPAL aimed at assessing the vulnerability of these water sources to climate change. This required the construction of a complex modeling framework, capable of simulating the watershed in general while focusing on the various water uptake points in detail. This framework had to tackle a number of interfaces between water resource compartments, including:

- the Castelo de Bode reservoir, EPAL's main source of water and where streamflow from the river Zêzere is collected in a large artificial lake;
- the Valada do Tejo withdrawal point, located just upstream from the estuary in the river Tagus, a secondary source of water which is dependent on transboundary streamflow from Spain, potentially affected by downstream saltwater tides associated with sea level rise;
- multiple groundwater uptakes in several aquifers.

In order to achieve these goals, a catchment-scale eco-hydrological model was applied to simulate the entire study area, linked with sub-models for different interfaces:

- a 2-D water quality model for the Castelo de Bode reservoir;
- a simple climate-based estimate for streamflow inputs from Spain;
- a 2-D hydrodynamic model for the interface between the river Tagus and the estuary;
- groundwater recharge and transport models for selected aquifers.

The framework had to tackle issues such as model links at the interfaces, including the link between different modeling concepts and different spatial and temporal scales and extents of modeling. The results indicate that, for the selected climate change scenarios (downscaled from the A2 and B2 scenarios taken from the HADCM3 GCM), the Lisbon water supplies will not be under threat as long as they are properly managed. Identified threats to management include the competition between consumptive and electrical production uses in the Castelo de Bode reservoir; potential water quality deterioration caused by increased phosphorous inputs in Castelo de Bode; important changes to streamflow from the Spanish part of the river Tagus; and the need to increase water uptakes to extend the water supply network to other populated areas.

KEY WORDS: *Urban water supplies, Climate change impacts, Integrated modelling framework.*

INTRODUCTION

Climate change scenarios for the Mediterranean region indicate an increase in temperature and decrease in rainfall by the end of the XXIst century (Giorgi, 2006). In spite of the variability between scenarios, this combination should increase climatic aridity, leading to lower available water resources (Nunes *et al*., 2008). This could lead to a greater pressure on remaining resources, which under water stress conditions might lead to conflict between uses or water quality issues (Alcamo *et al*., 2003).

To address these issues, the Empresa Portuguesa de Águas Livres (EPAL) has launched the ADAPTACLIMA-EPAL project, which aims to develop mid- and long-term adaptation strategies to decrease its vulnerability to the impacts of climate change. The project includes a multi-disciplinary team studying EPAL's different water uptakes inside the lower Tagus river basin, which supply over 4 million people, including the population of Lisbon. The focus is on present-day sources, mostly provisioned by surface water uptakes, and on alternative future sources provisioned by groundwater.

Previous studies performed for the Tagus river basin have suggested scenarios of a strong decrease in available water resources, when considering the river basin or a sample of headwater catchments (Cunha *et al*., 2002, 2006; Kilsby *et al*., 2007; Nunes *et al*., 2008; Nunes and Seixas, 2011). Some studies also suggest an increase in soil erosion (associated with phosphorus exports) despite the lower mean annual rainfall (Nunes *et al*., 2008, 2013). There is, however, a lack of studies which (i) specifically address the interfaces between the Tagus river basin and the water supply system, namely at the water uptake points, and (ii) focus on the impacts of climate change on water quality.

An analysis of the impacts of climate change on available water resources is complex, including the analysis of scenarios for climate, socio-economy, and eco-hydrology. In this case, scenarios must take into account decreases in water availability due to lower rainfall and higher potential evapotranspiration. Changes to water quality must also be taken into account, due to higher temporal variability of rainfall and hence nutrient exports; lower dilution of exported nutrients; higher air temperatures (affecting water stratification in large water bodies, nutrient cycles, and algal growth); and lower inflows of water to the river mouth and groundwater bodies (potentially leading to intrusions of saline seawater). Xu and Singh (2004) propose the sequential use of climate and eco-hydrological models, using downscaling methods to adapt the spatial scale of the former to the latter. In this particular case, basin-scale models of the Tagus watershed capable of reproducing water and nutrient yields must be coupled with local quality models for the water uptake points to evaluate changes at the water supply uptakes used by EPAL. This work can take advantage of pre-existing modeling efforts for parts of the water supply system (Coelho *et al.*, 2005; Nunes *et al.*, 2008).

The overall objective of this work was to study the impacts of climate change on the EPAL water supply system. To this end, an eco-hydrological model was applied to the entire study area, providing results for specific sub-models addressing local conditions of water availability and quality at points of interface with the water supply system. This modeling framework was used to study the impacts of climate change for water resource availability for short, mid and long-term scenarios, from 2010 to 2100.

METHODS

Study Area

The ADAPTACLIMA-EPAL project focused on the lower part of the Tagus river basin, located in Portugal (Figure 1). This area supplies water for the main uptake points for the EPAL water supply system. The points under study include:

- Castelo de Bode: a large reservoir collecting water from the Zêzere sub-catchment, providing c. 67% of EPAL's total water supplies. This is a multi-purpose reservoir including drinking water supply, hydropower production, flood protection and recreational uses. The Castelo de Bode dam is part of a cascade system which also includes upstream dams at Bouçã and Cabril. Water quality in the reservoir varies seasonally, due to thermal stratification in summer, and inter-annually when severe droughts occur.
- Valada-Tejo: a water uptake point close to the mouth of the Tagus river, providing c. 24% of EPAL's total water supplies. Around half of the streamflow at this point comes from Spain, entering the study area through the Fratel dam. Water quality may be affected by tidal saltwater coming from downstream only in the most extreme low flow periods.
- Alviela, Ota, Alenquer and Lezírias (close to Valada): uptake points collecting groundwater, presently used mostly to complement the system and providing c. 9% of total water supplies.

Modeling framework

The methodology was based on the sequential application of different methods to generate future climate, socio-economic, eco-hydrologic and water availability scenarios. Future scenarios were generated for three periods: 2010-2040, 2040-2070 and 2070-2100, with the following methods:

- Future climate scenarios, generated by statistical downscaling (Chandler, 2002) of projections from the HadCM3 Global Circulation Model, for CO_2 emission scenarios A2 and B2, resulting in daily time-series for rainfall and temperature.
- Socio-economic scenarios were generated from the downscaled projections by CIESIN (2002), including population, water use and land use projections.

These scenarios were used as inputs for an eco-hydrological modeling approach, applied for the entire study area, aiming to produce overall water availability predictions for the different resources and, in the Zêzere river basin (upstream of the Castelo de Bode dam), nutrient exports. The approach included three methods:

- Streamflow and nutrient generation in the Portuguese part of the basin were calculated using the Soil and Water Assessment Tool (SWAT) eco-hydrological model (Neitsch *et al.*, 2011). The model was calibrated and validated using data from 15 hydrometric stations representing both headwater catchments throughout the basin and the main water lines, as well as water quality data from 6 river and 3 reservoir sampling stations inside the Zêzere basin.
- Monthly streamflow inputs from Spain at Fratel were estimated using an empirical approach, based on a regression with rainfall and temperature close to the border, with similar climate to the one experienced in most of the Spanish part of the Tagus river basin.
- Piezometric levels at each water uptake point were estimated using an empirical approach based on a regression with climate variables, coupled with the ModFlow aquifer model (WHY 2005).

Finally, results from the SWAT model were used as inputs for two water quality models in the main water uptake points:

- Water quality in the Castelo de Bode reservoir was simulated using the 2-D hydrodynamic and ecological model CE Qual W2 (Cole & Wells, 2008). The simulation included nutrient cycles and algal growth, taking into account vertical stratification patterns.
- Water quality at the Valada-Tejo was simulated using a simple 2-D hydrodynamic model, simulating saline intrusion during high tide, low flow periods and taking into account sea level rise scenarios and possible streambed modifications.

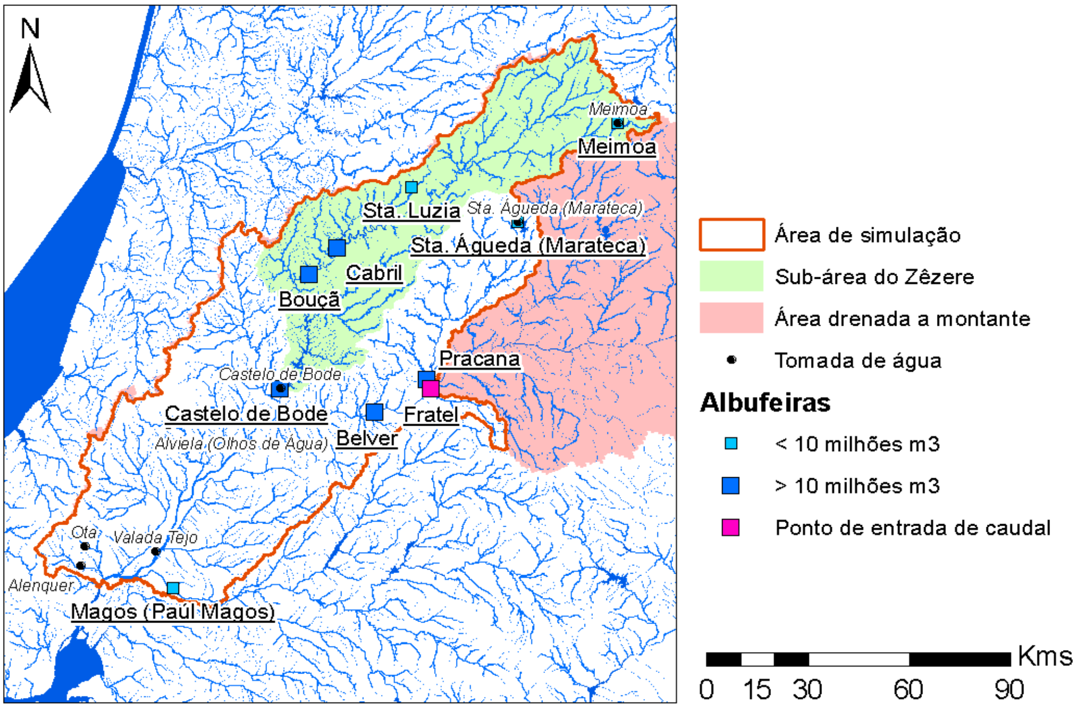

Figure 1. Study area for the ADAPTACLIMA-EPAL project (red line), including water uptake points (black circles), main reservoirs (blue squares), drainage area upstream from the study area (pink area) and location of the inlet for Spanish flows (pink square).

RESULTS

Future scenarios (Table 1) suggest a temperature increase from 1.7 to 3 ºC by 2100, especially in spring and autumn, combined with a rainfall decrease between 10 and 18%, throughout the entire wet season, leading to drier climatic conditions and an increase in the frequency of severe drought years. Scenario A2 leads to more extreme changes than scenario B2, especially for the end of the century. However, this is expected to be accompanied by a decrease in water consumption, through a decrease in agricultural land use, increased water use efficiency and changing individual consumption patterns.

Table 1. Overview of the main model results (T: temperature, PP: precipitation, EET: effective evapotranspiration, Q: streamflow, R: net aquifer recharge).

Period	***T***	***PP***	***EET***	***Q***	***R***
A2					
2010-2039	+0.2ºC	-5%	-2%	-8%	-15%
2040-2069	+1.2ºC	-7%	+3%	-19%	-31%
2070-2099	+3.0ºC	-18%	0	-38%	-56%
B2					
2010-2039	+0.4ºC	-8%	-2%	-13%	-25%
2040-2069	+1.2ºC	-8%	+2%	-17%	-35%
2070-2099	+1.7ºC	-10%	0	-22%	-28%

Despite the lower annual rainfall, evapotranspiration is expected to remain relatively unchanged, due to an increase in the amount of water used by vegetation. Therefore, the main consequence should be a decrease in streamflow and net aquifer recharge between, respectively , 22 and 38% and 28 and 56% by 2100 (Table 1).

For the Castelo de Bode reservoir, results indicate a decrease in inflows between 20 to 34% by 2100 (Figure 2). This decrease occurs mainly in autumn. For the near-term scenarios, this is mostly due to a decrease in median annual inflow; for the long-term scenarios, this is accompanied by lower inter-annual variability and a decrease of magnitude of wet year inflows (Figure 2). Nitrogen loads should suffer a small decrease (-7 to +2%) and Phosphorus loads a small increase (1 to 10%), with climate-related increases (mostly due to lower vegetation cover and enhanced soil erosion) being mitigated by lower agricultural land-use. N and P concentrations in inflows should increase due to lower dilution capacity of streams.

In the reservoir, the decreased inflows should nevertheless be sufficient to sustain consumptive uptakes: the worst-case inflow scenario of 1000 to 1500 $hm^3\ y^{-1}$ is well above the average annual consumption of 160 $hm^3\ y^{-1}$. These assertions, however, assume the prioritization of consumptive water use over hydropower generation, which presently averages 1400 $hm^3\ y^{-1}$. Despite an expected decrease in uncontrolled water releases due to the lower inflows during wet years, restrictions to hydropower production may be required in order to accommodate lower inflow periods and ensure water availability to keep the

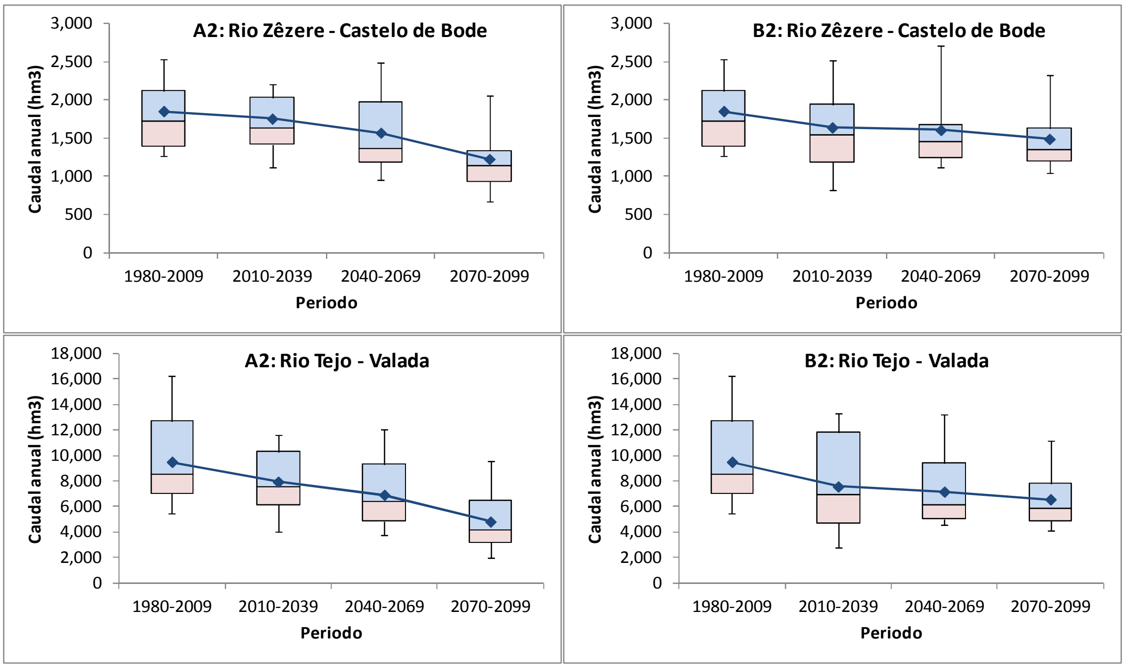

Figure 2. Inter-annual variability of streamflow arriving at the main EPAL water uptake points (boxes indicate the range between the 1st and 3rd quartiles, while whiskers indicate the range between the 10th and 90th percentiles).

capacity to supply consumptive water uses intact, pointing to the possibility of conflicts between both uses.

As for reservoir water quality, the increase in P inflows might lead to an increase in primary productivity, especially during wet years, and therefore increase the risk for eutrophication; however, the results do not indicate a severe degradation of water quality except in episodic occurrences.

For the Valada-Tejo uptake point, results indicate that streamflow is highly dependent on inflows from the Spanish part of the Tagus basin (c. two thirds), which show a greater sensitivity to climate change. Accordingly, streamflow is expected to decrease between 31 and 49% by 2100 (Figure 2), although in this case inter-annual variability remains more stable than for Castelo de Bode. In the worst-case scenario, the importance of Spanish inflows can decrease to c. half of total streamflow. In any case, the worst-case scenario of 3000 to 6000 $hm^3\ y^{-1}$ is well above the annual uptake of 60 $hm^3\ y^{-1}$ in this point. Furthermore, only a worst-case scenario of constant extreme low streamflow of 10 $m^3\ s^{-1}$ (c. minimum simulated monthly average flow for the period 2010-2100) combined with spring tides, and considering a sea-level rise of 0.8-1.0 m may induce relevant salinity increase at this point; therefore this would be at most an episodic occurrence and a potential risk associated only with significant sea-level rise scenarios.

Results for the groundwater uptake points only show a trend of declining piezometric levels for the long-term scenario (2070-2099); the exception is the Alviela uptake point, which shows instead a decrease in groundwater quality. This decrease cannot be considered a threat to water resource provisioning due to their current role as complementary systems and lower importance when compared with the surface water uptake points.

Finally, the results indicate a potential threat not foreseen at the start of the ADAPTACLIMA-EPAL project. The resilience of the EPAL water resources to climate change could lead to increased demands by populations not currently served by the EPAL system, where existing systems might prove less resilient. This could add to other unforeseen pressures on water resources, such as an increase in irrigation area collecting water nearby or upstream from EPAL uptake points. Further work is needed to assess these possibilities.

CONCLUSION

This work shows how a modelling framework can link regional-scale water balance with detailed analyses of local conditions at water uptake points, providing a tool for a detailed assessment of the impacts of climate change on water resource availability. In ADAPTACLIMA-EPAL, the results indicate that the system (including the Lisbon water supply) is resilient to the studied climate change scenarios, except on episodic events with low, but difficult to assess, probability of occurrence. This resilience, however, is dependent on an adequate management of water supplies, especially (i) the competitive use of water for power generation at the Castelo de Bode reservoir, and (ii) additional scenarios of water uptake from the system, either for other uses or through an expansion of the EPAL supply network.

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