Water Resources Management (2023) 37:3423–3437
https://doi.org/10.1007/s11269-023-03508-x

# Optimizing Reservoir Water Management in a Changing Climate

**Pedro Beça**[1,2] · **António C. Rodrigues**[2] · **João P. Nunes**[1,3] · **Paulo Diogo**[2] · **Babar Mujtaba**[2]

Received: 2 May 2022 / Accepted: 15 March 2023 / Published online: 5 April 2023


## Abstract

One of the UN agenda 2030 Sustainable Development goals is associated with water availability and its sustainable management. The present study intends to improve multipurpose reservoir management under climate change scenarios in water scarce regions such as the Mediterranean. Implemented methods include the sequential use of climate model results, hydrological modelling, and reservoir water balance simulation, which are used to estimate future water availability. This work focuses on developing an innovative reservoir management approach based on rule curves and a dynamic assessment of water needs, to improve the management of reservoirs that are dependent on a water transfer system. The proposed methods are implemented in two reservoirs located in a typical Mediterranean river basin and assessed under long-term climate change scenarios up to the year 2100. The results show that the proposed approach can ensure 100% of the urban water supply, improve the reliability of the irrigation supply from 75% to 86–91%, and provide 92–98% of the river ecological flow. It is also demonstrated that this management approach is beneficial, particularly in the case of multipurpose reservoirs in watersheds facing water scarcity risks, to optimize the balance between supply reliability, water transfer volumes, and costs.

**Keywords** Multipurpose reservoir management · Rule curve · Climate change adaptation · Water supply reliability

✉ Pedro Beça
pmbeca@fc.ul.pt

1 cE3c - Centre for Ecology, Evolution and Environmental Changes, & CHANGE - Global Change and Sustainability Institute, Faculty of Sciences, University of Lisbon (FCUL/U Lisboa), 1749-016 Lisbon, Portugal

2 MARE - Marine and Environmental Sciences Centre, NOVA School of Science and Technology, 2829-516 Caparica, Portugal

3 Soil Physics and Land Management Group, Wageningen University, P.O. Box 47, 6700 AA Wageningen, the Netherlands

## 1 Introduction

Climate change scenarios predicted for the Mediterranean region suggest this might be an especially vulnerable region to global change, with significant impacts on water resources (García-Ruiz et al. 2011; Tramblay et al. 2020). Even with the variability and uncertainty among the possible scenarios, the combination of impacts suggests an increase in climate aridity, thus decreasing the availability of water resources (Rocha et al. 2020), expanding the pressure over existing resources (Bogardi et al. 2012), degrading water quality (Molina-Navarro et al. 2014) and possibly intensifying use conflicts (Alcamo et al. 2003; Garrote 2017). These facts constitute effective risks to the availability, accessibility, and quality of water resources, and thus highlight the importance of implementing water management adaptation measures.

The challenges raised by climate change support the need to adopt different adaptation strategies. Some of these are associated with the changes in water availability and the duration and severity of likely increased droughts, determining the need to improve the resilience of supply systems and increase water availability and management capacity (Iglesias and Garrote 2015).

Changes in societal objectives and increasing supply demands, call for a re-thinking of reservoir operation criteria. Water management in multipurpose reservoirs is a complex decision-making process, with numerous objectives to be considered, which are often conflicting and imply competition between water users and stakeholders (Walker et al. 2015; Loucks 2017). The use of rule curves is a reference tool for reservoir management, but very often the complexity of its implementation and the difficulties related to an adequate and viable definition of these curves undermine the possibility of its practical use. Rule curves are traditionally used to regulate reservoir storage for flood control and/or hydropower production (Liu et al. 2011; Mower and Miranda 2013). In these cases, reservoir operating rules are intended to guide the water release to maximize the system's objectives, such as increasing energy production or reducing flooding events.

The use of rule curves to improve water availability under scarcity requires a different approach. Considering the scarcity of water resources, particularly in multipurpose reservoirs, the management goals for rule curves should be oriented towards the reduction of water shortages, both in quantity and duration, as well as improving water availability for all water users (Gu et al. 2017; Jin and Lee 2019; Garrote et al. 2023).

In the Mediterranean region water needs for agriculture are inverse to the typical precipitation regimes, thus the availability of water for the irrigation campaign is highly dependent on the storage from the wet season. Therefore, management criteria should be focused on water conservation to ensure its availability for different uses, as well as to account for the intense natural evaporation. Additionally, in systems where storage is complemented with water transfer from other sources (*e.g.* support reservoirs), volumes to be transferred need to be anticipated and take into account potential losses and energy costs.

This work aims to contribute to the improvement of the management of water supply systems, in multipurpose reservoirs that have associated water transfer infrastructures. The main goal is to develop an innovative reservoir management approach based on rule curves and a dynamic evaluation of water needs. This aims to increase water supply reliability reduce drought vulnerability and increase energy use efficiency.

For this purpose, implemented methods include the sequential use of climate models simulation results, hydrological modelling, and reservoir water balance modelling. This approach is supported by the design of operation criteria, as well as the optimization of anticipated water transfers, and implemented to evaluate climate change impacts on water availability in multipurpose reservoir systems. Three alternative management scenarios are compared, two of them using static water management rules and a third one using rule curves and a dynamic assessment of water needs and inflows.

## 2 Study Area

The case study is focused on a Mediterranean river basin, located in a Southern inland region of Portugal (Fig. 1). This includes two reservoirs, Monte Novo (MN) and Vigia (VG), which are part of the supply system for human consumption in the region's district capital (Évora) and nearby municipalities, providing water for a population of about 65 000 people. These reservoirs also represent an important source of water for irrigation in the region, supplying agriculture to an area of about 2 500 ha.

The climate of the study area is typically Mediterranean, with two deeply marked seasons, a hot and dry long summer, and a cold and somewhat wet winter. The summer is also characterized by low cloudiness, high evaporation from the reservoirs, as well as high evapotranspiration from the vegetation, which leads to an increased irrigation demand during this time of year (Tanasijevic et al. 2014; Fader et al. 2016). Years with low precipitation are frequent, thus the issues of water scarcity and quality are likely to be aggravated by the effects of potential climate change (Diffenbaugh et al. 2007; Iglesias et al. 2007; Nunes et al. 2017).

Both reservoirs are used for urban and agricultural water supply but with different relative relevance: in the MN reservoir the main use is domestic supply accounting for around 75% of yearly average demand, and in the VG agriculture represents around 90% of yearly average demand. Water management in both reservoirs is based on the premise that human

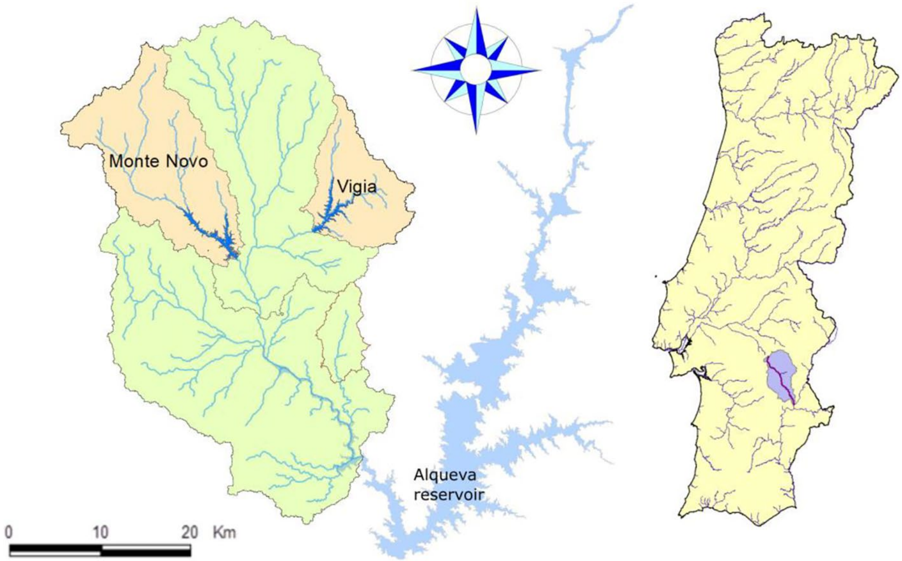


**Fig. 1** Study area location: the Monte Novo and Vigia reservoirs

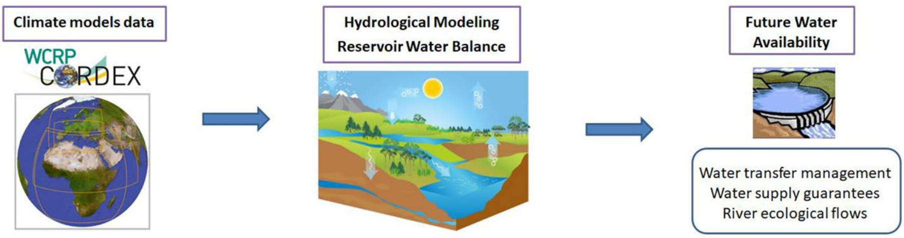


**Fig. 2** Scheme of the sequential modelling approach

consumption takes priority over other uses, thus agricultural water provision is subject to potential restrictions whenever urban supply is found to be at risk.

For both reservoirs, there is a water transfer system from the Alqueva reservoir,[1] for which the proposed approach aims to optimize management and improve the different use's reliability.

Agriculture is the main land use in the region, including several cultural systems but where irrigated olive groves and vineyards stand out, with the latter having a significant increase in recent years. In the MN irrigation area, there is only one irrigated crop—olive groves – with an area of 800 ha. In the VG irrigation perimeter, the main perennial crops are olive groves (about 500 ha) and vineyards (about 340 ha); seasonal crops are variable in area and can represent an additional area of 900 ha (*e.g.,* maize, sunflower, barley, tomato).

River runoff in the basin is highly variable, both intra and inter-annually, with about 90% of the river's natural flow concentrated on the wet semester (October–March). These hydrological conditions include both occasional floods and severe droughts that can last up to two to three years. At present ecological flows are not implemented in the basin, thus river flow downstream of the two reservoirs is reduced, though there is unrestricted runoff from the remaining areas of the catchment.

Some of the main challenges for water management in the study area: a) lack of a comprehensive water balance in the watershed's reservoirs; b) insufficient knowledge of climate change effects on future water availability; c) unmonitored river inflows into both reservoirs; d) inadequate definition of reservoir's operation criteria. The assessment of these issues is of significant relevance for future water availability, influencing agricultural management and crops yield in the watersheds.

# 3 Methods

## 3.1 Approach

For the objective of developing a multipurpose reservoir management approach to increase water supply reliability, three management scenarios are defined and tested to evaluate the effect of long-term climate change on water availability for different uses.

The proposed methods are tested using a sequential approach of climate simulation results, hydrological modelling, and reservoir water balance simulations (Fig. 2).

[1] The Alqueva is the largest dam and artificial lake in Western Europe, with a storage capacity of 4 150 $hm^3$. This reservoir supplies water for irrigation and urban use for the Alentejo region in southern Portugal.

**Table 1** Reference storage volumes (%) and transfer operation time (h)

| VG reservoir | | | MN reservoir | | | Water transfer |
|---|---|---|---|---|---|---|
| No Rules | Static Rules | Dynamic Rules | No Rules | Static Rules | Dynamic Rules | operation time |
| – | < 70% | < RULE CURVE | – | < 80% | < RULE CURVE | 10 h/day |
| – | < 55% | < 75% RULE CURVE | – | < 65% | < 80% RULE CURVE | 14 h/day |
| < 25% | < 25% | < 40% RULE CURVE | < 25% | < 25% | < 45% RULE CURVE | 18 h/day |

Climate model results are obtained from the EURO-CORDEX program considering the scenarios RCP4.5 and RCP 8.5. An ensemble of eight global and regional models are used (CM5_CCLM4, CM5_RCA4, CM5A_RCA4, CM5A_WRF33, EC-Earth_CCLM4, EC-Earth_HIRHAM5, EC-Earth_RACMO22E, EC-Earth_RCA4) (see Supplementary material).

From the climate model results, reservoir inflows are calculated using hydrological modelling using HEC-HMS, calibrated from 1990 to 2005, and validated for the hydrological years of 2005–2015 (see Supplementary material). From the inflow results, monthly reservoir water balances are simulated from 2021 to 2100, for each of the three management scenarios in the two basins—MN and VG.

### 3.2 Reservoir Management Scenarios

Three management scenarios are established to determine water management and including irrigation (IRR) potential restrictions, ecological flows (EF), and water transfer system operation. In the developed model the hierarchy of use is urban supply (URB), which is a legal requirement, then EF and IRR.

Water availability is highly dependent on the water transfer system, which needs to be operated based on the foreseen reservoir water storage and water demand, to ensure 100% of URB, and maximize the reliability of the supply for IRR and EF.

The method used for estimating the EF is based on Godinho et al. (2014), who estimated values from 12 to 15% of the total annual flow under natural conditions, with the objective of maintaining river ecosystem health downstream of three dams in the same basin of the present study area. In the present study, we assumed a value of 15% of total annual flow under natural conditions, with a monthly distribution that follows the natural runoff pattern in the period before the dam's construction (1944–1979).

The three scenarios are: "No Rules", "Static Rules", and "Dynamic Rules". For each of the management scenarios reference storage volumes are used to determine how the water transfer system is operated. This decision is made at the beginning of each month, according to the observed stored volumes which are compared with the reference volumes described in Table 1, which also includes the number of hours for the transfer system operation.

The "No Rules" scenario is the one closest to the present situation, and thus represents a "Business as usual" scenario in which the transfer system is operated only when the domestic supply is at risk and in an intensive way. In the "Static Rules" and "Dynamic Rules" scenarios the transfer is operated in a way so that the reservoirs can have a similar water availability.

Considering the limitations of the water transfer system, ensuring 100% of the URB water needs may also require IRR and EF restrictions when the volume in the reservoir is at shortage risk considering the foreseen demands. These restrictions are set for each of the management scenarios in the following way:

1. No Rules: water may be withdrawn from the reservoir until the urban supply is at risk. No supply for IRR below 30% of the normal maximum pool level (NPL) and 25% for EF.
2. Static Rules: When storage is below 50% of the NPL, IRR and EF are restricted to 70% of the needs. No supply for IRR below 25% NPL and 20% for EF.
3. Dynamic Rules: IRR and EF are restricted below 40% NPL to the levels given by Eq. 1. No supply for IRR below 25% NPL and 20% for EF.

For the objective of maximizing the IRR and EF supply and at the same time guaranteeing 100% of urban supply, Eq. 1 is defined as:

$$EF_i = D_i \times \frac{VS_i - \sum_{i=1}^{N} TD_i + \sum_{i=1}^{N} In_i}{40\%NPL} \tag{1}$$

where $i$ is the month, $EF_i$ is the effective supply (IRR or EF) in each month $i$, $D_i$ is the demand (IRR or EF), $VS_i$ is the volume stored, $TD_i$ is the total water demand (URB, IRR and EF), $In_i$ is the inflow and NPL is the normal pool level. $TD_i$ and $In_i$ are based on the historic (1971–2000) monthly average values. To anticipate six months of demands and inflows, N = 6.

From the restrictions defined for the "Static Rules" at 50% NPL results a controlled deficit of 70% of the demand. In the "Dynamic Rules" the controlled deficit is dynamically adjusted using Eq. 1. Below the "No supply" levels defined water is not supplied resulting an uncontrolled deficit. For each water need and month $i$ an objective function is defined as:

$$Z_i = \frac{EF_i}{D_i} \tag{2}$$

so that $Z_i = 1$ if the demand $D_i$ is completely satisfied, and 0 if no supply is provided.

The advantages of the "Dynamic Rules" are: a) take into account the forecast of future water needs and inflows to adjust the transfer activation thresholds based on the curve rules, b) maximize the objective function (Eq. 2), and c) minimize controlled and uncontrolled deficits by adjusting the IRR and EF supply according to the anticipated needs (Eq. 1).

The water balance in each reservoir for future scenarios in the period 2021–2100, allows the estimations of the reliability of the system to provide water for all uses (URB, IRR and EF). The reliability of the supply system is defined as the probability to deliver water satisfying certain criteria. Volumetric reliability (McMahon et al. 2006) is defined as (Eq. 3):

$$R_{vol} = 1 - \sum_{i=1}^{N} \frac{Sh_i}{D_i} \quad 0 < R_{vol} \leq 1 \tag{3}$$

where $R_{vol}$ is the volumetric reliability, $Sh_i$ and $D_i$ are the amounts of water shortage and demand in month $i$, respectively, and N is the number of time intervals in the simulation, so that $R_{vol} = 1$ if the demand $D_i$ is fully satisfied.

The algorithm developed uses a simulation model of the operation of each reservoir. At each time step, the model performs the following computations for each reservoir and climate model:

(a) Supply URB water demands, which is a legal priority use.
(b) Subtract evaporation losses, based on water surface area and climate models' potential evaporation.
(c) Increase reservoir storage with the inflow volume estimated by hydrological modelling and the water transfer criteria (Table 1).
(d) Allocate the volumes needed for EF release and IRR (EF takes priority over IRR).
(e) Calculate supply deficits if there are demand restrictions.
(f) Estimate water spillage if there is excess storage above NPL.

The model provides the temporal evolution of the storage in each reservoir, the volumes supplied to each of the demands (URB, IRR and EF), and the losses from evaporation and water spills above NPL.

# 4 Discussion

## 4.1 Climate Scenarios Trends

The climate scenarios results can be summarized as the variation of the following variables (Fig. 3) a) precipitation, b) potential evapotranspiration calculated by the FAO Penman–Monteith method (Allen et al. 1998), c) irrigation demands estimated by the FAO water production function (Steduto et al. 2012), for olive groves in the MN basin, and a weighted average for olive groves and vineyards for the VG basin.

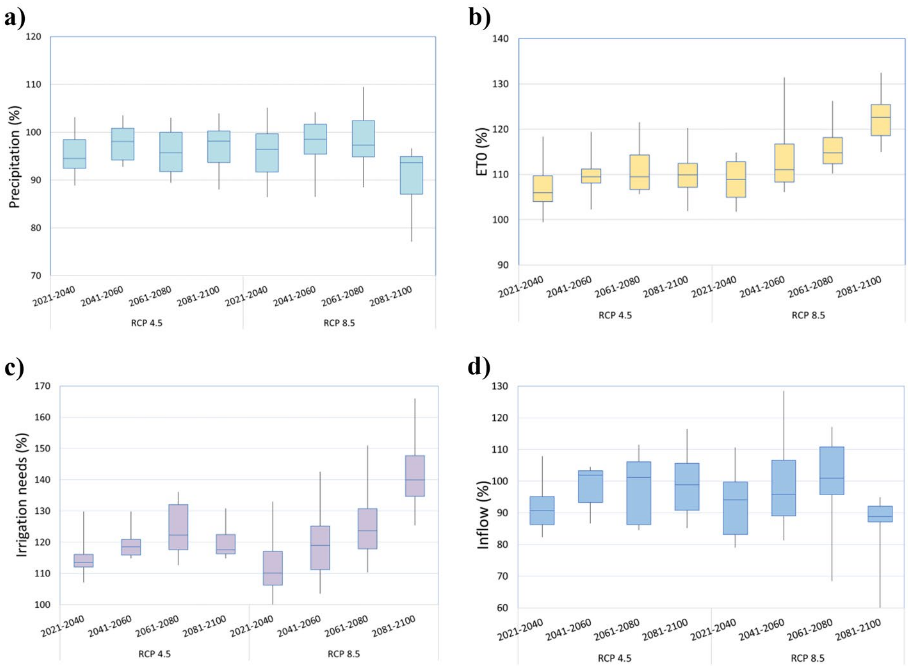


**Fig. 3** Variability and changes in **a**) precipitation, **b**) ET0, **c**) irrigation needs, **d**) runoff

The differences between the climate models, graphics in the form of "box plots" are presented, where the "boxes" represent the variation between the first quartile (25$^{th}$ percentile) and the third quartile (75$^{th}$ percentile), and the line in the middle represents the median value (50$^{th}$ percentile). The "wicks" represent the variation between the minimum and maximum values. The values are indexed to the control period (1971–2000), corresponding to the value 100. Future values are expressed as percentages of the difference from the control value. The comparison is performed in four periods (2021–2040, 2041–2060, 2061–2080, and 2081–2100).

Precipitation (Fig. 3a) shows a slight decrease for both RCP scenarios, though more significant for RCP 8.5 in 2081–2100. These results are consistent with those obtained by other authors for the Alentejo region; Lionello and Scarascia (2018) report a decrease in annual precipitation of about 50 mm (circa 10%) towards the end of the 21$^{st}$ century, and Tuel et al. (2021) mention a decrease between 20–40 mm for RCP 4.5 and 30–50 mm for RCP 8.5.

Potential evapotranspiration (ET0) (Fig. 3b) displays a significant increase which is more substantial for RCP 8.5. Results consistent with García-Ruiz et al. (2011), who projected for the region an increase of 200–300 mm (14–21%) in the period 2040–2070.

Future irrigation needs for olive groves (Fig. 3c) show a significant increase for both RCP scenarios, though more expressive in RCP 8.5 in a similar increase pattern of ET0. Fader et al. (2016) mention that gross irrigation needs increase between 4 and 18% in the Mediterranean. For Olive groves, Tanasijevic et al. (2014) estimate an increase in net irrigation requirements between 18,5% and 37% by 2050.

Inflows to each reservoir are estimated from watershed hydrological simulations under climate scenarios. The hydrological model was successfully calibrated and validated (see Supplementary Material). Figure 3 d) displays the results for the MN basin (very similar results for the VG basin). Results show a runoff decrease in the period 2021–2040, and in the periods 2041–2060 and 2061–2080, the median values are close to the control period, which is mainly associated with an increase in extreme precipitation events. In the period 2081–2100, for RCP 8.5, there is a very significant decrease in the runoff, derived from the combined effects of a reduction in precipitation and an increase in ET0. For both RCP scenarios (4.5 and 8.5), there is a high variability in the runoff, mainly related to the climate models' uncertainty which is also reported by several authors (Montaldo and Oren 2018; Sordo-Ward et al. 2019).

Results from climate data, irrigation needs, and hydrological modelling, indicate that both reservoirs are likely to be significantly affected by climate change. Particularly in the RCP 8.5 scenario, increased IRR demands combined with reduced inflow, are likely to increase water scarcity. Similar results have been found by del Pozo et al. (2019) and Tramblay et al. (2020).

### 4.2 Reservoir Water Balance

Based on the results presented in the previous section, it was possible to simulate the water balances in the reservoirs and estimate the water availability, the water transfer needs as well as diverse uses reliability. The results obtained for the simulations developed in the three management scenarios are summarized in Table 2, which displays the average values for the eight climate models in the simulation period (2021–2100).

**Table 2** Simulation results for the three management scenarios

| MN reservoir | RCP 4.5 | | | RCP 8.5 | | |
|---|---|---|---|---|---|---|
| | NO RULES | STATIC RULES | DYNAMIC RULES | NO RULES | STATIC RULES | DYNAMIC RULES |
| Average stored volume (% NPL vol.) | 56.8% | 65.2% | 64.5% | 55.0% | 63.2% | 62.8% |
| URB reliability (% vol. needed) | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |
| IRR reliability (% vol. needed) | 76.8% | 84.5% | 87.9% | 73.7% | 82.4% | 85.5% |
| IRR objective function > 85% vol (% years) | 74.1% | 81.3% | 85.9% | 70.3% | 77.5% | 82.3% |
| IRR uncontroled deficit (% months) | 11.0% | 4.7% | 3.3% | 12.9% | 5.7% | 3.8% |
| EF reliability (% vol. needed) | 92.7% | 90.6% | 93.3% | 91.7% | 89.5% | 91.8% |
| EF objective function > 85% vol (% years) | 81.6% | 81.0% | 85.4% | 81.3% | 78.2% | 82.8% |
| EF uncontroled deficit (% months) | 2.9% | 0.5% | 0.2% | 3.5% | 0.8% | 0.2% |
| Transfer volume (% NPL/year) | 13% | 28% | 27% | 14% | 29% | 29% |
| Transfer energy cost (k€/year) | 15.7 | 29.1 | 26.6 | 17.4 | 30.4 | 28.3 |
| VG reservoir | RCP 4.5 | | | RCP 8.5 | | |
| | NO RULES | STATIC RULES | DYNAMIC RULES | NO RULES | STATIC RULES | DYNAMIC RULES |
| Average stored volume (% NPL vol.) | 60.0% | 67.2% | 65.9% | 57.6% | 64.2% | 63.7% |
| URB reliability (% vol. needed) | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |
| IRR reliability (% vol. needed) | 78.8% | 90.5% | 90.8% | 75.0% | 87.8% | 89.0% |
| IRR objective function > 85% vol (% years) | 73.9% | 82.1% | 87.0% | 67.1% | 77.1% | 84.3% |
| IRR uncontroled deficit (% months) | 9.7% | 1.3% | 0.5% | 11.3% | 1.8% | 0.6% |
| EF reliability (% vol. needed) | 93.3% | 91.0% | 97.8% | 93.0% | 89.5% | 97.5% |
| EF objective function > 85% vol (% years) | 81.0% | 79.4% | 92.1% | 80.9% | 73.9% | 91.5% |
| EF uncontroled deficit (% months) | 7.7% | 0.1% | 0.1% | 9.2% | 0.2% | 0.2% |
| Transfer volume (% NPL/year) | 3% | 16% | 15% | 3% | 17% | 17% |
| Transfer energy cost (k€/year) | 2.7 | 9.4 | 9.3 | 3.1 | 10.4 | 10.3 |

Average stored volume is expressed in percentage of NPL volume and is slightly higher for the "Static Rules" compared with the "Dynamic Rules", though this does not translate into a better performance as measured by the variables displayed in Table 2.

In all the scenarios it is possible to obtain 100% reliability for URB supply throughout the simulation period (2021–2100). This is possible because URB takes priority over other uses, and the water transfer system can satisfy this need.

Reliability expressed as % of the total demand is higher for the "Dynamic Rules", in both reservoirs and the two RCP scenarios. Reliability measured by the "objective function" (Eq. 2) represents the number of years (in %) in which at least 85% of the demand is fulfilled. When applied to IRR and EF, both results also show a relevant improvement in reliability, which is higher than the one expressed as % of the total demand.

The variable "uncontrolled deficit" represents the number of months (in %) in which the scenario has a total restriction on the water supply. Generally, "Dynamic Rules" has the best performance, and "No Rules" the less desirable one.

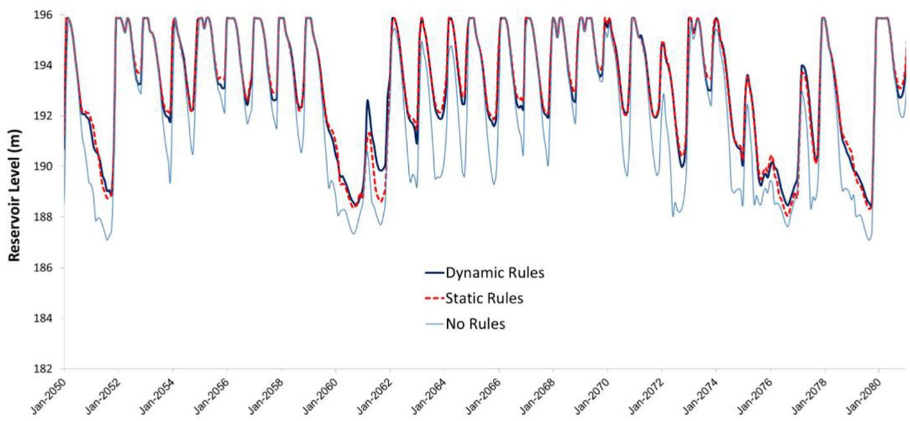


**Fig. 4** MN reservoir level for each management scenario

The transfer volumes are similar for the "Static Rules" compared with the "Dynamic Rules" since both are designed to have a similar potential capacity to satisfy the various demands. There is a slight advantage for the "Dynamic Rules" energy use, associated with better planning of the transfer operation.

Figure 4 displays an example of the reservoir time series for one climate model (EC-Earth_HIRAM5) in the RCP 8.5 scenario and the three management rules. Similar reservoir levels are generally displayed by the "Static" and "Dynamic" Rules, however, the advantage of the latter can be seen in the summers of 2061 and 2076, where the availability of water is higher in this scenario. The lower levels in the "No Rules" scenario show the advantage of an anticipated operation of the transfer system.

### 4.3 Water Uses and Reliability

The results of future water supply reliability (Eq. 3) are presented in Fig. 5, with IRR in the top row, and EF in the lower row. These results are based on the monthly calculation of the difference between the volumes of water that are needed, and the volumes that are supplied, given the restrictions that the management scenarios impose.

Reliability patterns are very similar for both reservoirs. IRR reliability for the control period (1990–2020) is around 80%, thus the "No Rules" scenario indicates a reduction in reliability. Both the "Static" and "Dynamic" Rules scenarios show an improvement in IRR reliability. This is generally higher for the RCP 4.5 scenario, as expected due to the combination of climate scenarios trends described in Section 4.1. The "Dynamic Rules" lead to better management results and provide a more favourable combination between IRR and EF supply reliability. EF reliability is lower for the "Static Rules" scenario, mainly because the restrictions for EF are imposed earlier.

The satisfaction of EF generates an increase in water transfer requirements and a slight decrease in IRR reliability. Compared with a hypothetical absence of EF release, the IRR reliability would increase to around 95% for both reservoirs. The increase would be greater for the MN case since the competition between uses is higher. Similar results have been obtained by Xu (2020), who mentions that in reservoirs with significant competitive uses, increasing EF guarantee decreases IRR reliability.

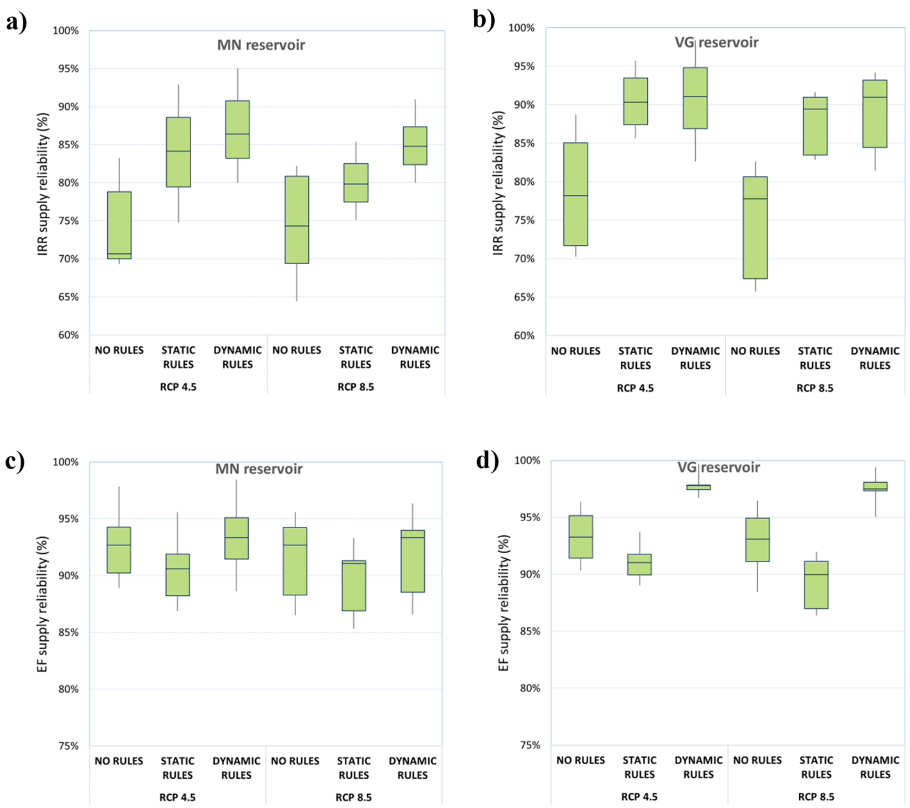


**Fig. 5** Water supply reliability for IRR **a**) and **b**), and EF **c**) and **d**)

These results are comparable to those obtained by Garrote et al. (2023) who found that "adaptive rules" can improve the supply reliability and reduce the restrictions, when a "random inflow" series is used, which is a condition similar to the use of eight climate models to generate inflow series by hydrological modelling.

EF reliability in the MN reservoir is similar for "No Rules" and "Dynamic Rules" (93%) and in the VG case the highest (98%) for "Dynamic Rules". This is linked to the higher competition between uses in the MN reservoir. These results indicate that the proposed "Dynamic Rules" management scenario yields a higher satisfaction of EF requirements, as established with the selected approach.

The implemented EF release pattern is based on the natural river flow regimes, observed before the construction of the dams. EF considers the monthly volumes of water required to maintain the river ecosystem integrity downstream of the dams. However, as McMillan (2021) mentions, other hydrological characteristics need to be observed, such as flow magnitude, frequency, duration, rate of change, and seasonal timing.

The situation in the case study is similar to that of many intermittent rivers in southern Europe which are intercepted by dams. The EF regime implemented in this study allows for the alternation of flowing and low-flow phases, which is beneficial to support a wide range of ecosystem processes and services that are fundamental to maintaining river ecosystem health downstream of the existing dams (Acuña et al. 2020; Stubbington et al. 2020).

This study introduces the release of EF in both reservoirs, which is presently not implemented. Considering that the obtained results indicate a satisfactory performance of the proposed “Dynamic Rules”, the addition of EF further supports the relevance and adequacy of the approach towards the increase of water management sustainability, by promoting the improvement of the rivers’ ecological state downstream of the reservoirs.

These results demonstrate that the “Dynamic Rules” approach can represent a more efficient and sustainable option than the other management scenarios, providing a better combination between the reliability of water supply, transfer volumes, and associated costs.

## 5 Conclusions

Water reservoirs in Mediterranean areas such as the Alentejo region are fundamental to guarantee water supply to diverse uses. Efficient water management is paramount to future water availability and the capacity of reservoirs to satisfy all the demands. At present, the MN and VG reservoirs have significant reliability limitations, and future climatic trends indicate that water scarcity is likely to be aggravated.

Considering the dependency on the water transfer system from the Alqueva reservoir, adequate anticipation of required flows is essential to optimize supply reliability, energy use and costs. In this scope, this work contributes to the development of adaptation measures in reservoir management, through the definition and application of an innovative approach based on rule curves and a dynamic assessment of water needs.

This study clearly shows that the use of the proposed “Dynamic Rules” may have multiple benefits in reservoir management. Namely, there are significant advantages in the planning and management of multipurpose reservoirs and water transfer systems.

Results for both reservoirs demonstrate that the approach can optimize the balance between water supply reliability, transfer volumes and costs. The approach allows water managers and farmers to know in advance which restrictions are needed to be established in each irrigation season. This allows water users to adequately plan their choices, reducing supply uncertainty and scarcity risks. This is particularly relevant for farmers who need to organize resources and plan irrigation schedules every season.

Based on the obtained results it can be concluded that the main goal of the study has been achieved. The “Dynamic Rules” developed and implemented demonstrated to be an effective climate change adaptation measure, increasing the resilience of water supply systems. The proposed approach can be replicated in other reservoirs, particularly those that have multiple uses and/or a water transfer system.

Suggestions for future work include water quality analysis, namely considering that this can represent additional conditions for the definition of reservoir operation, influencing rule curves and restrictions for different water uses. Another approach that can be adopted is the use of other time scales, namely weekly or daily water balances for short-term forecasting and reservoir management.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s11269-023-03508-x.

**Author Contributions** Conceptualization: P.B., A.C.R. and P.D.; case study design and methods: P.B., A.C.R., J.P.N. and P.D.; material preparation, data collection and analysis: P.B. and P.D.; writing—original draft preparation: P.B.; writing—review and editing: all authors. All authors read and approved the final manuscript.

**Funding** Open access funding provided by FCT|FCCN (b-on). This research was partially funded by the collaborative international Consortium INNOMED financed under the ERA-NET WaterWorks2015 co-funded Call, an integral part of the 2016 Joint Activities developed by the Water JPI. The authors P.B. and J.P.N. acknowledge the support from cE3c—Center for Ecology, Evolution and Environmental Change through the strategic project UIDB/00329/2020, & CHANGE—Global Change and Sustainability Institute, Faculty of Sciences, University of Lisbon (FCUL/ULisboa), Portugal. The authors A.C.R., P.B., P.D. and B.M. acknowledge FCT—Fundação para a Ciência e a Tecnologia (Portugal) through the strategic project UIDB/04292/2020 granted to MARE—Marine and Environmental Sciences Centre.

**Data Availability** Data used for this work was accessed from public sources. Meteorological and hydrological data is available at https://snirh.apambiente.pt. Additional data for precipitation is obtained from the Iberia01 dataset, available at https://digital.csic.es/handle/10261/183071. Climate models data was obtained from the EURO-CORDEX program, available at https://euro-cordex.net/060378/index.php.en.

## Declarations

**Competing Interests** The authors have no relevant financial or non-financial interests to disclose.



## References

Acuña V, Jorda-Capdevila D, Vezza P, de Girolamo AM, McClain ME, Stubbington R, Pastor AV, Lamouroux N, von Schiller D, Munné A, Datry T (2020) Accounting for flow intermittency in environmental flows design. In: Journal of Applied Ecology (Vol. 57, Issue 4). Blackwell Publishing Ltd, pp 742–753. https://doi.org/10.1111/1365-2664.13590

Alcamo J, Döll P, Henrichs T, Kaspar F, Lehner B, Rösch T, Siebert S (2003) Global estimates of water withdrawals and availability under current and future "business-as-usual" conditions. Hydrol Sci J 48(3):339–348. https://doi.org/10.1623/hysj.48.3.339.45278

Allen RG, Pereira LS, Raes D, Smith M (1998) FAO Irrigation and drainage paper No. 56. Rome: Food and Agriculture Organization of the United Nations 56(97):e156

Bogardi JJ, Dudgeon D, Lawford R, Flinkerbusch E, Meyn A, Pahl-Wostl C, Vielhauer K, Vörösmarty C (2012) Water security for a planet under pressure: Interconnected challenges of a changing world call for sustainable solutions. In: Current Opinion in Environmental Sustainability (Vol. 4, Issue 1, pp. 35–43). https://doi.org/10.1016/j.cosust.2011.12.002

del Pozo A, Brunel-Saldias N, Engler A, Ortega-Farias S, Acevedo-Opazo C, Lobos GA, Jara-Rojas R, Molina-Montenegro MA (2019) Climate change impacts and adaptation strategies of agriculture in Mediterranean-climate regions (MCRs). In: Sustainability (Switzerland) (Vol. 11, Issue 10). MDPI. https://doi.org/10.3390/su11102769

Diffenbaugh NS, Pal JS, Giorgi F, Gao X (2007) Heat stress intensification in the Mediterranean climate change hotspot. Geophys Res Lett 34(11). https://doi.org/10.1029/2007GL030000

Fader M, Shi S, Von Bloh W, Bondeau A, Cramer W (2016) Mediterranean irrigation under climate change: More efficient irrigation needed to compensate for increases in irrigation water requirements. Hydrol Earth Syst Sci 20(2):953–973. https://doi.org/10.5194/hess-20-953-2016

García-Ruiz JM, López-Moreno II, Vicente-Serrano SM, Lasanta-Martínez T, Beguería S (2011) Mediterranean water resources in a global change scenario. In: Earth-Science Reviews (Vol. 105, Issues 3–4), pp 121–139. https://doi.org/10.1016/j.earscirev.2011.01.006

Garrote L (2017) Managing water resources to adapt to climate change: facing uncertainty and scarcity in a changing context. Water Resour Manage 31(10):2951–2963. https://doi.org/10.1007/s11269-017-1714-6

Garrote L, Granados A, Spiliotis M, Martin-Carrasco F (2023) Effectiveness of adaptive operating rules for reservoirs. Water Resour Manage. https://doi.org/10.1007/s11269-022-03386-9
Godinho F, Costa S, Pinheiro P, Reis F, Pinheiro A (2014) Integrated procedure for environmental flow assessment in rivers. Environ Process 1(2):137–147. https://doi.org/10.1007/s40710-014-0012-z
Gu W, Shao D, Tan X, Shu C, Wu Z (2017) Simulation and optimization of multi-reservoir operation in inter-basin water transfer system. Water Resour Manage 31(11):3401–3412. https://doi.org/10.1007/s11269-017-1675-9
Iglesias A, Garrote L, Flores F, Moneo M (2007) Challenges to manage the risk of water scarcity and climate change in the Mediterranean. Water Resour Manage 21(5):775–788. https://doi.org/10.1007/s11269-006-9111-6
Iglesias A, Garrote L (2015) Adaptation strategies for agricultural water management under climate change in Europe. In: Agricultural Water Management (Vol. 155). Elsevier, pp 113–124. https://doi.org/10.1016/j.agwat.2015.03.014
Jin Y, Lee S (2019) Comparative effectiveness of reservoir operation applying hedging rules based on available water and beginning storage to cope with droughts. Water Resour Manage 33(5):1897–1911. https://doi.org/10.1007/s11269-019-02220-z
Lionello P, Scarascia L (2018) The relation between climate change in the Mediterranean region and global warming. Reg Environ Change 18(5):1481–1493. https://doi.org/10.1007/s10113-018-1290-1
Liu X, Guo S, Liu P, Chen L, Li X (2011) Deriving optimal refill rules for multi-purpose reservoir operation. Water Resour Manage 25(2):431–448. https://doi.org/10.1007/s11269-010-9707-8
Loucks DP (2017) Managing water as a critical component of a changing world. Water Resour Manage 31(10):2905–2916. https://doi.org/10.1007/s11269-017-1705-7
McMahon TA, Adeloye AJ, Zhou SL (2006) Understanding performance measures of reservoirs. J Hydrol 324(1–4):359–382. https://doi.org/10.1016/j.jhydrol.2005.09.030
McMillan HK (2021) A review of hydrologic signatures and their applications. Wiley Interdiscip Rev Water 8(1). https://doi.org/10.1002/wat2.1499
Molina-Navarro E, Trolle D, Martínez-Pérez S, Sastre-Merlín A, Jeppesen E (2014) Hydrological and water quality impact assessment of a Mediterranean limno-reservoir under climate change and land use management scenarios. J Hydrol 509:354–366. https://doi.org/10.1016/j.jhydrol.2013.11.053
Montaldo N, Oren R (2018) Changing seasonal rainfall distribution with climate directs contrasting impacts at evapotranspiration and water yield in the Western Mediterranean Region. Earth's Futur 6(6):841–856. https://doi.org/10.1029/2018EF000843
Mower E, Miranda LE (2013) Frameworks for amending reservoir water management. Lake Reservoir Manage 29(3):194–201. https://doi.org/10.1080/10402381.2013.829893
Nunes JP, Jacinto R, Keizer JJ (2017) Combined impacts of climate and socio-economic scenarios on irrigation water availability for a dry Mediterranean reservoir. Sci Total Environ 584–585:219–233. https://doi.org/10.1016/j.scitotenv.2017.01.131
Rocha J, Carvalho-Santos C, Diogo P, Beça P, Keizer JJ, Nunes JP (2020) Impacts of climate change on reservoir water availability, quality and irrigation needs in a water scarce Mediterranean region (southern Portugal). Sci Total Environ 736. https://doi.org/10.1016/j.scitotenv.2020.139477
Sordo-Ward A, Granados A, Iglesias A, Garrote L, Bejarano MD (2019) Adaptation effort and performance of water management strategies to face climate change impacts in six representative basins of Southern Europe. Water (Switzerland) 11(5). https://doi.org/10.3390/w11051078
Steduto P, Hsiao TC, Fereres E, Raes D (2012) Crop yield response to water (Vol. 1028). fao Rome
Stubbington R, Acreman M, Acuña V, Boon PJ, Boulton AJ, England J, Gilvear D, Sykes T, Wood PJ (2020) Ecosystem services of temporary streams differ between wet and dry phases in regions with contrasting climates and economies. People and Nature 2(3):660–677. https://doi.org/10.1002/pan3.10113
Tanasijevic L, Todorovic M, Pereira LS, Pizzigalli C, Lionello P (2014) Impacts of climate change on olive crop evapotranspiration and irrigation requirements in the Mediterranean region. Agric Water Manag 144:54–68. https://doi.org/10.1016/j.agwat.2014.05.019
Tramblay Y, Koutroulis A, Samaniego L, Vicente-Serrano SM, Volaire F, Boone A, Le Page M, Llasat MC, Albergel C, Burak S, Cailleret M, Kalin KC, Davi H, Dupuy JL, Greve P, Grillakis M, Hanich L, Jarlan L, Martin-StPaul N, … Polcher J (2020) Challenges for drought assessment in the Mediterranean region under future climate scenarios. In: Earth-Science Reviews (Vol. 210). Elsevier B.V. https://doi.org/10.1016/j.earscirev.2020.103348
Tuel A, Kang S, Eltahir EAB (2021) Understanding climate change over the southwestern Mediterranean using high-resolution simulations. Clim Dyn 56(3–4):985–1001. https://doi.org/10.1007/s00382-020-05516-8

Walker WE, Loucks DP, Carr G (2015) Social responses to water management decisions. Environ Process 2(3):485–509. https://doi.org/10.1007/s40710-015-0083-5

Xu W (2020) Study on multi-objective operation strategy for multi-reservoirs in small-scale watershed considering ecological flows. Water Resour Manage 34(15):4725–4738. https://doi.org/10.1007/s11269-020-02685-3