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On the Choice of Optimal Reservoir Operating Rules in a Changing Climate for the Sustainable Management of Drinking Water Sources

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Abstract

The effect of climate change on water availability is a growing concern for decision-makers involved in resource management, as well as within the hydrological and hydraulic engineering communities. To ensure the resilience of water supply systems, it is essential to adapt the sustainable and integrated management of drinking water sources to the expected changes in the magnitude and occurrence of hydrological droughts. This paper introduces a methodological framework for the sustainable management of water resources in a coastal region of Northern Italy under climatic change, aimed at modelling a multi-basin water supply reservoir, which represents the primary and most sustainable source of the system. The approach involves the multi-objective optimization of its withdrawal rules under both historical and future meteorological forcings, aiming to maximize reservoir production while meeting the demand during water scarcity conditions. The reconstruction of the historical operation of the dam controls and the estimates of the reservoir minimum demand requirements further support the implementation of the methodology. Utilizing a Parameterization-Simulation-Optimization approach and a wide range of climate models, the findings offer valuable insights to support decision-makers. Specifically, the research quantifies future expected relative changes in optimal operating rules based on different management policies. It also outlines the corresponding expected patterns of withdrawal volumes and potential water system failures throughout the century. This information allows to effectively assess the risk associated with future water scarcity and aids in developing long-term resource management strategies, thereby mitigating stress on less sustainable water sources.

Keywords Optimal reservoir management · Integrated water resources · Drinking water supply · Parameterization-simulation-optimization · Adapting operating rules · Drought

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1 Introduction

An effective and integrated management of drinking-water resources requires the assessment of the impacts of water scarcity, related to periods of hydrological drought, on the use of the available sources. Many regions around the world, including the Mediterranean, are facing more and more frequent water scarcity conditions and are expected to see a further intensification of the gap between water supply and demand in the coming years, due to a combination of climatic and anthropogenic factors (EEA 2010; IPCC 2023; Kirkland 2023; Toth et al. 2018). In a context of growing concern about the impacts of climate change and drought events on water availability, sustainable and integrated management of different drinking water sources is crucial to ensure the resilience of water supply systems (see e.g. Ahmadi et al. 2025; Felisa et al. 2022; Mateus and Tullos 2017; Moghadam et al. 2022).

In such an integrated management framework, it is essential to optimize the operation of mountain reservoirs, which allow high-quality water to be supplied through gravity-fed networks, thus mitigating the overexploitation of groundwater sources and reducing the use of lower-quality and more energy-demanding alternative sources.

Within the broad spectrum of approaches for defining optimal reservoir management rules, the parametrization–simulation–optimization strategy (PSO, Koutsoyiannis and Economou 2003) has been proved particularly effective in faithfully reproducing the complexity of real-world systems (Giuliani et al. 2021), since it combines the detailed system representation allowed by simulation models with the efficiency attained by optimization; applications of PSO have therefore risen considerably in the last decade (Ashbolt et al. 2016; Giuliani et al. 2016; Jose and Srinivasan 2025; Kumar and Kasthurirengan 2018; Lerma et al. 2013, 2015; Spiliotis et al. 2016; Yang and Ng 2017). Regardless of the adopted approach, one of the most important drivers for the operation of water supply reservoirs is the users' demand, which generally governs the water balance. Therefore, accurate analysis of historical water consumption is also required (e.g. Cominola et al. 2023; Toth et al. 2018).

In the last few decades, water resources analysts have also considered climate change scenarios in planning reservoir operations and adaptation strategies. Particularly, it is essential to evaluate the effectiveness of reservoir management rules that have been optimized based on past and present hydro-climatic information, when subjected to future climatic stress conditions. To this end, several experts have tested the resilience of current operational reservoir rules (i.e., designed for historical hydro-meteorological conditions) by forcing the hydrologic system with one or more regional climate scenarios and estimating the expected changes in water availability (e.g. Carvalho-Santos et al. 2017; Chadwick et al. 2020; Chaves et al. 2023; López-Moreno et al. 2014; Mereu et al. 2016; Padiyedath Gopalan et al. 2021; Peres, 2019). Some studies have gone a step further by searching for new management rules that could be effective under changing climatic conditions and by comparing the results of different optimization runs conducted by forcing the system either with historical or on future hydro-climatic time series (Beça et al. 2023; Giuliani et al. 2016; He et al. 2020; Moghadam et al. 2022; Nourani et al. 2020; Tukimat and Harun 2019; Zhang et al. 2017; Zhou and Guo 2013). However, such studies generally considered only a small ensemble of regional climate scenarios, which is a limitation for evaluating the reliability of adapted operating rules, especially in those regions (like the Mediterranean, see e.g. Todaro et al. 2022) where climate models are not or may not be in agreement on the expected changes in projected meteorological forcings and in their seasonality.

Assessing the temporal pattern of future meteorological forcings is particularly important in areas characterized by strong seasonality also in the demand, such as in many tourist coastal areas, where seasonal climatic variations have even more pronounced impacts on water resource planning.

This study presents a methodology for the sustainable management of drinking water sources under climatic change in a coastal region of Northern Italy. The water supply system of the region, which is served by different water sources, including groundwater, rivers and a mountain reservoir, is required to meet a strongly seasonal water demand due to coastal tourism, resulting in significantly higher water consumption during the hottest and driest summer months. The work aims to optimize the operational management of the water supply reservoir, which represents the main and the most environmentally sustainable (high-quality water and less energy demanding distribution) water source of the system, under both current and future climatic conditions, and to evaluate the expected variations in optimal operating rules. For this purpose, the methodology includes the sequential use of hydrological modelling - forced by historical meteorological data and by the outputs of a large ensemble of 10 regional climate models - and reservoir water balance modelling. Following a parameterization-simulation-optimization (PSO) approach, monthly reservoir operating rules are defined for both the historical period and for each of the future scenarios by means of a multi-objective optimization algorithm. This is the first-ever optimization of the drinking and multi-source water system of the region, which is especially challenging for the highly seasonal nature of the demand. In addition, the main novelty of the approach is represented by the utilization of a PSO approach based on the implementation of a fully comprehensive model for the multi-basin reservoir operations capable of accounting for the system's complex real-world constraints, coupled with the use of a full ensemble of climate projections.

The final objective of the analysis is to test and propose a framework to inform long-term resource management planning against future water shortage risk and to reduce reliance on less sustainable sources, by (i) evaluating relative changes in operational rules, and (ii) assessing the historical and future patterns of withdrawal volumes and demand deficit volumes obtained under the different scenarios.

2 Case Study and Data Collection

The study area analyzed in this work is the Romagna region, in Northern Italy, which is one of the most economically developed areas in Europe, also characterized by an extremely profitable seaside tourist industry, mainly concentrated in the summer months (Toth et al. 2018).

RomagnaAcque – Società delle Fonti is the regional water supplier, which provides wholesale water to the retail water companies, serving a total of more than one million permanent residents and several millions of summer tourists. The water supply network (bottom-right in Fig. 1) is served by multiple water sources: the major sources are wellfields all across the lowlands, a channel fed by the Po river (and requiring intensive treatment processes), and the Ridracoli reservoir in the Apennines, which represents the focus of the study.

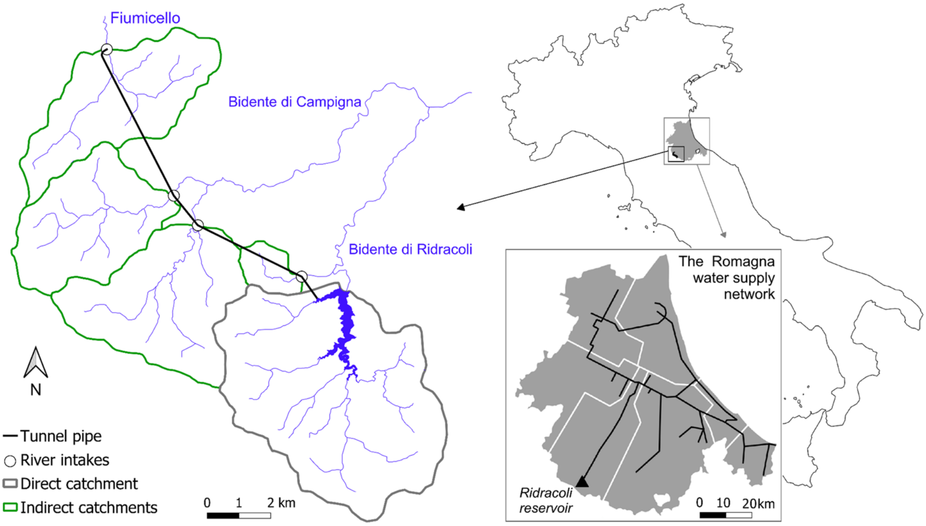

Fig. 1 Left: catchments feeding the Ridracoli reservoir: the upstream basin closed at the dam (grey contour) and the four indirect catchments (green contours) connected to the lake with a system of intakes and tunnel pipes. Bottom-right: rough scheme of the water supply network of the Romagna region

The Ridracoli reservoir is indeed the most environmentally-sustainable and less energy demanding water source in the system. In fact, maximizing the use of the high-quality and gravity-fed water from the reservoir not only offers economic advantages, but also allows to mitigate the groundwater overexploitation, which, particularly in coastal regions, can cause subsidence, saline intrusion, and irreparable harm to the fragile coastal ecosystem. The reservoir itself meets half of the demand of the users, providing on average 54 million m^3 per year, that may be delivered over the entire water distribution network of the Romagna region. Conversely, the other sources provide water “locally”, i.e. to limited portions of the region. For this reason, in this work we will refer to such alternative sources with the term “Local Sources”.

The reservoir system is quite complex since the lake, located on the river Bidente, is fed not only by the “direct” catchment closed at the dam (around 37 km^2), but also by four additional nearby catchments in the North-West connected to the reservoir with a system of intakes and tunnel pipes (left in Fig. 1). The additional contributing drainage area of such nearby catchments is around 50 km^2, but the system of intakes and tunnel pipes has a maximum capacity of 15 l/s. Drinking water supply is the main and driving purpose of the reservoir.

An essential preliminary phase of the approach entailed the collection of all data and information regarding the reservoir management history and constraints, as well as data regarding historical water demand from the supply network and information about the other Local Sources. For brevity, more details are reported in the Supplementary Information (Section S1).

2.1 Climate Data

Historical meteorological observations are available for a number of ground sensor across the study area. However, in order both to enhance the replicability of the experiment and to be consistent with future climate model outputs (see below), the E-OBS dataset (Cornes et al. 2018) is used for estimating past meteorological forcings. E-OBS is a gauge-based and large-scale gridded meteorological product, developed by the ECA&D initiative, which provides a comprehensive suite of climatic variables across Europe at 0.1° spatial resolution including daily minimum and maximum temperatures and daily precipitation depths from 1950 to present. The accuracy of the E-OBS data set in representing precipitation and temperature spatial field is not uniform across Europe, but for the study region Sarigil et al. (2024) demonstrated the reliability of E-OBS, which proved to be able to well reproduce the observed streamflow series when used to force a rainfall-runoff model.

For the simulation of the future climatic forcings, this study exploits an ensemble of regional climate simulation chains, belonging to the Coordinated Regional-climate Downscaling Experiment for Europe (EURO-CORDEX, Jacob et al. 2014). In particular, an ensemble of ten GCM-RCM modelling chains, forced by the RCP 8.5 emission scenario, is used (the list is reported in Table S1 of the Supplementary Information). The projections are bias-corrected by Dosio (2016) and available all over Europe. The bias-correction was performed by means of the technique developed by Piani et al. (2010) using E-OBS as reference datasets, which further supports the choice of using such data for representing the historical climate.

3 Methodology

The goal of the work is to identify operation rules for prioritizing the use of high-quality water from the Ridracoli reservoir, in order to reduce the exploitation of other water sources within the served area, under current and future climatic conditions. Optimal reservoir management therefore requires not only to ensure sufficient water storage to overcome drought periods and guarantee the minimum demand volumes required by users, but also to maximize the overall volumes withdrawn from the reservoir, reducing spillage and thus mitigating the water stress on the other supply sources. In complex real-world systems, the optimization of the operational rules may be carried out in combination with the simulation of the system behavior, i.e. the so called parametrization–simulation–optimization (PSO, Koutsoyiannis and Economou 2003). Given both the already mentioned PSO efficacy in faithfully reproducing the complex nature of real-world systems (Giuliani et al. 2021) and the availability of information regarding past operating decisions and the technical constraints of the study system, a PSO approach is adopted here.

The proposed methodological framework is presented in Fig. 2. The first step is the set-up of the simulation framework: the rainfall-runoff modelling of the five basins feeding the reservoir (Fig. 2a, Sect. 3.1.1) and the model for the simulation of the reservoir system (Fig. 2b, Sect. 3.1.1). Then, the reservoir operation is optimized by assessing the minimum demand from the reservoir (Fig. 2c, Sect. 3.2.1), establishing a functional form of the withdrawal rules (Fig. 2d, Sect. 3.2.2) and optimizing their parameters (Fig. 2e, Sect. 3.2.3).

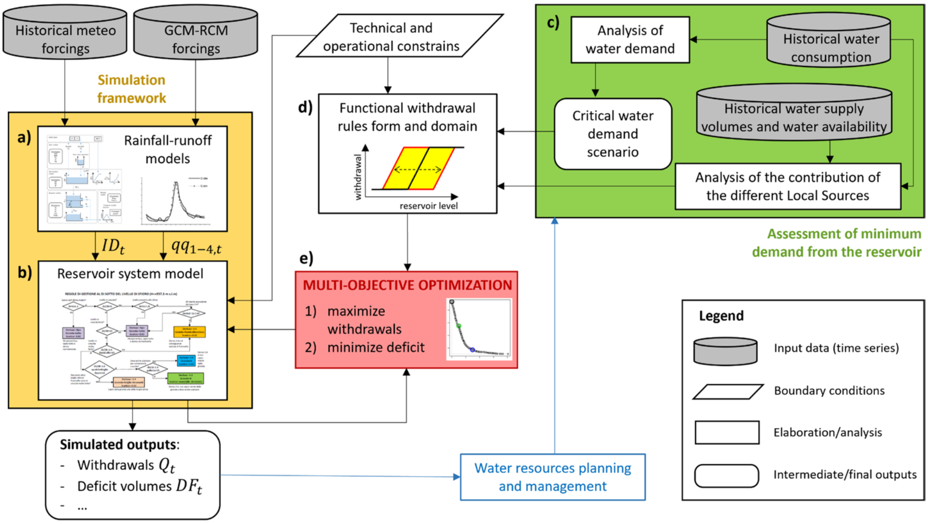

Fig. 2 Methodological framework for the optimization of the withdrawal rules

The PSO approach, described in detail the next subsections, is applied multiple times under different historical or future climate scenarios (Sect. 3.3).

3.1 Simulation Framework

3.1.1 Rainfall-runoff Modelling

A rainfall-runoff model (panel *a)* in the yellow block in Fig. 2), which simulates the hydrological processes leading to the transformation of precipitation into river runoff, is needed to propagate future GCM-RCM climate projections and simulate the inflows to the reservoir and the river flow at the river intakes in the coming decades. To ensure consistency in the results over past and future years, hydrological simulations are also used for the historical period, even though some historical flow observations are available (and have been used for parameterizing the rainfall-runoff model).

The daily lumped TUW model (Viglione and Parajka 2018), a version of the HBV model (Bergström 1976; Lindström et al. 1997), is here implemented over each one of the river basins. For the sake of brevity, a detailed description of model routines and parameterization can be found in Section S3 and in Neri et al. (2020).

The parameterized rainfall-runoff models provide in input to the second module of the simulation framework the time series of the streamflow generated over the direct basin (here named ID_t) and over the four nearby "indirect" basins, just upstream of the river intakes (here named $qq_{1-4,t}$).

3.1.2 Reservoir System Model

The core of the simulation framework is the reservoir system model (panel *b)* in the yellow block in Fig. 2), which includes all the operations on the reservoir controls as well as the management of the river intakes on the indirect catchments. The model is based on the water balance equation for the reservoir:

$$V_{t+1} = V_t + ID_t + II_t - E_t - S_t - R_t - Q_t \quad (1)$$

where V_t and V_{t+1} are the stored volumes at the beginning and at the end of time step *t*, respectively; ID_t is the inflow generated over the direct basin and II_t is the inflow transferred from the indirect catchments (intercepted at river intakes and delivered to the reservoir through the tunnel pipe); E_t is the evaporation from the reservoir, obtained as the product of the water surface area and the evaporation rate (the latter estimated by means of the modified Penman formulation proposed by Linacre 1977); S_t is the spillway outflow depending exclusively on the storage level (since it is not gated); R_t is the outflow from the dam bottom outlets and Q_t is the withdrawal outflow, which is then treated at the downhill treatment plant and fed into the water supply network. All the quantities of Eq. 1 are expressed as volumes (m^3).

The inflow from the tunnel pipe II_t is function of the flow volumes that are intercepted at the intakes, which in turn depend on the streamflow available in the rivers ($qq_{1-4,t}$) and on the operations on the intake gates. Such maneuvers, together with those that control the release from the bottom outlets R_t, belong to the reservoir system controls, subject to technical and regulatory constraints. An in-depth analysis of the historical records of reservoir operations, in collaboration with the utility managers, allowed to model all the operational maneuvers concerning intakes (and thus II_t) and releases R_t based solely on the state of the system at time *t*, that is the reservoir volume (V_t) and its rate of increase ($V_t - V_{t-1}$). For the sake of brevity, the detailed description of the model which regulates operations on II_t and R_t is not reported here. Finally, withdrawal outflow Q_t, is treated separately in the next sections, being the variable to be optimized.

It should be noted that the reservoir system model is built to be run at hourly time step in order to verify the strict constraints regarding the rate of increase of reservoir volumes and the operations on the river intakes. On the other hand, the future rainfall and temperature series used in input to the rainfall-runoff model, and thus the resulting streamflow simulations, are at daily scale. Therefore, the daily streamflow time series provided in input to the hourly reservoir system model are assumed to be uniformly distributed over the 24 h: the effects of this approximation on the water balance were shown to be negligible following a sensitivity analysis (not shown here for sake of brevity).

3.2 Optimal Reservoir Operation: Formulation and Optimization of the Withdrawal Rules

The definition of optimal reservoir management rules can be obtained by following a broad spectrum of approaches, that have been classified in the literature in different ways (e.g. Macian-Sorribes and Pulido-Velazquez 2020). In case a rule form can be identified (by interacting with the reservoir managers and on the basis of information on past operating decisions), the use of *a priori* functional rules is convenient, especially when interested in evaluating the effect of different demand or climate scenarios on the reservoir management (e.g. Beça et al. 2023). In this approach, the mathematical formulation of the desired operating rules (defined as *a priori* rule form, see Macian-Sorribes and Pulido-Velazquez, 2020) is decided before running the optimization algorithm. The optimization then essentially calibrates the parameters of the *a priori* rule form to achieve the best performance.

3.2.1 Withdrawal Admissible Range: Assessment of Minimum Demand from the Reservoir

The first step in the identification of the rule form is defining their domain by establishing the admissible maximum and minimum values of the withdrawals (Q_t) along the year. While the maximum (here named MQ) is fixed by the technical constraints of the pipes dimension and the capacity of the treatment plant, the minimum withdrawal volume (here named mQ) represents the portion of the regional water demand which cannot be provided by the Local Sources at any given time *t*. Therefore, it depends both on the water demand from the customers and on the capacity of the Local Sources themselves in the different parts of the water supply network. The green block (c) in Fig. 1 summarizes the approach for assessing the minimum demand volumes from the reservoir. For the sake of brevity, the description of methodology and its outcomes are reported in Section S4 (SI). Its implementation leads to the definition of the overall minimum flow that must be withdrawn from the Ridracoli reservoir, mQ_j, for any given month of the year *j* in order to satisfy the demand that cannot be fulfilled by the Local Sources.

3.2.2 Formulation of Withdrawal Operating Rules

Once the admissible range of withdrawals has been set, the adopted PSO approach implies establishing the form of the withdrawal operating rules and its parameters (block *d)* in Fig. 2), whose optimal values are obtained iteratively combining simulation and optimization.

In this application, the withdrawal operating rules, which prescribe the flow to be withdrawn at time *t*, Q_t, are expressed as a function of only the stored volume V_t, but adopting different rules for the different months *j* of the year, to account for the seasonality of the inflows and of the demand. After a comprehensive consultation process with RomagnaAcque engineers and several experimental trials, it was decided to adopt as rule form the piecewise linear function presented in the left panel of Figure S2 (SI), which shows the relationship between Q_t and the stored volume V_t in the *j*-th month of the year (black line) and its admissible domain (green polygon).

The adopted formulation is based on a set of preliminary assumptions, that regulate the withdrawal as follows, for increasing values of V_t:

- when V_t is below the minimum drawdown threshold *LV*, withdrawal is not allowed (Q_t=0). Therefore, when the storage is below the *LV* threshold, the reservoir does not meet the required demand from the downstream network, and a deficit volume DF_t occurs (Figure S2, right panel): DF_t is defined as the water volume that, despite being requested by the downstream network, cannot be withdrawn and delivered to the users (i.e., it quantifies the system failure).
- above the *LV* threshold, no deficit occurs, and the withdrawal is equal to the minimum monthly required demand mQ_j (this implying that in such times all the Local Sources are exploited at their maximum capacity) until the stored volume V_t reaches the value

x_j, which represents the second threshold of the rule form, which varies monthly. x_j is a decision variable and must be defined for each month in the optimization procedure.

- when V_t is above x_j, the withdrawal Q_t increases (thus allowing to reduce the stress on the Local Sources) linearly with the stored reservoir volume, up to the maximum admissible value *MQ*. The rate of increase is given by the slope of the linear branch of the curve. Such slope, here named *a*, is fixed a priori according to the maximum admissible rate of change that is allowed in the inflow at the treatment plant.

The corresponding mathematical expression of the rule form $Q_t(V_t)$ and of the deficit $DF(V_t)$ is defined by the following piecewise-defined functions:

$$Q_t = \begin{cases} 0, \ V_t < LV \\ mQ_j, \ \ LV \leq \ V_t < x_j \\ \min(mQ_j + a\,(V_t - x_j)\,, MQ), \ \ x_j \leq \ V_t < V_c \end{cases} \tag{2}$$

$$DF_t = \begin{cases} mQ_j, \ V_t < LV \\ 0, \ otherwise \end{cases} \tag{3}$$

where *LV* and *a* are fixed a priori for the already mentioned technical constraints of the system, whereas x_j (with *j*=1,…,12) are 12 decision variables to be optimized (one for each month of the year *j*), thus allowing to define 12 different monthly rules. Parameters x_j are allowed to assume values between *LV* and an upper limit UV_j, which is derived, given the geometrical formulation of the curve, as a function of the minimum demand mQ_j and the fixed slope *a*.

3.2.3 Optimization

The parametrization of the monthly withdrawal rules (block *e)* in Fig. 2), that is the optimization of the 12 x_j parameters, is conducted (for all the climatic conditions described in Sect. 3.5) by means of the multi-objective optimization algorithm NSGA-II (Deb et al. 2002), which is widely adopted for the optimization of reservoir operating rules (e.g., among many others, Dai et al. 2017; Kim et al. 2008; Liu et al., 2020; Xiong et al. 2024). The aim is twofold: (i) maximizing the withdrawal volumes over the entire simulation period and, at the same time, (ii) minimizing overall water deficit volumes. Therefore, two objective functions are implemented: (i) the average annual withdrawal volume (OF_1) and (ii) the average annual deficit volume (OF_2), to be maximized and minimized respectively:

$$OF_1 = \frac{1}{N_y} \sum_t Q_t \ to \ maximize \tag{4}$$

$$OF_2 = \frac{1}{N_y} \sum_t DF_t \ to \ minimize \tag{5}$$

where N_y is the number of years in the simulation period. As NSGA-II settings, a population size of 200 members and 100 iterations are used for each simulation scenario.

3.3 Simulation-optimization Scenarios

Before using the outcome of the GCM-RCM modelling chains for predicting the future scenarios, the same climate models are first tested over the historical period and compared with the results obtained when feeding the system with the observed meteorological data over the same control period. To be consistent with the EURO-CORDEX convention (Jacob et al. 2014) and with the procedure applied by Dosio (2016), who adjusted the outputs of the considered GCM-RCM ensemble, the period 1981–2010 (with the year 1981 always used as warm-up for rainfall-runoff modelling and excluded from the validation of the system simulation) is here used as a reference for the current climatic conditions.

The ten EURO-CORDEX GCM-RCM meteorological time series cover the full period 1981–2100, but the optimization of the rules for the future will refer only to the period 2071–2100 (i.e., the furthest future 30-year period).

Twenty-one simulation-optimization scenarios have been carried out:

- one observed-historical (OH) scenario: the operating rules are optimized for the historical control period 1982–2010 by forcing the model with observational E-OBS meteorological fields;
- ten CORDEX-historical (CH_{1-10}) scenarios: the operating rules are optimized for the historical control period 1982–2010 by forcing the model with each of the ten bias-corrected GCM-RCM meteorological fields for such period;
- ten CORDEX-far-future (CF_{1-10}) scenarios: the operating rules are optimized for the furthest future period 2071–2100 by forcing the model with each of the ten bias-corrected GCM-RCM meteorological fields expected for the furthest future.

For each of the above twenty-one scenarios, a different set of withdrawal operating rules is obtained repeating the simulation-optimization procedure.

4 Results and Discussion

4.1 Expected Future Climatic Changes

In a preliminary phase, the selected climate modelling chains (Table S1) are validated against observations (E-OBS), to verify their ability to adequately reproduce historical climate, comparing, in particular, daily precipitation and maximum and minimum temperatures. The outcomes of such validation (reported in Section S6 of the SI) confirm that bias-corrected GCM-RCMs are more suitable to represent the current climate in the study area in respect to the raw time-series, which are thus not considered in the following analyses.

Following such verification, the future pattern of seasonal precipitation and temperature are evaluated. Figure 3a illustrates the expected changes in monthly mean areal precipitation simulated by the GCM-RCM ensemble across the three future time horizons. These changes are expressed as the ensemble average ratio between future and historical simulations (control period), shown for both the raw and bias-corrected climate model outputs. On average, precipitation during the months of March to October is projected to progressively decrease, reaching up to 30% reduction in the summer months by the end of the century. Conversely,

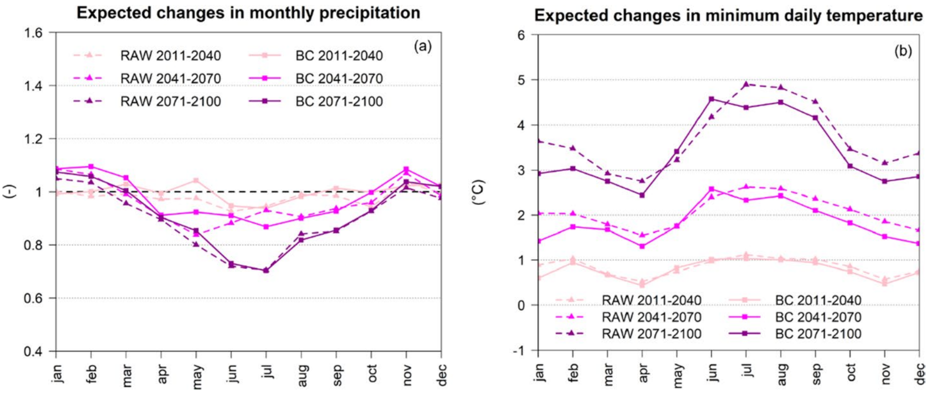

Fig. 3 Future changes simulated by the GCM-RCM ensemble. Left: Expected changes in the ensemble's monthly areal mean precipitation for different future time horizons, expressed as a ratio to the historical period. Right: Expected changes in the mean daily minimum temperature relative to the historical period

winter precipitation is expected to show a slight increase (approximately 5–10%). Similarly, Fig. 3b illustrates the results for the average daily minimum temperature: the GCM-RCMs project a growing trend over the century, rising by more than 4 °C in summer for the long-term future horizon. Similar results are obtained for the mean daily maximum temperature, which are not shown here for brevity.

4.2 Optimal Reservoir Operating Rules

For each of the simulation-optimization scenarios presented in Sect. 3.5, the NSGA-II algorithm produces a Pareto frontier of non-dominated and equally-eligible solutions. Figure 4 reports the results for the twenty-one simulation-optimization scenarios, where x-axis refers to the first objective function OF_1 (i.e. average annual withdrawal volume, to maximize), while y-axis to OF_2 (i.e. average annual deficit volumes, to minimize): the blue frontier refers to the non-dominated solutions obtained for the observed historical scenario (OH), the red Pareto frontiers are the solutions of the ten CORDEX-historical simulation-optimization scenarios on the same historical control period ($CH_{1–10}$), while the orange frontiers are the solutions of the ten CORDEX-far-future runs on the period 2071–2100 ($CF_{1–10}$).

As expected, ranges and forms of the frontiers are strongly related to the available water budget and thus to the temporal dynamics of precipitation during the simulation period. Looking at historical runs in fact, $CH_{1–10}$ frontiers (red) differ substantially one from the other, despite their good agreement with the reference observed precipitation (E-OBS), showed in Figure S3 (SI). This is primarily due to the fact that even slight differences in the simulated occurrence of daily precipitation amount and timing can have a significant impact on the water balance of the system. Additionally, the highly variable temporal patterns of precipitation across different GCM-RCMs have a significant cascading effect on the dynamics of rainfall-runoff transformations, on the hydrological drought events, and ultimately, on the actual water availability in the reservoir along the years. Therefore, the specific operation rules, which are devised for each chain to avoid deficit conditions throughout the simulated drought events, may differ substantially. Despite such variability of the curves, the $CH_{1–10}$ runs (red fronts) are consistently distributed symmetrically and uniformly around

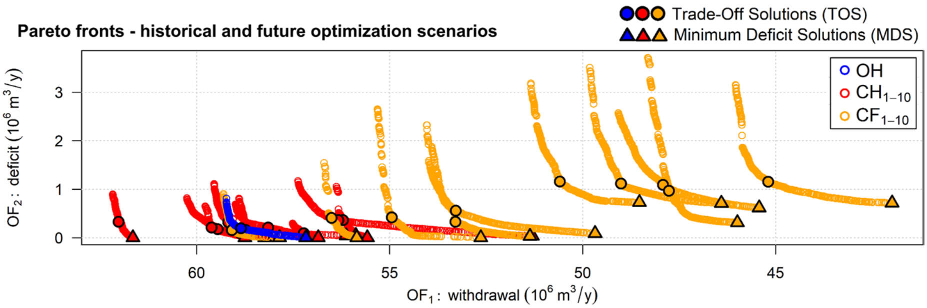

Fig. 4 Pareto solutions for each of the simulation-optimization scenarios: observed-historical (OH, blue dots), ten CORDEX-historical (CH$_{1-10}$, red dots) and ten CORDEX-far-future (CF$_{1-10}$, orange dots). Trade-Off (TOS) and Minimum Deficit Solutions (MDS) are highlighted with bold dots and triangles respectively

the observed-historical optimization (blue front, OH), which suggests that the overall GCM-RCM ensemble can well represent the historical water availability and management in the system. To further verify the representativeness of the ensemble of GCM-RCM scenarios for simulating historical water availability and reservoir management, the outcomes of the simulation framework obtained in the historical period for OH and for the ten CH$_{1-10}$ optimization scenarios are compared. Such analysis, showed in detail in Section S7 of the Supplementary Information, demonstrates that the pattern of CORDEX-historical CH$_{1-10}$ simulations overall agrees with that of the observed-historical OH run. Therefore, this confirms that the selected ensemble of GCM-RCMs may be considered suitable for simulating the historical (current) management of the system and can be used as reference to evaluate differences with simulation-optimization performed on future time periods.

The effect of the occurrence of single water scarcity periods in the different scenarios is even more pronounced for future CF$_{1-10}$ runs which, in agreement with the expected decrease in precipitation (see Fig. 3a), are shifted to the right-upper portion of the graph, corresponding to lower withdrawals (that decrease along the x-axis) and higher deficits in the objective-space.

The Pareto front resulting from the multi-objective optimization procedure represents a multitude of non-dominated alternative operation rules (each one corresponding to a set of monthly withdrawal rules). In practice, the choice of the optimal operating rule depends on the management policies that the resource manager chooses to adopt, keeping in consideration a wider framework of information including the environmental and socio-political consequences of each solution. In order to analyze and comparing the impact of the different rules on the two contrasting objectives and on the resulting reservoir behavior, two specific solutions for each Pareto front are here selected as possible reference among the possible optimal alternatives:

- the equal Trade-Off Solution (TOS), also known as 'knee' point and defined as the point which has the shortest Euclidian distance from the ideal solution of each Pareto front (i.e. the point of coordinates $[\max(OF_1);\ \min(OF_2)]$ in the present case), highlighted with bold dots in Fig. 4. Although both objectives are expressed in water volumes, we calculate the Euclidean distance in a standardized space for each Pareto front. This standardization, achieved by scaling each axis to the maximum and minimum values of the objective functions, accounts for the differing operational meaning and impact of the quantities. Such solution is commonly used to evaluate optimization results (Dumedah et al. 2010) and represents an equally balanced optimum solution.

- the Minimum Deficit Solution (MDS), which represents the solution corresponding to the lowest cumulated deficit volume during the entire simulation period (highlighted with bold triangles). This is the most conservative solution, assuming the lowest level of risk of failure to supply the system and it is an important benchmark for the utility, even if it does not keep into account the disadvantages deriving from an overexploitation of the alternative sources.

4.3 Expected Changes in the Optimal Reservoir Management

4.3.1 Expected Relative Changes of Withdrawal Operating Rules

The first aim of the work is to quantify to what extent the withdrawal operating rules should change in order to adapt the system management policies to future climatic forcings. To this end, the withdrawal operating rules obtained when optimizing during respectively historical CH_{1-10} or future periods CF_{1-10} are compared. Trade-Off Solutions (TOS) and Minimum Deficit Solutions (MDS), highlighted in Fig. 4 with bold triangles and dots respectively, are selected to quantify such differences.

As described in Sect. 3.2.2, the withdrawal rules vary monthly and consist in piecewise linear functions, where the only decision variables are the 12 parameters x_j (one parameter for each month j). Given the mathematical formulation of the rules (see Eqs. 2 and 3 and Figure S2), lower x_j corresponds to a less conservative rule form (i.e. withdrawal starts increasing above the strictly needed values, mQ_j, when the reservoir is less full). Therefore, the greater is the parameter x_j, the more conservative is the withdrawal rule, i.e. the greater is the reservoir volume threshold above which the rule prescribes to start to increase the withdrawal.

The optimized rules for current and future scenarios are compared by showing their resulting monthly parameters x_j along the year. Panels a and b of Fig. 5 show the average values (over all the 10 CORDEX scenarios) of the rule parameters x_j when optimized respectively during the historical control period 1982–2010 (CH_{1-10}, red line) or during the long-term future time horizon 2071–2100 (CF_{1-10}, orange line). Two solutions from each Pareto front are considered: the average x_j values (over the ten CH_{1-10} or CF_{1-10} runs) for the Trade-Off Solutions (TOS, panel a) and for the Minimum Deficit Solutions (MDS, panel b) respectively. The closer the parameters are to their upper limit UV_j (upper dashed black line), the more conservative the rule is, since less water is withdrawn, and vice versa. In fact, such an upper limit establishes the most conservative curve, allowing for maximum withdrawal MQ only when the stored volume reaches the maximum reservoir capacity V_c (Eq. 2).

As expected, looking at the overall differences between the two solutions, average MDS rules (Fig. 5b) are indeed closer to UV_j and therefore more conservative than TOS ones (Fig. 5a). Also as expected, future rules (orange lines) are more conservative than those optimized for the historical period, given the expected decrease of inflow volumes. However, when focusing on the differences between CH_{1-10} and CF_{1-10} average rules, a stronger shift of future x_j parameters towards their upper limit UV_j is observed for MDS solutions,

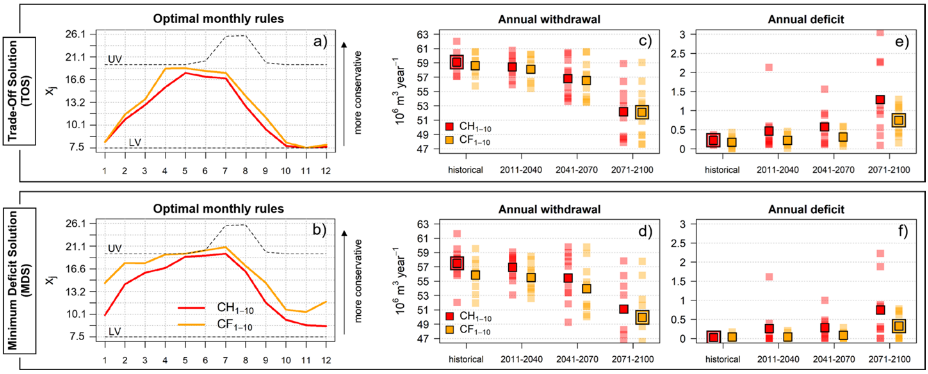

Fig. 5 Left panels (**a**-**b**): ensemble average values of the parameters x_j of the withdrawal rules in each month j when calibrated during the historical period 1982–2010 (CORDEX-historical scenarios CH$_{1-10}$, red lines) or during the long-term future time horizon 2071–2100 (CORDEX-far-future scenarios CF$_{1-10}$, orange lines) for Trade-Off Solutions (TOS, a) and Minimum Deficit Solutions (MDS, b). Central and right panels (**c**-**f**): Average annual withdrawal (**c**-**d**) and average annual deficit (**e**-**f**) volumes simulated during the historical control period and the future time horizons by adopting the operating withdrawal rules optimized for the TOS (top, c and e) and MDS (bottom, d and e) solutions of the CORDEX-historical (red, CH$_{1-10}$) and CORDEX-far-future (orange, CF$_{1-10}$) optimizations. Shaded dots refer to the individual GCM-RCM scenarios while bold dots to the ensemble average

especially in the more humid months from autumn to spring. On the other hand, for the TOS solution, that is less conservative since it allows some deficit conditions to occur, the expected changes in the withdrawal rules are smaller and limited to spring and summer months. This confirms that, similarly to what observed in the previous section, when prioritizing the minimization of deficit (MDS), the operating rules are more strongly influenced by the severity and the dynamics of single drought events that occur differently in the different scenarios.

4.3.2 Historical and Future Patterns of Withdrawals and Deficit Volumes

Finally, the pattern of withdrawals and deficit volumes resulting when simulating the reservoir management adopting the different set of operating rules are compared. In order to understand what would happen using a fixed set of rules (designed respectively over the historical or future scenarios) over all the decades, reservoir operation is simulated over the entire period 1982–2100 twice (by adopting the operating withdrawal rules corresponding respectively to the TOS and MDS solutions) for each of the ten CH$_{1-10}$ and of the ten CF$_{1-10}$ simulation-optimization scenarios (for a total of 40 model runs: two Pareto front points, TOS and MDS, for each of the ten GCM-RCMs, following either the rule optimized under current or future climate).

Therefore, the operating rules optimized for historical climatic conditions are used to run the simulation framework not only on the same control period, but also over all the future decades. Analogously, the operating rules optimized under the climatic conditions expected for the farthest time horizon (2071–2100) are used to simulate the reservoir management over the entire 1982–2100 period.

As an example of the possible outcomes that could be analyzed, Fig. 5 shows the average annual withdrawals (central panels c and d) and deficit volumes (right panels e and f) in the four three-decades periods (historical, 2011–2040, 2041−2027 and 2071–2100), when considering the set of operating rules optimized for historical (red dots, CH_{1-10}) or far-future (orange dots, CF_{1-10}) climatic conditions.

In line with the anticipated decrease in precipitation, the magnitude of deficit volumes (panels e and f) increases throughout the century, especially for the less conservative (TOS) rules designed over the historical period (red squares in panel e). The deficit magnitude is overall greater for TOS Pareto solutions. However, the difference between the use of historical or future operating rules for the same decades (i.e. the drop between the corresponding red and orange bold dots) are similar when considering the TOS (panel e) or the most conservative MDS solutions (panel f).

For what concerns withdrawal volumes (panels c and d), the impact of the use of operating rules optimized for different climatic conditions changes consistently with the choice of the Pareto solution: for the TOS rules, the reduction of withdrawals resulting from using the future-based rules (i.e. differences between red and orange markers), that is due to the expected lower hydrological availability, is lower than in case of MDS in all the time-horizons. This is, as already highlighted, due to the fact that optimal rules for less conservative management policies (TOS) do not change substantially between present and future climatic conditions (panel a).

In general, the results assist decision-makers by estimating how expected climatic changes impact the water system while maintaining optimal reservoir operation. For instance, by assuming the future revision of the management rules, i.e. by comparing the double-bordered red markers of the historical period, on the left-hand side, with the double-bordered orange markers for the farthest future, on the right-hand side of each panel, the production is projected to have a similar relative decrease (approximately 12%) from present to end-of-century conditions for both the policies. On the other hand, when adopting Trade-Off rules (TOS) the decrease in potable volumes is slightly more limited in absolute terms, and the expected increase along the future decades in deficit volumes is 0.4 million m^3/year greater compared to the most conservative solution (MDS).

5 Concluding Remarks

The study modelled the behavior of the multi-basin water supply system and the management of the Ridracoli reservoir, optimizing its operational withdrawal rules under both historical and future meteorological forcings, aiming at reducing system failure (reservoir deficit conditions occurring during hydrological droughts), while maximizing the overall water volumes supplied from the reservoir (thus reducing stress on other, less sustainable, and more energy-demanding regional sources). Overall, the results indicate that, even when adapting the optimal reservoir management to the predicted reduced hydrological availability, the relative decrease in yearly production at the end of the century is expected to be approximately 12%, regardless of the adopted management policy. In particular, it was possible to quantify relative changes between the withdrawal rules optimized in reference to historical and future scenarios, and to estimate the corresponding expected patterns of withdrawal volumes and water deficit volumes, i.e., the total volumes of user demand that would not be met in future decades, resulting in water shortages which may lead to severe consequences, especially to the local tourism economy.

The experiment shows that the greater the priority given to minimizing deficit volumes, the more sensitive the optimal rules are to the dynamics of single drought events. On the other hand, management policies that aim for a trade-off between the two objectives are more robust and tend to remain optimal despite changing climatic conditions.

The findings also enable the estimation of expected changes in the reservoir behavior for future time-horizons: in general, the pattern of overall withdrawals and water deficit volumes obtained when applying optimized rules show how the adoption of highly risk-averse management policies aiming at zero-deficit conditions would imply a substantial reduction in the total volumes supplied from the reservoir along the years, at the expenses of an increased exploitation of the alternative (and less sustainable) sources in the region. Conversely, management policies that involve a slightly greater risk of incurring sometimes in deficit conditions allow for a partial counterbalance of the expected future decrease in water availability, thus mitigating water stress on the alternative sources.

It must be acknowledged the main limitation of the study, that is related to assumptions about the future stationarity of specific boundary conditions of the system. In particular, the rainfall-runoff model, used to simulate discharges at the catchment outlets, was parameterized according to the historical hydrological conditions and cannot therefore account for other possible future changes beyond those in climatic inputs, such as, changes in the basin land use or root zone capacity. In addition, further research studies may address the use of regional water demand models (see Toth et al. 2018) to predict the future demand that, when combined with the simulation framework developed herein, would allow a more thorough analysis of the synergistic impact of future availability and demand on the system.

Despite these limitations, the proposed approach for optimizing operating rules in relation to both present and future climates may be replicated in other study regions, provided that reservoir and demand data are available. The authors believe that the outcomes of this approach may be beneficial to decision-makers for evaluating future water shortage risk and for informing long-term water resource management planning, also in order to mitigate the water stress on less sustainable water sources.

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Declarations

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

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