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Seasonal forecast-informed reservoir operation. Potential benefits for a water-stressed Mediterranean basin

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ABSTRACT

The increased seasonal demand for water puts pressure on Mediterranean water resources, which are often exploited in a non-renewable way. Besides, climate change can alter hydroclimatic patterns and exaggerate freshwater stress. Flexible operation of existing water reservoirs is one of the most cost-effective ways to mitigate water-related stress by storing water when it is abundant and releasing it when droughts persist. In this context, hydroclimatic forecasts can be central in properly informing reservoir operation. Nevertheless, the link between forecast skill and forecast value is neither easily predictable nor necessarily positive. Each system requires specific forecasts according to its characteristics, and the skill of existing forecast systems does not necessarily translate into a significant gain in system performance. In this work, we develop downscaled seasonal forecasts of reservoir inflow for the Faneromeni irrigation dam on Crete island. We then quantify the value of these seasonal forecasts in informing the reservoir operations. While the current operation of this reservoir is based on the available storage at the beginning of the irrigation season, we investigate alternatives by using the Evolutionary Multi Objectives Direct Policy Search method, which allows the design of flexible rules to cope with the variability of the hydrologic conditions as well as to include forecast information for conditioning operational decisions. Under historical climate conditions, results demonstrate a notable enhancement in performance solely by implementing more flexible operating policies. Incorporating perfect forecasts results in an additional improvement of 4% on average throughout the period from 1993 to 2019. However, when using actual forecasts, this gain diminishes to 1%. These outcomes support the exploration of potential trade-off solutions that effectively balance the competing demands within the region.

Practical implications

Water availability in the Mediterranean is driven mainly by seasonal precipitation patterns, while water use maximizes with an opposite seasonal pattern, primarily dominated by agriculture. As a result, water management decisions in the region are based mainly on the seasonal status of the water resources, which is getting progressively crucial as the end of the dry summer period is reached. Therefore, the knowledge of a potentially prolonged dry or wet onset in advance provides the opportunity to improve drought risk management, especially in the context of a changing climate.

Water-control structures, such as water reservoirs, appear to be increasingly essential to compensate for the different precipitation time distribution and to shift water from wet to dry seasons. In addition, more efficient management of existing structures can improve the system's performance and resilience with significantly lower costs rather than planning new ones. However, traditional management practices are challenged by the progressive and substantial drying, thus calling for more flexible and anticipatory strategies to support the sustainable use and preservation of water resources in the Mediterranean region.

In recent years, seasonal forecasting has progressed, using the most recent advancements in weather and climate modelling research. Several studies have looked at the additional benefit of employing streamflow forecasts for informing reservoir

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operations. The rising forecast skill is providing new possibilities for adopting forecast-informed reservoir operations.

Our work evaluates the value of seasonal forecasts and flexible operating policies in guiding reservoir management of the water-stressed Messara valley in south-central Crete, Greece. This reservoir is a crucial component of the region's water infrastructure and a key factor in the growth of the local primary sector's economy. The reservoir provides water to agricultural irrigation districts of the area, competing to access the basin's scarce water resources. The reservoir has traditionally been run according to a simple rule that suggests releasing a volume equal to a pre-agreed demand during the irrigation season (from May to November). However, the system is struggling due to the summer droughts and extremely high inflow fluctuation, frequently preventing the reservoir from fully topping during the wet season.

We utilized streamflow forecasts with a seven-month lead time to inform Faneromeni reservoir operation policies. A "no forecast-informed" scenario served as a benchmark to quantify the added value of the "forecast-informed". In order to accomplish this, it was necessary first to comprehend the primary water-related dynamics and the various objectives of the parties involved and subsequently to develop a reservoir model for supporting the design of improved operating strategies. Then, Pareto-optimal operating policies were designed, allowing the exploration of the trade-offs across the considered objectives as well as informing the operating policies with forecast information.

Results indicate that introducing flexible rules, even not based on forecasts, can significantly boost system performance. Analyzing the trade-offs between the considered objectives reveals that perfect seasonal forecasts (observations) appear to be a useful instrument in the Faneromeni reservoir operation, leading to a significant improvement in the system's performance. When considering a real forecast product, we discovered that its skill places a cap on how well real forecast-informed policies can perform. This could be due to the fact that we used the median of the ensemble; however, this means that we lost the inflow variability and missed wet years when there was room to expand the water supply. Therefore, it would appear necessary to carefully choose the best forecast member to enhance the system's functionality. The interannual inflow variability has a high degree of variability, which makes it challenging to identify a fixed percentile of the predicted ensemble distribution.

Our findings are expected to improve the management of water resources for sustainable water exploitation, and the framework we developed can be used at other study sites with similar problems.

Data availability

Data will be made available on request.

Introduction

Water resources in the Mediterranean are already under pressure from the combined impacts of human interventions and anthropogenic climate change (Fader et al., 2020; Gudmundsson et al., 2021; Koutroulis et al., 2019; Pokhrel et al., 2021). Significant streamflow changes have been observed in the recent past (Gudmundsson et al., 2017; Kadir et al., 2020), and the overexploitation of groundwater resources is clearly detectable in large-scale satellite gravity data (Rodell et al., 2018). As a result, more than 180 million people in the region are considered water poor, and an additional 60 million face different levels of water stress, according to estimates by the Union for the Mediterranean (UfM).

Water availability in the Mediterranean is driven mainly by seasonal precipitation patterns (Burak and Margat, 2016; García-García et al., 2022; Mariotti et al., 2002), while water use maximises with an opposite seasonal pattern, primarily dominated by agriculture (Fader et al., 2020). The region experiences the majority of its precipitation during the winter months, while the summer period is characterized by dry conditions; however, it is during this dry season that the demand for water reaches its peak. Decisions in the agricultural sector are thus closely linked to the temporal availability of the water resources and the water demand from distinctive types of irrigated cultivation, which are extensively practised during dry periods. Furthermore, the intensity of tourism activities in the Mediterranean maximises mostly during the water-scarce summer. As a result, water management decisions in the region are largely based on the seasonal status of the water resources, which is getting progressively crucial as the end of the dry summer period is reached. Therefore, the knowledge of a potentially prolonged dry or wet onset in advance provides the opportunity to improve drought risk management (An-Vo et al., 2021; Hansen, 2002; Sánchez-García et al., 2022; Suárez-Almiñana et al., 2022; White et al., 2017), especially in the context of changing climate. Most future climate scenarios denote a progressive and substantial drying of the region (Betts et al., 2018; Hertig and Tramblay, 2017; Tramblay et al., 2020), indicating a shift for over 40% of Mediterranean land to drier states (Koutroulis, 2019). This shift will challenge traditional management practices thus calling for more flexible and anticipatory strategies to support a sustainable use and preservation of water resources in the Mediterranean region.

Water-control structures, such as water reservoirs, appear to be increasingly important to compensate for the different precipitation time distribution and to shift water from wet to dry seasons. In addition, more efficient management of existing structures can improve the system's performance and resilience with significantly lower costs rather than planning new ones (Gleick, 2002). However, drought hazard is substantially modulated by reservoir operation, i.e., Brunner (2021) showed that reservoir regulation affects drought hazard locally by reducing severity but increasing duration. In this context, careful water use planning is needed to ensure sustainable use and protection of water resources. Such planning should be based on the comprehensive assessment of water balance components, advanced monitoring and early warning systems, climate, and socio-economic factors. Among these, collaborative governance bottom-up processes are of prime importance because it promotes equity amongst users, enhances long-term water resource sustainability, provides technical benefits such as better estimates of water abstraction and precise understanding of the water balance and helps in the implementation of demand and supply measures (Huntjens et al., 2011; Margerum and Robinson, 2015; van Buuren et al., 2019). The design and implementation of participatory and integrated management strategies (e.g., Giuliani et al., 2022; Soncini-Sessa, 2007) requires the adoption of a posteriori generation technques to discover the full set of Pareto optimal (or approximate) solutions prior to eliciting the decision maker's preferences (Giuliani et al., 2014). This approach allows overcoming the limitations of a priori multicriteria decision making (Keeney and Raiffa, 1976) or monetisation-based hydro-economic approaches including Cost-Benefit analysis (Harou et al., 2009), where the relative value of different operational objectives is estimated/hypothesised a-priori by making strong assumptions that could bias the final decision making problem (Haimes and Hall, 1977).

Seasonal forecasting has advanced in recent years, putting into practice the latest weather and climate modelling research improvements (Giuliani et al., 2020; Yang et al., 2021, 2020). The increasing forecast skill is opening new possibilities for implementing forecast-informed reservoir operations, with several research studies that have examined the added value of using streamflow forecasts for informing reservoir operation around the world (Anghileri et al., 2016; Giuliani et al., 2020; Lee et al., 2022; Turner et al., 2017; Yang et al. 2020) as well as practical application especially in the Western US (Delaney et al., 2020; Jasperse et al., 2020). Although some of these studies show

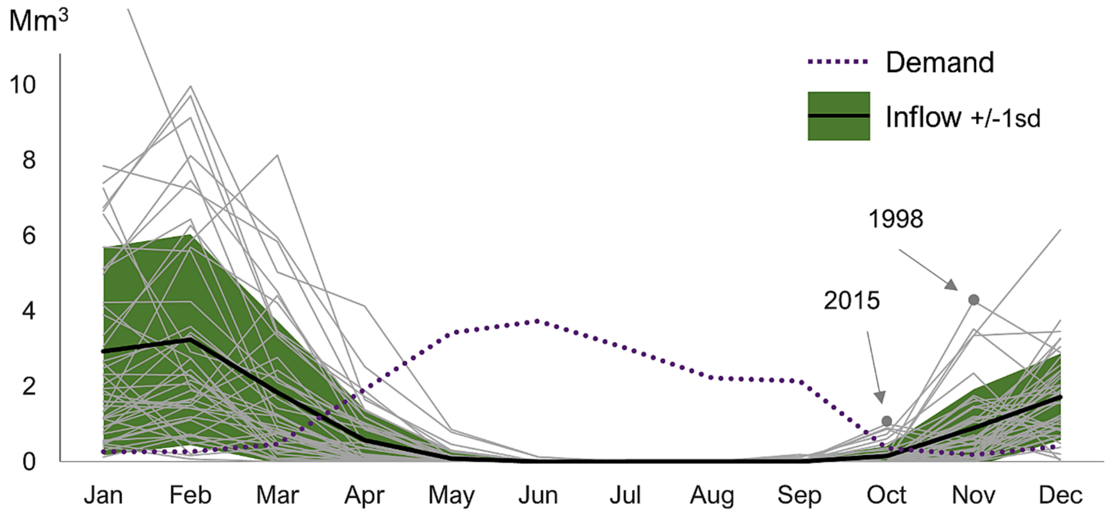

Fig. 1. Seasonal patterns of water demand and reservoir inflow. Green line indicates the average historical inflow [Mm^3] in the dam while gray lines are the individual years. Dotted line indicates the demand seasonality [Mm^3]. Shaded area correspond to +/- 1 standard deviation of inflows over the 1974–2019 period. exceptionally high inflows of 2015 and 1998 are highlighted. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

different results according to the characteristics of the case study and the forecast accuracy (Yang et al., 2021; Lee et al., 2022), the potential forecast-induced benefits appear clear and promising (Giuliani et al., 2021).

In this study, we investigate the value of seasonal hydrological forecasts in informing reservoir operation in the water-stressed Messara basin on the island of Crete. The area constitutes Crete's most important agricultural region, thus, freshwater is the critical resource controlling the region's development, and its growing demand is a severe environmental stressor. Groundwater is the primary source of irrigation, and overexploitation of the underlying aquifer has led to a severe dropdown. The Faneromeni dam was recently constructed to augment water availability during dry periods; however, its management is challenging due to the multiple end-users with competing interests and the conventional-static operation applied. In light of these challenges and in collaboration with end-users, we developed a reservoir model for supporting the design of improved operating strategies tailored to the local water control system. We developed and provided climate forecast information on water balance components at the seasonal time scale. We finally assessed the benefit arising from the potential adaptation of flexible policies alone and then from forecast-informed policies. Our results show that, under historical climate conditions, the use of flexible policies, even if not informed by forecasts, is able to improve the system performance substantially.

Material and methods

Case study

The Messara valley in the southcentral part of the island of Crete, Greece (Fig. 2) is the most agricultural-intensive region of the island. The main land-use activities are olive growing, greenhouse vegetable cultivations, cereal growing, grapevine and fruit cultivation, and grazing (Koutroulis et al., 2016). Historically, irrigation needs have driven an over-exploitation of the groundwater and the salinisation of the coastal aquifer (Varouchakis et al., 2022), motivating the construction of the Faneromeni. The downstream region of Timpaki is a highly exploited area concerning the greenhouse cultivations because of the year-round favourable climatic conditions. Therefore, the reservoir's primary purpose is to support the increased irrigation water demand of the Messara valley. The reservoir covers an area of about 100 ha with a capacity of 17 Mm^3. The dam is over-sized with respect to the water potential of its drainage area because the original design assumed that it would be filled with the excess flow of the nearby Platis river. Instead, the main inflow is the Koutsoulidis intermittent stream, a tributary of the main Geropotamos river, since the diversion has never been constructed. It is an earth-filled dam with a concrete spillway. The dam was completed in 2005 and filled for the first time in 2010, while the irrigation networks were completed in 2013. The total construction cost was 60 M€, including the cost of the irrigation networks. The average annual inflow in the reservoir is 13 Mm^3 (minimum 4.7 Mm^3 and maximum 29.5 Mm^3), and the annual renewable quantity is 8.7 Mm^3 for a return period of 10 years.

The efficient management of water resources is of great importance, particularly during the dry period from May to September, when water demand reaches its highest levels (Fig. 1). However, in years with ample rainfall during late winter and spring, a water reserve is formed, offering flexibility in managing water resources throughout the summer. Furthermore, the occurrence of early autumn rainfall provides additional relief to the system through supplementary inflows. To assess the potential impact of early autumn supplementary inflows, we examine the historical data for the months of October and November. In October, there exists a probability exceeding 20% for an additional 0.2 Mm^3 of water to flow into the system. Similarly, in November, the average inflow is approximately 0.6 Mm^3, with a probability exceeding 28% of receiving an extra 0.5 Mm^3 of inflow above the average. Predicting the onset of an early wet autumn period would further enhance the utilization of water reserves during the dry summer period. The successful exploitation of water reserves during the dry summer period can have significant implications for resource allocation. These additional water resources can be diverted towards crops under deficit irrigation or can reduce the reliance on groundwater pumping, leading to substantial energy savings and lower irrigation water prices. Based on the aforementioned seasonal hydroclimatic and demand patterns, our analysis specifically focuses on the highlighted period above to identify strategies for maximizing water resource utilization while also considering the potential benefits year-round.

The reservoir is primarily operated to irrigate 4,700 ha in the valley of Messara. In particular, two macro-regions are distinguished: the first is composed of Skourvoula, Galia, Faneromeni, Voroi, Tympaki, and its water demand must be satisfied at 100% (we called this macro-region the Priority zone (P)), as the reservoir is the only source of irrigation. The other is composed of large agricultural zones (consisting of 60% olive trees, 30% vegetables, and 10% of other cultivation), named A, B,

Table 1
Faneromeni agricultural districts water demand (Mm^3/year).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
Skourvoula	0.013	0.013	0.018	0.047	0.112	0.123	0.118	0.090	0.090	0.017	0.011	0.013	0.667
Galia	0.014	0.014	0.019	0.050	0.118	0.130	0.124	0.095	0.095	0.018	0.012	0.014	0.702
Faneromeni-Vori	0.047	0.047	0.063	0.165	0.215	0.237	0.226	0.172	0.172	0.032	0.022	0.047	1.446
Vori - new irrig. network	0.012	0.012	0.016	0.041	0.106	0.117	0.111	0.085	0.085	0.016	0.011	0.012	0.622
Ksirikos anadasmos	0.015	0.015	0.020	0.053	0.138	0.152	0.145	0.111	0.111	0.021	0.014	0.015	0.810
Total P zone	0.101	0.101	0.136	0.356	0.690	0.759	0.724	0.552	0.552	0.103	0.069	0.101	4.246
Zone A (100%)	0.126	0.126	0.168	0.441	0.602	0.660	0.516	0.344	0.430	0.172	0.115	0.126	3.825
Zone B (100%)	0.010	0.010	0.035	0.233	0.443	0.480	0.369	0.277	0.240	0.018	0.000	0.040	2.154
Zone C (100%)	0.037	0.037	0.135	0.890	1.692	1.832	1.410	1.057	0.916	0.070	0.000	0.154	8.231
Zone A (42.9%)	0.054	0.054	0.072	0.189	0.258	0.283	0.221	0.148	0.185	0.074	0.049	0.054	1.641
Zone B (42.9%)	0.004	0.004	0.015	0.100	0.190	0.206	0.158	0.119	0.103	0.008	0.000	0.017	0.924
Zone C (42.9%)	0.016	0.016	0.058	0.382	0.726	0.786	0.605	0.454	0.393	0.030	0.000	0.066	3.531
Total ABC zone (100%)	0.172	0.172	0.338	1.563	2.736	2.972	2.295	1.678	1.586	0.261	0.115	0.321	14.210
Total ABC zone (42.9%)	0.074	0.074	0.145	0.671	1.174	1.275	0.984	0.720	0.680	0.112	0.049	0.138	6.096
P zone + ABC zone(100%)	0.274	0.274	0.474	1.919	3.426	3.731	3.019	2.230	2.138	0.364	0.184	0.422	18.456
P zone + ABC zone(42.9%)	0.175	0.175	0.281	1.027	1.864	2.034	1.709	1.272	1.232	0.215	0.118	0.239	10.342

and C, and their aggregated demand has to be satisfied at 42.9% on an average hydrological year. We called the latter zone ABC for simplicity. The reservoir contributes to the irrigation of the zone ABC in combination with groundwater withdrawals during the irrigation period (May-Oct). In Table 1, the details of regional annual water demand are reported.

The reservoir is operated by a management committee consisting of the three main agricultural water management authorities, the region's municipal authority, and the water authority of the Region of Crete. The current rule suggests releasing a volume equal to the demand during the irrigation season with no releases in the winter period. In normal conditions at the beginning of the irrigation season, the water availability guaranteed by the reservoir is 8.5 Mm^3, which is expected to cover the demand in the following months. If at the beginning of the irrigation season the reservoir storage is not sufficient to provide 8.5 Mm^3, then the release is reduced by a constant factor equal to the ratio between the observed storage over 8.5 Mm^3. It is noticeable that this deficit is entirely burdened on ABC, while P demand has to be totally satisfied anyway (if physically possible).

Today, the Faneromeni reservoir constitutes an indispensable water resource for the region and a major driver for the local economic development of the Messara's primary sector. Nevertheless, the system is suffering due to very dry conditions during the summer and substantial inflow variability, which is often unable to completely fill the reservoir during the winter season. Seasonal precipitation variability of the East Mediterranean is primarily driven by atmospheric and oceanic circulation. An important factor is the North Atlantic Oscillation (NAO), which influences the strength and location of the atmospheric circulation in the wider eastern Mediterranean region (Seager et. al., 2020). During a positive phase of the NAO, the westerly winds are stronger, and the East Mediterranean receives more precipitation. In contrast, a negative phase of the NAO weakens the westerly winds and reduces precipitation. Additionally, the Mediterranean Sea plays a role in the precipitation variability as it can either enhance or suppress precipitation depending on sea surface temperatures and atmospheric pressure patterns. Warm sea surface temperatures in the eastern Mediterranean have been found to also correlate to precipitation (Pasrtor et. al., 2019). However, the annual reservoir inflow exceeds the target irrigation demand almost 50% of the time during 1973–2019 based on measured and reconstructed data, indicating the possibility and room for further improving the current Faneromeni operation. Furthermore, the large inflows variability gives, in principle, the opportunity to increase the water supply in wet years, and this could allow either to improve the irrigation supply for the ABC zone or to provide irrigation also during the winter season.

Modeling the system

The model of the system reproduces the dynamics of Faneromeni reservoir by using a mass-balance equation (Equation (1) with a monthly time-step. In Equation (1), s_t is the reservoir storage (m^3), and a_{t+1}, E_{t+1} and r_{t+1} represent the inflow, the evaporation and the reservoir release volume in the time interval $[t, t+1)$, respectively. In the adopted notation, the time subscript of a variable indicates the instant when its value is deterministically known. Inflow (a_{t+1}), evaporation (E_{t+1}), and release (r_{t+1}) have a t + 1 subscript because their actual value could be known only at the end of the time-step due to their uncertain nature.

$$s_{t+1} = s_t + a_{t+1} - E_{t+1} - r_{t+1} \tag{1}$$

The volume of water released in one month is given by a non-linear function (Soncini-Sessa, 2007) that depends on the reservoir storage at the beginning of the month s_t, the release decision u_t, and the net inflow (i.e., inflow minus evaporation losses). This function allows the effect of the uncertain net inflows between the time t (at which the decision is taken) and the time t + 1 (at which the release is completed) to be represented. The actual release might not be equal to the decision due to existing legal and physical constraints on the reservoir level and release, including spills when the reservoir level exceeds the maximum capacity. When we consider the adoption of flexible operating policies, the release decision u_t is determined at each time step t by a closed-loop policy p as a function of the month of the year m_t, the reservoir storage s_t, and, for forecast-informed policies, the inflow forecast $\hat{q}_{t+\tau}$ over the lead time τ.

The main users served by the Faneromeni reservoir are the farmers in the Messara Valley. Given the importance of the agricultural activities in the region, the farmers would like to have more surface water to reduce irrigation costs and to reduce pressure on the groundwater, which is threatened by the high pumping rate for agricultural irrigation needs that is causing a gradual depletion of it as well as its contamination with salted seawater.

We model their interest by computing the monthly average irrigation reliability (J^i, see Equation (2) over the evaluation horizon H (expressed in terms of number of months), defined as the ratio between the monthly irrigation supply (Y_{t+1}) and the corresponding demand (W_t), i.e.

$$J^i = \frac{1}{H} \sum_{t=1}^{H} \left(Y^i_{t+1} / W^i_t \right) \tag{2}$$

where Y_{t+1} (m^3) is the monthly irrigation supply and W_t (m^3) the corresponding demand of the i-th agricultural zone (i = P, ABC).

To capture the spatial and temporal dynamics of the system introduced in the previous section, we compute four different indicators of reliability, with the first two representing the ability to satisfy the total annual demand in P (P^T) and ABC zone (ABC^T), while the others

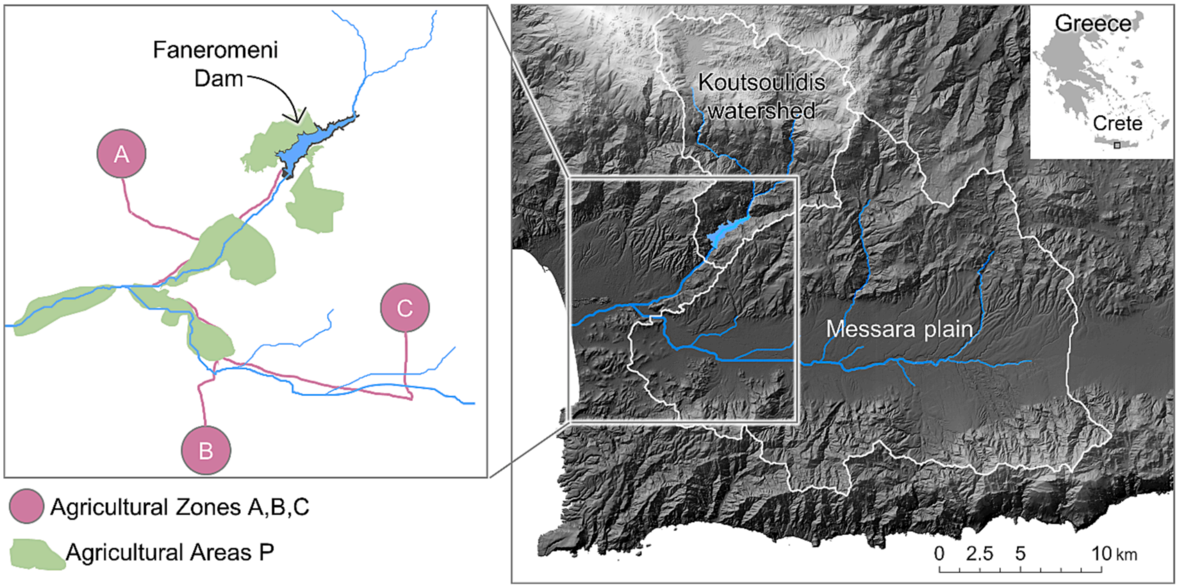

Fig. 2. Study site location. Koutsoulidis watershed is filling the Faneromeni dam, which supports the irrigation of the agricultural areas P throughout the year and the Agricultural zones A, B and C of the wider Messara plain during the irrigation period (May-Oct).

represent the ability to satisfy only the seasonal demand (May-November) in P zone (P^S) and ABC zone (ABC^S).

Seasonal forecast

Past seasonal forecast (hindcast) data for precipitation and temperature, for the European Centre for Medium-Range Weather Forecasts ECMWF SEAS5 model (IFS Cycle 43r1, (Johnson et al., 2019)) were obtained from the Copernicus Climate Data Store (CDS). These data span between 1993 and 2019 and comprise 25 ensemble member simulations that are initialised at equivalent intervals (monthly), at the starting point of the 214 days long-range simulation (~7 calendar months). In their work, (Grillakis et al., 2018) show that seasonal forecast data exhibit a lead time-dependent bias compared to the historical observations, especially in the precipitation parameter. Hence, a data reconstruction was performed to adjust for biases, with the forecast data being rearranged to create seven seamless lagged ensemble time series with similar lead time characteristics (MacLachlan et al., 2015). Then, each time series was adjusted for biases using (Grillakis et al., 2017, Grillakis et al., 2013) methods, which have been found to perform best with seasonal forecast data (Grillakis et al., 2018) for the region of Crete. The adjusted data were used to drive the HYPE hydrological model (Lindström et al., 2010) to estimate the dam inflow. The model was calibrated and validated using the same precipitation and temperature data used for the aforementioned bias adjustment of the seasonal forecasts. Since the observed flow data span between 1973 and 1993, the calibration period was set to 1973–1982, while the validation to 1983–1993. The model exhibited good performance with the seven-day aggregated flows to obtain Kling-Gupta Efficiency (Gupta et al., 2009) of 0.851 and 0.79 for the calibration and validation periods, respectively, as well as 0.903 and 0.736 according to the Nash – Sutcliffe metric (Nash and Sutcliffe, 1970). Furthermore, the overall flow bias was estimated at − 4.4% and 1.8% for the calibration and validation periods, respectively. The calibrated model was then used to extend the simulated discharge to 2019. This time series served as a perfect forecast flow estimation. More details about the calibration can be found in (Grillakis et al., 2018). For each ensemble member simulation, the HYPE model was initialised on the first day of the simulation, using the soil water state provided by the perfect forecast simulation for the same date.

Operating policy design and assessment of forecast value

The optimal operating policies p^* of the Faneromeni reservoir with respect to the four indicators introduced in the previous section can be designed by solving a multi-objective optimal control problem formulated as follows:

$$p^* = argmin_p \mathbf{J}(p) = \left| P^T, ABC^T, P^S, ABC^S \right| \quad (3)$$

The operating policies are optimised using the Evolutionary Multi-Objective Direct Policy Search (EMODPS) method (Giuliani et al., 2015a) a Reinforcement Learning approach that combines direct policy search, non-linear approximating networks, and multi-objective evolutionary algorithms. This method has been demonstrated to be effective in solving these types of multi-objective policy design problems featuring the possibility of enlarging the information used for conditioning operational decisions (Giuliani et al., 2020; Giuliani et al., 2015b; Zatarain Salazar et al., 2016). The assessment of the forecast value was performed over the period 1994–2019, when both forecasts and inflow series were available. Practically, we firstly designed a set of Basic Operating Policies (BOPs) without considering any forecast information to generate a benchmark useful to assess the forecast value. Secondly, we designed a set of Perfect Operating Policies (POPs) using the observed value of the inflow forecasts to quantify potential improvement generated by an ideal forecasts product, namely the EVPI (Expected Value of Perfect Information). Lastly, we used a real forecasts product (see the previous Section) to design the Informed Operating Policies (IOPs) to investigate the actually achievable improvement associated with this kind of forecasts.

Results and discussion

Seasonal forecast skill

The forecast skill of the HYPE simulated dam inflow, forced with the seasonal forecast meteorological variables was assessed. Fig. 3 shows the level of agreement between the most likely (the median of the 25 ensemble members) tercile category forecasted, and the respective tercile category of the perfect forecast. The terciles were defined from the respective 33rd and the 66th percentile of the perfect forecast and the seasonal forecast climatological flow data. Note that October's 33rd and

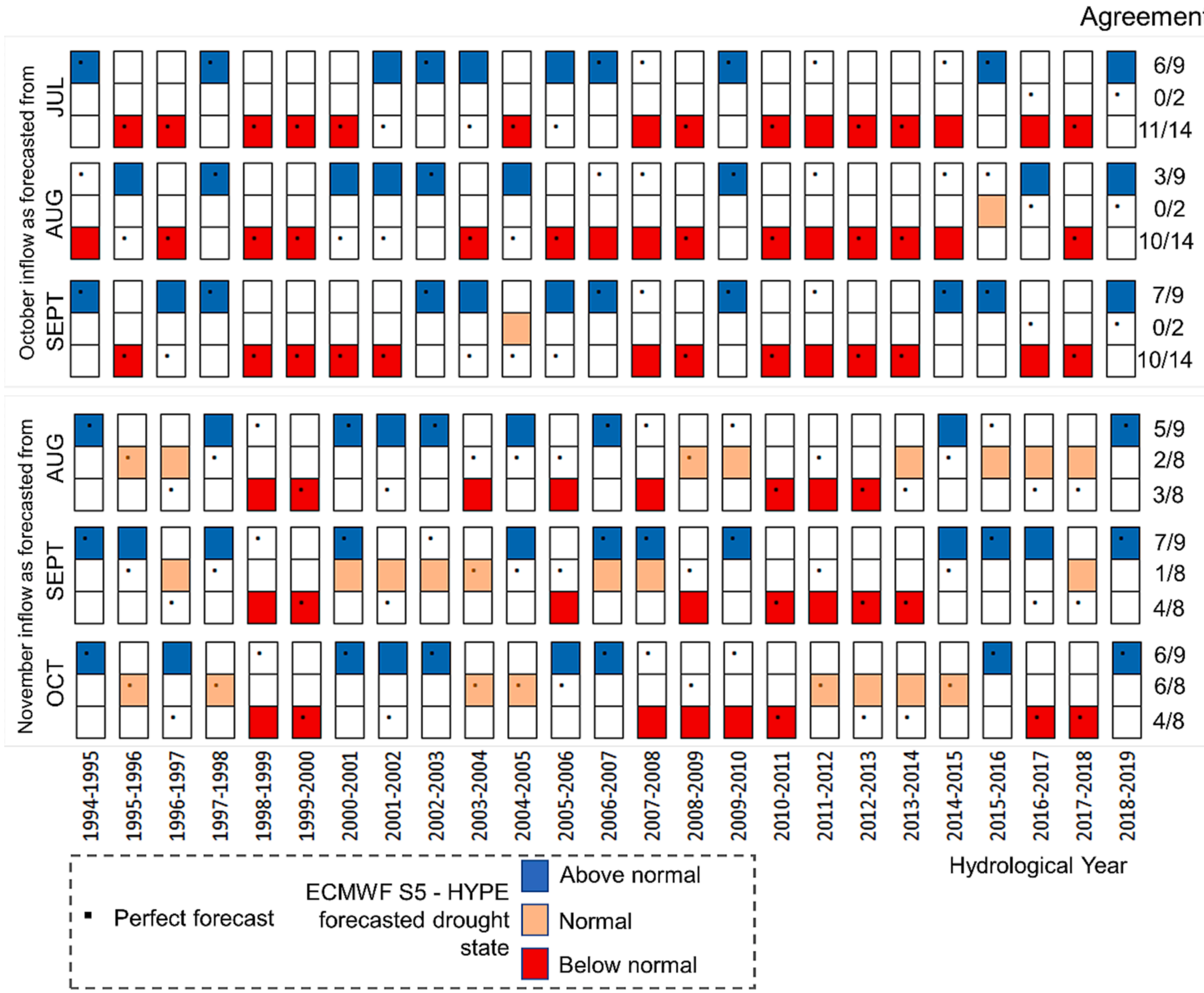

Fig. 3. Most likely tercile category prediction match for dam inflow of October and November months, from one, two and three months ahead, for 25 hydrological years. In colour boxes, the seasonal forecast state and, with a dot, the actual state according to the perfect forecast drought state. At the right is the fraction of successfully forecasted months. The terciles were defined from the respective 33rd and 66th percentile of perfect forecast and seasonal forecast climatological flow data.

66th percentile are almost identical and near zero since there is no inflow in the reservoir during this month. To that end, the "normal" flow category is almost not present in the results of Fig. 3 for October's inflow. The overall results show that in 25 years of seasonal forecast evaluation, October's below normal tercile is successfully forecasted 17, 13 and 17 times, since July, August and September forecasts, respectively. The respective results for November are 10, 12 and 16 times. We further estimated the probability of a false positive prediction for a wet October and November. This estimation shows the probability of false forecast in case stakeholders decide to utilise a prediction of a wet upcoming October or November, by exploiting resources over the predefined annual allocation (8.5 Mm^3). This failure probability was estimated at 40%, 66% and 36% for October, from three two and one months ahead, and 33%, 42% and 33% for November, respectively. It is worth noting that, in the case of a false positive wet prediction, the probability of an actually dry October (November) was estimated between 20% and 33% for October and 8% to 20% for November.

Trade-off analysis

This section illustrates the results of the trade-off analysis by exploring the 4-dimensional Pareto front obtained from the operating policies design. In particular, the Faneromeni operation performance of policies without forecast information (BOPs) are compared against those of current operating rule (described in Section 2.1).

In Fig. 4, the objectives referring to total covered-demand are represented by x- and y-axis, while the seasonal covered-demand ones are represented with the colour (ABC^S) and the size (P^S) of the points, respectively. The ideal solution would be a large yellow point in the figure's upper right corner. This bi-dimensional projection clearly shows a strong trade-off between the covered demand ratios in the two regions (P^T and ABC^T): increasing P^T values implies decreasing the performance in terms of ABC^T, and this generally holds also for the seasonal objectives. It can also be noticed that the solution of the current operating rule is largely dominated by the Pareto optimal policies designed via EMODPS, at least in terms of P^T and ABC^T.

In general, it is possible to recognise a positive correlation between P^T and P^S, and between ABC^T and ABC^S (see Supplementary Fig. S1).

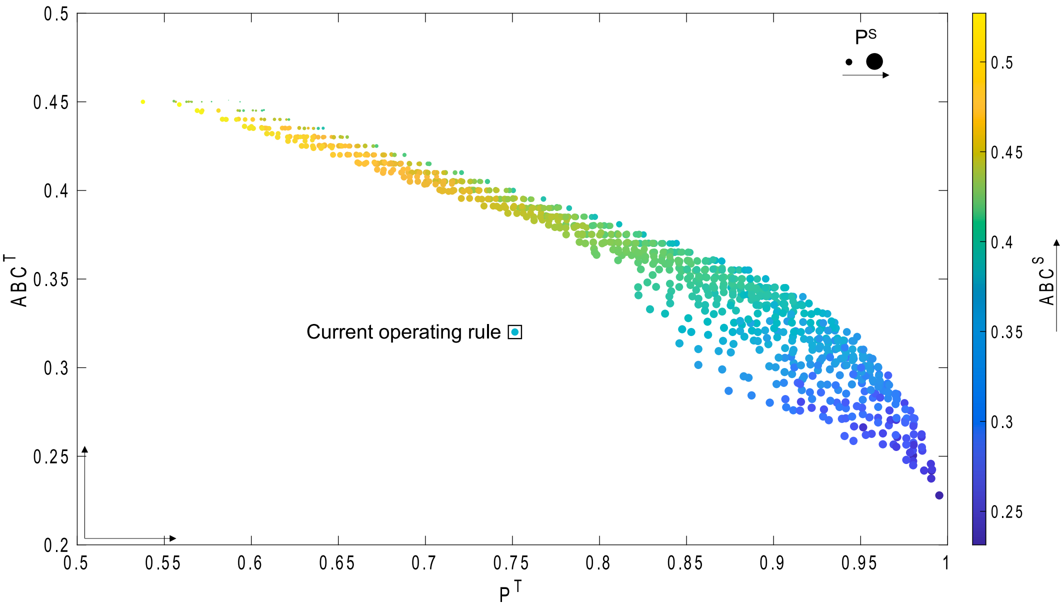

Fig. 4. Bi-dimensional projection of the 4-dimensional, not forecast-informed optimisation Pareto front shows a strong trade-off between the two irrigated regions. The point size represents the P^S objective. The squared green point at $P^T = 0.75$ and $ABC^T = 0.32$ represents the current operating rule performance. The ideal solution would be a large yellow point in the figure's upper right corner. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Since most of the water demand occurs during the irrigation season, maximising the total covered demand ratio can increase the seasonal objective values. However, the same performance in P^T can be achieved with different values of P^S depending on the temporal allocation of the water supply. This also holds true for ABC^T and ABC^S. In fact, total objectives ignore the distribution of the deficit within the year, whereas seasonal objectives only consider the water supply during the irrigation season.

Forecast value

In this section, we build on the results reported in Fig. 4 to quantify the forecast value as the gain in performance attained by informing the operating policy with forecast information.

Fig. 5 contrasts the performance of the Basic Operating Policies not informed by any forecast information (i.e., the same solutions reported in Fig. 4) against the Informed Operating Policies that use the seasonal forecasts described in Section 3.1 and the Perfect Operating Policies that use perfect inflow forecast. Results show that the three Pareto fronts have a very similar shape, with a large part of the POP set that overlaps the BOP one, thus suggesting the space for improvement is relatively small. Nevertheless, it is remarkable that the POPs are able to reach better performance around the inflexion point of the Pareto front. This is a promising result because the negotiation of a compromise solution between the competing objectives will probably take place here. The real forecast-informed solutions (IOPs) are located between the BOPs and the POPs, and this is reasonable since the forecast used by these solutions are affected by errors. Notably, IOPs are also largely overlapped with the BOPs, except for the rightmost region of the P^T-ABC^T space. This result suggests that forecasts can potentially improve the system's performance, but the considered forecast product's skill is insufficient to generate large benefits when operating the system. Beside the exploration of the use of seasonal information in the IOPs reported in Fig. 5, we tested the use of both forecasts with 1 month and 7 months leadtimes. Results (not shown) show that the 1 month leadtime forecasts are not able to further improve the performance of the IOPs.

The forecast value can be quantified by looking at the horizontal improvement obtained by IOPs and POPs with respect to the current operating rule (the improvement in terms of seasonal objectives is not reported here given the priority of the water supply system is assigned to the P zone). Table 2 shows the horizontal improvement in total and seasonal objectives attained by the new policies, including the Basic Operating Policies to distinguish the contribution of the forecast information from the one generated by the implementation of a more flexible operating policy than the current operating rule. As total objectives are concerned, it can be seen that most of the improvement with respect to the current operating rule is attributable to the use of flexible policies, rather than the use of forecasts. Indeed, the best BOP associated with the current performance in ABC^T allows increasing the performance of P^T by more than 25%. The IOP leads to an additional small increase, but is only the POP that can significantly improve the P^T performance. Similarly, when considering the seasonal objectives, it can be noted that the improvements are generally lower than the ones in the total objectives. This is due to the fact that the system is currently operated to satisfy the seasonal objectives, so there is less room to improve them. Anyway, the same considerations of the previous case hold true, except for the fact that here the IOP has the same performance as the BOP, thus registering a null value of the real forecasts.

To understand how the forecast information affects the system operation, a sub-set of solutions has been selected from Fig. 5 and analysed by looking at the corresponding simulated reservoir dynamics. In particular, in Fig. 6 we show the trajectories of the reservoir level generated by the three solutions discussed in Table 2 (BOP_T, IOP_T and POP_T). It can be noted that the BOP_T produces a higher oscillation and a lower average reservoir level with respect to the current operating rule. This remarks the ability of the BOP_T to fully use the reservoir storage, which avoids some winter spillages (the reservoir water level ranges from 128 to 156 m a.s.l.). The POP_T solution even exacerbates this strategy substantially drawing down the reservoir at the end of the irrigation season. This is because the policy knows that the incoming inflow during the winter will be able to refill the reservoir, at least partially. The trajectory generated by the IOP_T lies between the POP_T and the BOP_T ones: when it is more similar to the POP_T trajectories it means that the forecasted inflow is similar to the actual realisation (perfect forecast), and so the forecast information has been valuable; on the contrary, when the IOP_T and BOP_T trajectories are close it means

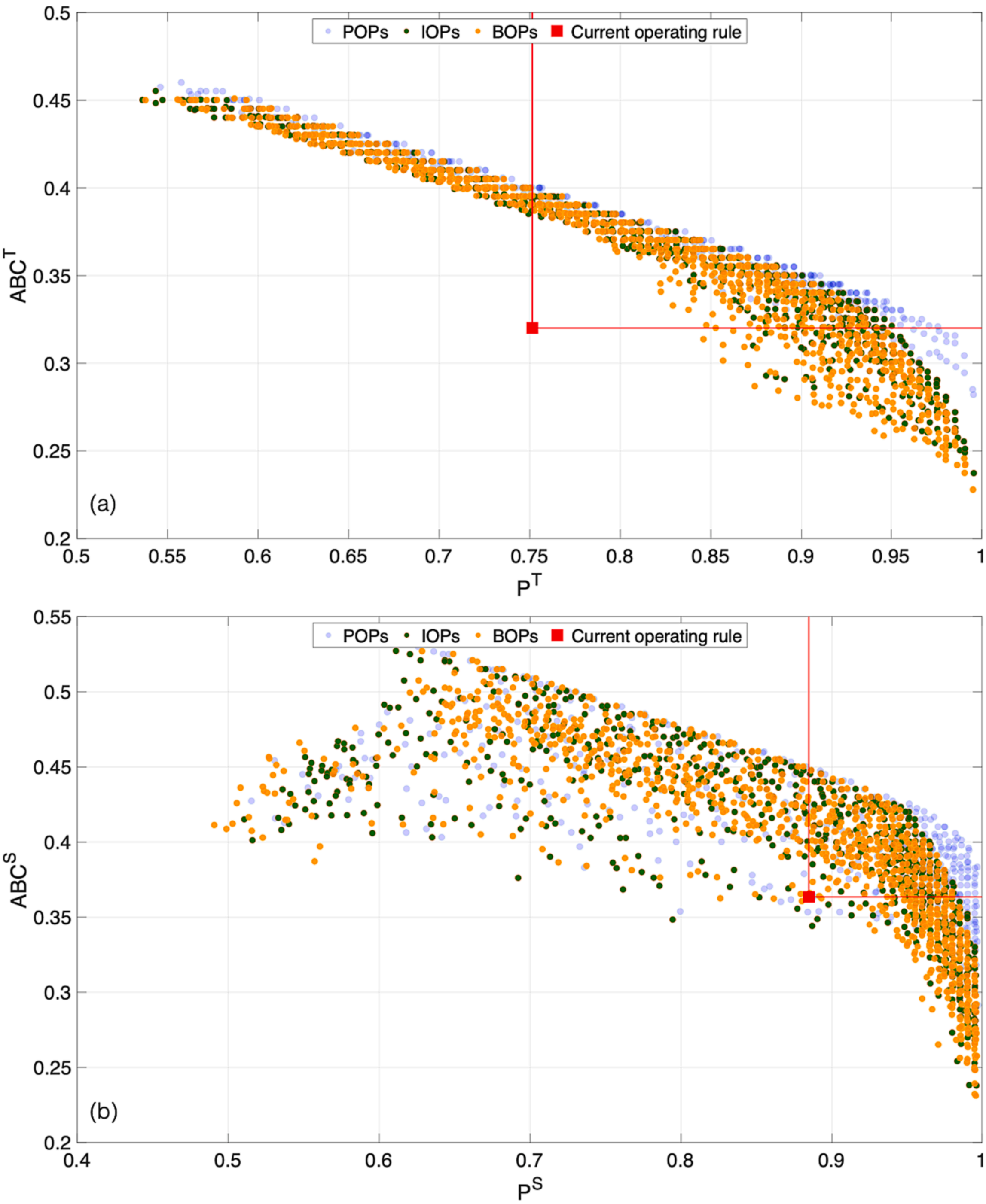

Fig. 5. Comparison of the bi-dimensional projections of the BOPs (yellow dots), IOPs (green dots) and POPs (blue dots) Pareto fronts obtained for total (a) and seasonal (b) objectives. The red square represents the current operating rule, and the red lines identify the space of the non-dominated solutions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that the forecast hasn't been useful to the reservoir operation. It is worth noting that during exceptional multi-year drought events, such as 2005–2008, the four trajectories overlap: this is because the limited reservoir capacity and the seven months lead time of the considered forecasts do not allow implementing an inter-annual water transfer to compensate the extremely low inflows during this extreme drought event. This finding confirms how the forecast value depends on not only the forecast skill (actual vs. perfect forecasts) but also the hydrological conditions (normal vs extremely dry years).

Finally, in order to provide some recommendations to the operators of the Faneromeni dam, we analyze in more detail the reservoir level-release relationship for different policies by visualizing the simulated trajectories in a set of monthly scatterplots (Fig. 7). The figure shows that the current operating rule implements constant releases in the irrigation season that do not vary with the reservoir level, except for extremely low levels. On the contrary, the three new policies adjust the release according to the level and the month on the year. We can notice how the perfect forecasts suggest the POP_T to implement lower releases than the BOP_T at the beginning of the irrigation season (May-June), with the saved water that allows higher releasees during the next months of the irrigation season. The IOP_T is not able to reproduce this strategy in May and June, probably because the real forecasts tend to

Table 2
Forecast value of the selected IOPs and POPs.

Total objectives	ABC^T	P^T	P^T improvement with respect to current operating rule	P^T improvement with respect to BOP_T	P^T improvement with respect to IOP_T
Current operating rule	0.32	0.751	–	–	–
BOP_T	0.32	0.942	25.43%	–	–
IOP_T	0.321	0.95	26.50%	0.85%	–
POP_T	0.321	0.976	29.96%	3.61%	2.74%
Sesonal objectives	ABC^S	P^S	P^S improvement with respect to current operating rule	P^S improvement with respect to BOP_S	P^S improvement with respect to IOP_S
Current operating rule	0.364	0.885			
BOP_S	0.366	0.981	10.85%	–	–
IOP_S	0.366	0.981	10.85%	0.00%	–
POP_S	0.366	0.995	12.43%	1.54%	1.54%

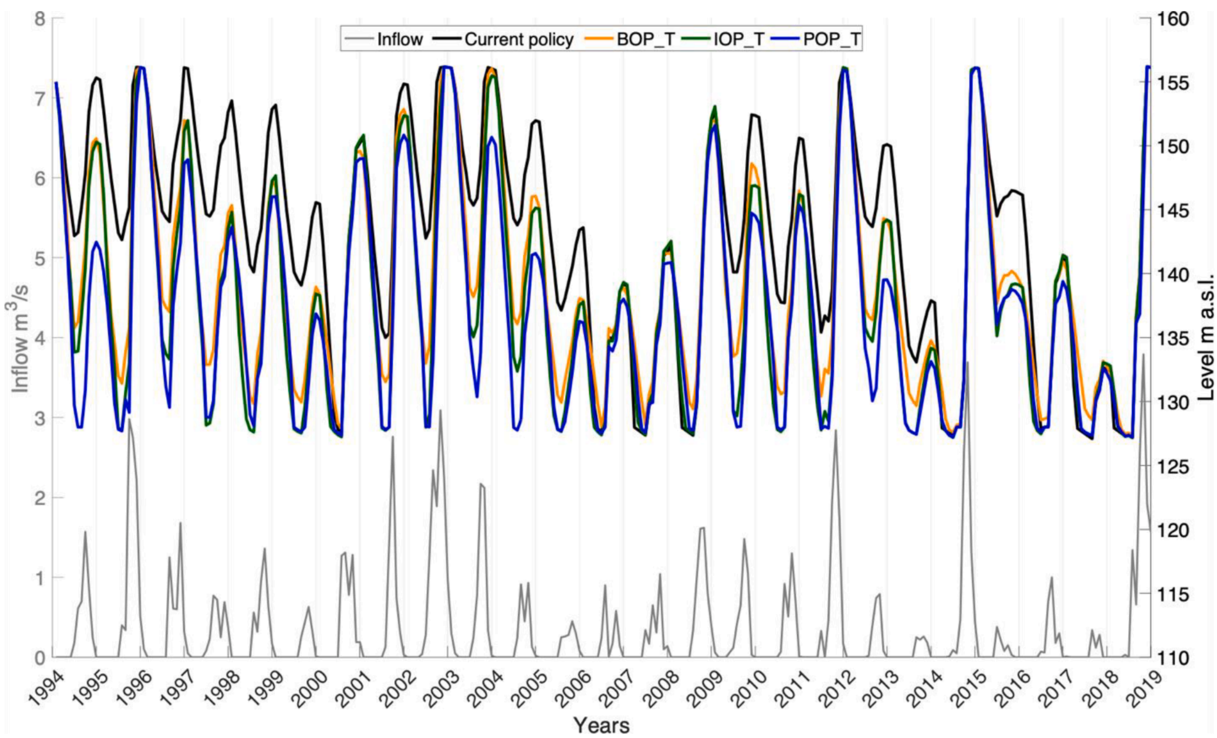

Fig. 6. Faneromeni reservoir level trajectories generated by the simulation of BOP_T (orange line), IOP_T (green line), POP_T (blue line), and the current operating rule (black line) plotted against the monthly inflow (gray line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

overestimate the real inflow in this period of the year. In October and November, both the IOP_T and the POP_T tend to generate higher releases than the BOP_T by taking advantage of the information about the incoming winter inflow. Finally, the current operating rule does not release any water outside the irrigation season (i.e., from December to April), while the other policies suggest positive releases to satisfy also the winter water demand. Interestingly, the IOP_T is the solution implementing the smallest release in these months to save water for the incoming irrigation season because forecasts tend to underestimate the spring inflow.

Conclusions

This work focuses on the assessment of the value of seasonal forecasts in informing reservoir operations in a water-stressed Mediterranean basin. This reservoir is located in the south-central part of Crete, in the Messara valley, and constitutes an indispensable water infrastructure for the region and a major driver for the local economic development of the primary sector. The Faneromeni reservoir provides water to two irrigation districts competing to access the basin's scarce water resources. Historically, the reservoir is operated with a simple rule that suggests releasing a volume equal to the demand during the irrigation season (from May to November) with no releases in the winter period and gives the priority of the water supply to one of the two irrigation districts. However, the system is suffering due to summer drought and very large inflow variability, which is often unable to completely fill the reservoir during the winter season. Seven-month lead time streamflow forecasts are used to inform the operating policies of the Faneromeni reservoir. In order to quantify the forecast value, we first design the not forecast-informed operating policies representing a benchmark. This required first to understand the main water-related dynamics and the different stakeholders involved, and subsequently to develop a reservoir model for supporting the design of improved operating strategies. Four objectives have been defined, representing the percentage of the annual and

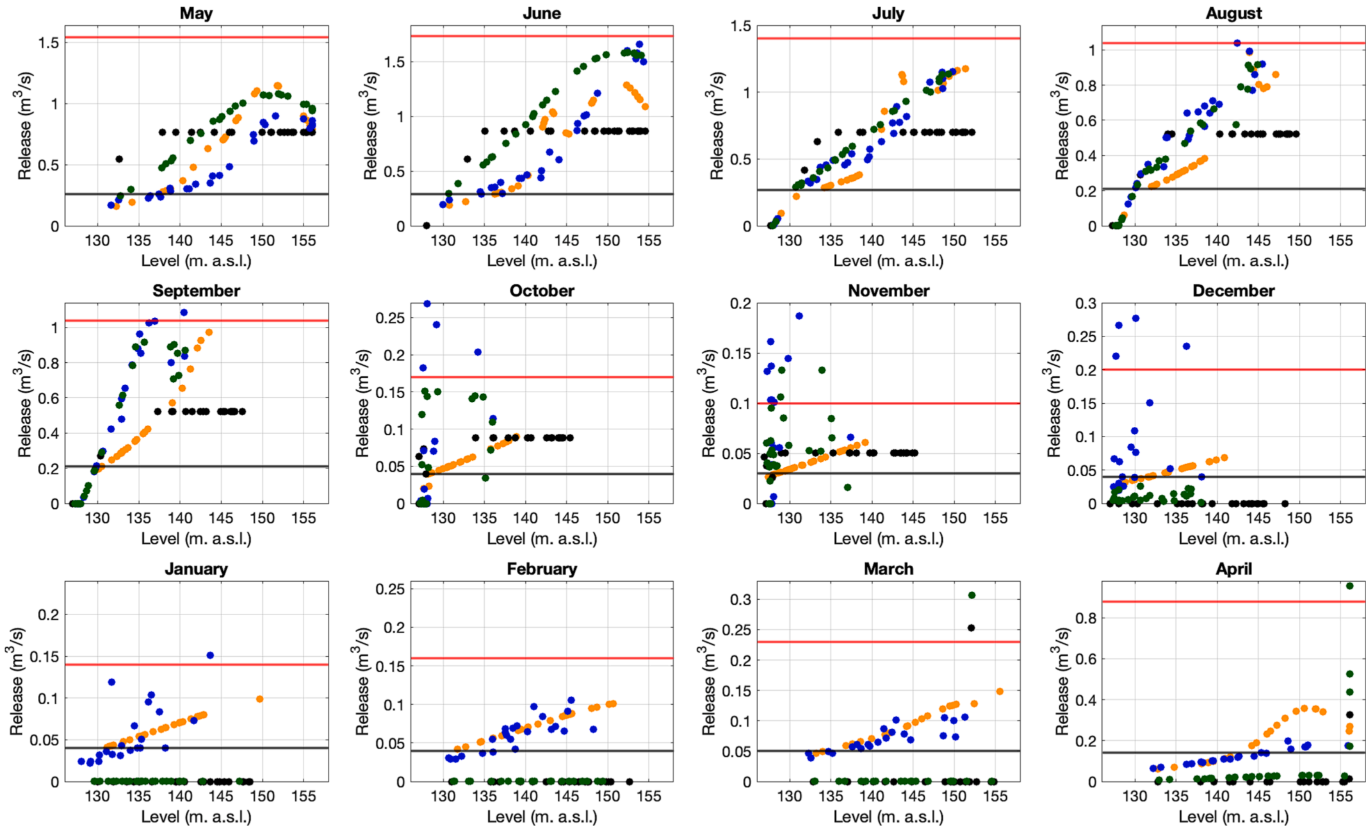

Fig. 7. Monthly level-release scatterplots generated by the simulation of BOP_T (orange dots), IOP_T (green dots), POP_T (blue dots), and the current operating rule (black dots). The black and red horizontal lines represent the P zone and the total (P + ABC) water demand, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

seasonal (May-November) demand covered in the two irrigation districts. Then, Pareto-optimal operating policies were designed using the Evolutionary MultiObjectives Direct Policy Search optimisation approach, which allows exploring the trade-offs across the considered objectives as well as informing the operating policies with forecast information.

Results show that the use of flexible policies, even if not informed by forecasts, is able to substantially improve the system performance. We analysed the trade-offs between the considered objectives, pointing out the competition between the irrigation districts and the temporal component of the water supply problem, that influences the value of the seasonal objectives. Seasonal perfect forecasts appear to be a useful instrument in the Faneromeni reservoir operation, leading to a significant improvement in the performance of the system. Considering a real forecast product, we found that its skill constitutes a limit for the performance of the real forecast-informed policies. We used the median of the ensemble to compute the real forecast value, but this implies losing the inflow variability and detecting wet years, when there is room to increase the water supply. Future research can focus on developing post-processing methodologies for sub-sampling the forecast ensemble (e.g., Dorbryin et al. 2018) in order to select the best forecast member(s) that provide the most valuable information for advancing the reservoir operation.

Our work attempts to give a comprehensive assessment of incorporating seasonal forecasts into reservoir operations while acknowledging the limitations of the forecast product. Our results are expected to improve the current practices used by local practitioners by showcasing the benefits of flexible operating policies and the additional contribution that forecast information can bring. Interestingly, the interactions with the local authorities suggested these benefits may go beyond the ones quantified here in terms of improved irrigation supply as a primary concern in the region is related to the high energy cost of pumping groundwater. An improved reservoir operation allows reducing the volumes to be pumped and, therefore, lower the associated pumping costs, making the approach more attractive for the local decision makers.

We recognize the current insufficiency of forecast skill and the importance of considering and communicating associated uncertainties. The limited experience of local operators with seasonal forecasts contributes to their hesitance in trusting and acting upon the forecast information. Despite these limitations, we acknowledge the increasing skill of seasonal forecasts due to advancements in forecasting systems and postprocessing techniques. While managing expectations and addressing skepticism is crucial, exploring the potential benefits of sufficiently skilled forecasts allows us to understand future possibilities and the value they can provide to water management decisions.

CRediT authorship contribution statement

Nicola Crippa: Formal analysis, Software, Data curation, Visualization, Writing – original draft. **Manolis G. Grillakis:** Formal analysis, Methodology, Software, Writing – review & editing, Data curation, Visualization. **Athanasios Tsilimigkras:** Writing – review & editing. **Guang Yang:** Methodology, Formal analysis, Software. **Matteo Giuliani:** Conceptualization, Methodology, Writing – review & editing, Supervision, Resources, Funding acquisition. **Aristeidis G. Koutroulis:** Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft, Supervision, Resources, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cliser.2023.100406.

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