Journal of Hydrology: Regional Studies 46 (2023) 101339

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Multi-objective optimal design of interbasin water transfers: The Tagus-Segura aqueduct (Spain)

Carlotta Valerio [a,b,*], Matteo Giuliani [c], Andrea Castelletti [c], Alberto Garrido [b,d], Lucia De Stefano [a,b]

[a] *School of Geological Sciences, Complutense University of Madrid, Calle José Antonio Nováis 12, 28040 Madrid, Spain*
[b] *Water Observatory, Botín Foundation, Calle de Castelló 18, 28001 Madrid, Spain*
[c] *Department of Electronics, Information, and Bioengineering, Politecnico di Milano, P.za Leonardo da Vinci, 32, 20133 Milan, Italy*
[d] *CEIGRAM, Technical University of Madrid, Paseo Senda del Rey 13, 28040 Madrid, Spain*

ARTICLE INFO

Keywords:
Interbasin water transfer
Tagus-Segura aqueduct
Multi-objective evolutionary optimization
Direct policy search
Environmental flow

ABSTRACT

Study region: The Tagus-Segura aqueduct (TSA) is a large and strategic water transfer scheme in Spain that connects Entrepeñas and Buendía reservoirs in the Tagus river headwaters to the Segura river basin, a highly stressed Mediterranean area.

Study focus: The operating rules of the TSA underwent several modifications over the years, and the debate about which are the optimal parameters to meet the interests of the parties involved is still open. We employed Evolutionary Multi-Objective Direct Policy Search to jointly optimize the re-operation of the headwaters dams and the water transfer policy with respect to four conflicting objectives: Tagus and Segura water demands, hydropower production and socioeconomic benefit of the population living on the shores of the headwaters reservoirs. We tested the optimization under the baseline and the 2027 scenario, which foresees an increased environmental flow (EF) in the Tagus river.

New hydrological insights for the region: The proposed operating rule presents optimized control parameters, a higher degree of freedom and a transferred volume that cyclically varies according to the hydrological stage of the year. In the 2027 scenario, despite the increased EF, the deficit in the aqueduct shows a limited increase compared to the historical solution (+10%), while the storage deficit is strongly reduced (−73%). This benefits the population living on the reservoirs shores and also ensures more stability to the aqueduct functioning.

1. Introduction

Water scarcity is a major global challenge (Dolan et al., 2021), affecting about four billion people worldwide (WWAP, 2020). Increasing water resources demand, climate change impacts and water quality deterioration further exacerbate the natural uneven spatio-temporal distribution of freshwater (Shumilova et al., 2018). Interbasin water transfers (IBWTs) are often conceived as solutions to water distribution unbalances and are likely to expand in the future. According to Duan et al. (2022), IBWTs redistribute 1.2% of global renewable water resources annually, and this percentage is expected to increase (Gupta and van der Zaag, 2008). Shumilova et al. (2018) identified 34 existing water transfer megaprojects and 76 under construction or in the planning phase. While IBWTs can

* Corresponding author at: School of Geological Sciences, Complutense University of Madrid, Calle José Antonio Nováis 12, 28040 Madrid, Spain.
E-mail address: carval02@ucm.es (C. Valerio).

https://doi.org/10.1016/j.ejrh.2023.101339
Received 3 August 2022; Received in revised form 22 January 2023; Accepted 8 February 2023
Available online 18 February 2023

help satisfy water demands in arid and semiarid regions (Zhang et al., 2015), they often raise concerns about their social, environmental, and economic impacts (Veena et al., 2021) and their future sustainability in a fast-changing environment has been questioned (Duan et al., 2022).

IBWTs are considered one of the most controversial topics in the water resources planning field (Zhang et al., 2015), often fuelling tensions between the origin (donor) and receiving regions. Lessons learnt from existing IBWTs reveal that a deficient regulatory framework at the time of infrastructure design can cause adverse impacts on the entire system (de Andrade et al., 2011; Veena et al., 2021). Donor basins frequently experience severe hydrological alteration through flow reduction (WWF, 2009) and interruption of river connectivity (Grant et al., 2012) and can be affected by salinization problems (Zhuang, 2016). Although some water transfers enabled the restoration of water recipient ecosystems (e.g. Allison and Meselhe, 2010), they may also facilitate the spread of contaminants as well as alien species invasion (Rasmussen, 2002). IBWTs also cause significant energy consumption (Ming et al., 2017) and are proven to increase water demand in the recipient basins, generating unsustainable expansion of urban and irrigated areas (WWF, 2009).

The Tagus-Segura aqueduct (TSA) in Spain is among the major IBWT projects in the world (Shumilova et al., 2018). It was built in the 1970s to transfer a maximum of 650 $hm^3/year$ from Entrepeñas and Buendía reservoirs in the Tagus headwaters to the Segura river basin for irrigation and domestic water supply purposes. Since it entered into operation in 1979, the TSA has been one of the most controversial topics in water management in Spain (Senent-Aparicio et al., 2021) and has generated strong tensions among the stakeholders involved (Morote et al., 2020).

The TSA system has been widely studied from different perspectives. Several authors focused on its socioeconomic and environmental impacts (Hernández-Mora et al., 2014; Hernández-Mora and del Moral, 2015; Melgarejo-Moreno et al., 2019; Morote et al., 2017, 2020; San-Martín et al., 2018; WWF, 2009), while other authors analysed the effects of climate change on the infrastructure (Aparicio et al., 2013; Lobanova et al., 2017; Pellicer-Martínez and Martínez-Paz, 2018; Sahouri, 2014). Alternative management strategies to deal with the expected reduction in water resources have been proposed (Morote et al., 2017; Rey et al., 2016).

The TSA operation is subject to a water transfer rule defined by Royal Decree 638/2021 that presents four levels, based on the total volume stored in Entrepeñas and Buendía reservoirs and the inflow to the system in the previous twelve months. Each level establishes the monthly quantity of water that can be transferred to the Segura river basin. Moreover, a maximum monthly release to the Tagus river is set, depending on the domestic, irrigation and environmental demands in the Tagus upper basin. The rule has been long contested by both sides, generating debates, especially on the high occurrence of level 3 or 4, where minimum or no water transfer is allowed, and on the most adequate environmental flow to be set in the Tagus river. The control parameters of the rule underwent several modifications over the years until the approval of the current rule in 2021, and the debate about which are the optimal parameters to meet the interests of all the parties involved is still open (Larraz et al., 2020; SCRATS, 2020).

Setting adequate operating rules is key to manage conflicts between donor and receiving regions. Policies and regulations are essential to guarantee the success of water transfer projects (Zhuang, 2016). However, reservoirs are usually operated with non-efficient predefined ruled (Macian-Sorribes and Pulido-Velazquez, 2020) and the expected design goals are often not achieved (Dobson et al., 2019). Although the problem of designing optimal reservoir operations has been extensively studied, the complexity of real-word systems limited the practical application of the methods proposed in the literature (Ren et al., 2019). Multi-objective simulation-optimization frameworks recently emerged as a valuable strategy for optimal resource allocation (Heinz et al., 2007; Maier et al., 2014; Veena et al., 2021). Several studies have been conducted to design optimal operating rules addressing multiple objectives, such as agricultural, urban and ecological water demand, hydropower generation and energy consumption (Gu et al., 2017; Ma et al., 2020; Ming et al., 2017; Zeng et al., 2014; Zhu et al., 2014). The most representative simulation-optimization method is the evolutionary multi-objective direct policy search (EMODPS), which combines direct policy search, a nonlinear approximating network, and a multi-objective evolutionary algorithm (Giuliani et al., 2016). EMODPS exploits the parameterization of the operating policies and explores the associated parameter space to find a parameterized policy that optimizes the expected system performance (Giuliani et al., 2018). The effectiveness of EMODPS in addressing reservoirs operation in complex multi-objective contexts has been demonstrated (for a review, see Giuliani et al., 2021 and references therein), and its potential to improve water transfer strategies has been recently explored (Ren et al., 2019; Veena et al., 2021).

After the recent modification of the TSA water transfer rule in 2021, no further changes are expected in near future. However, the topic is still intensely debated, with the collision of opposing views: from one side, the respect for the priority of the donor basin and the achievement of its good ecological status, and on the other side, the concern on the effects that such a goal would produce on the economy of the recipient regions. While some proposals have been made to improve the water transfer rule (de Lucas, 2019; CEDEX, 2020; Larraz et al., 2020), advanced methods such as the EMODPS have not yet been tested. By applying this approach to the TSA case, this paper intends to widen the solutions space explored so far and to contribute to the ongoing debate on the present and future of this controversial water transfer in Spain. We also evaluate the potential of the EMODPS approach to guide the design of alternative operating rules for water transfers, with the ultimate goal of mitigating tensions between recipient and donor regions and seeking to fulfil the environmental needs of the donor basin.

We employ EMODPS to optimize the operation of the TSA with respect to four potentially conflicting objectives: (i) the Tagus water demands (urban water supply, irrigation and environmental flow maintenance); (ii) the Segura water demands (urban water supply and irrigation); (iii) hydropower production downstream of the Entrepeñas and Buendía dams; and (iv) the socioeconomic benefit of the population living on reservoirs' shores. We jointly optimize the re-operation of the two headwaters reservoirs and the existing water transfer policy, thus allowing the exploration of trade-offs between objectives and the definition of an operating rule that could benefit the main stakeholders involved. We tested the optimization under a scenario of increased environmental flow in the Tagus river, as established by the 2021–2027 Tagus River Basin Management Plan. This allowed us to assess the effect produced by this

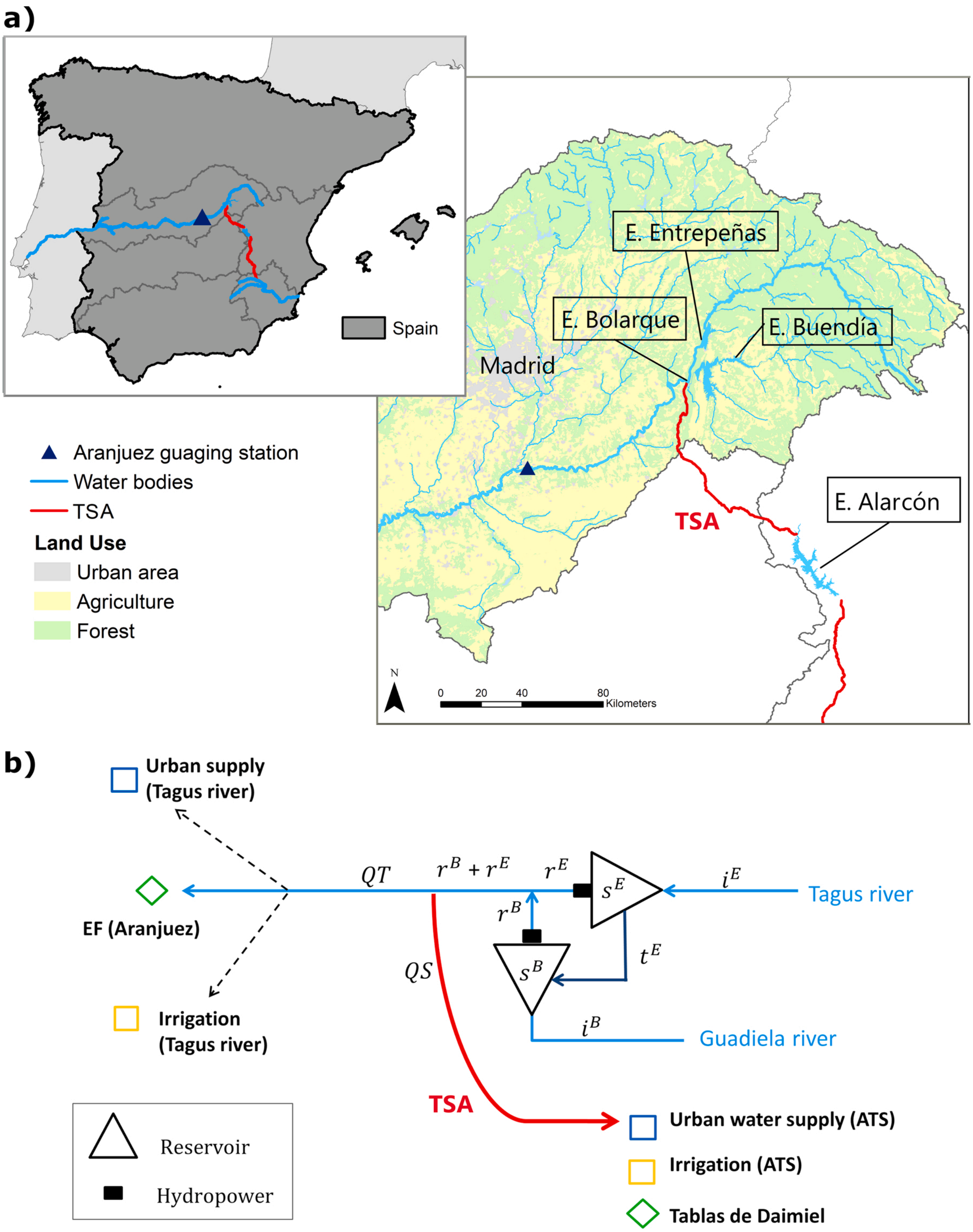

Fig. 1. (a) Study area and its location in the Iberian Peninsula. (b) Topological map of the system.

mitigation measure on the competing objectives and design an operating rule sufficiently robust to deal with such a scenario.

2. Case study description

2.1. The TSA system

The TSA system, in operation since 1979, consists of a 286 km-long pipeline with a maximum annual transfer capacity of 650 hm^3. The donor regions include Castilla-La Mancha, Madrid and Extremadura. Up to 600 $hm^3/year$ are allocated to the region of Murcia (Segura river basin), the province of Alicante in the Valencia region and, to a lesser extent, the province of Almería in Andalusia. In addition, 50 $hm^3/year$ can be transferred to the Guadiana basin for ecological and urban water supply purposes. The TSA infrastructure begins in the Bolarque reservoir, downstream from the headwaters reservoirs Entrepeñas and Buendía (Fig. 1a). From Bolarque, the water is pumped to the Bujeda reservoir, from where it is conducted towards the Alarcón reservoir on the Júcar river, and then to the Talave reservoir on the Mundo river, the main tributary of the Segura river (Melgarejo-Moreno et al., 2019).

The aqueduct connects river basins that are strategic for water resources management in Spain and Portugal (Senent-Aparicio et al., 2021). The Tagus river basin is the longest river in the Iberian peninsula and supplies water resources to approximately 15% of the Spanish and 30% of the Portuguese population (Lobanova et al., 2017). The increasing water demand and the high number of dams regulating the river led to water scarcity problems and poor ecological status in some water bodies (Sondermann and de Oliveira, 2021). The Segura basin is one of the most water-stressed regions in the Mediterranean basin (Aldaya et al., 2019). The estimated annual structural deficit in the basin is 458 $hm^3/year$, especially concerning the agricultural water use, which represents 86% of the total demand in the basin (CHS, 2015). Climate change is expected to further exacerbate this deficit (Rupérez-Moreno et al., 2017). The intensely irrigated horticultural and fruit crops are essential to sustain the basin's economy. The export of vegetables and fruits to EU countries can exceed 70% of the total production, so the region has become known as the orchard of Europe (Martin-Gorriz et al., 2021). The TSA enabled the socioeconomic development of southeast Spain (Morote et al., 2020). According to the Central Irrigation Union of the Tagus-Segura (SCRATS by its Spanish acronym), the aqueduct generates a total economic impact of more than € 3.013 billion (i.e., 4.6% of the gross domestic product) and provides 106,566 direct jobs in the Alicante and Murcia provinces (SCRATS, 2020). On the other side, the TSA spurred the uncontrolled expansion of irrigation and urban water demand, leading to the paradox of increasing the initial water deficit in the receiving basin (Hernández-Mora and del Moral, 2015; WWF, 2009).

Since 1997, the water transfer rule foresees four levels, according to which the transferred volume is calculated at the beginning of each month (Table 1). The transferred volume varies according to the total storage of Entrepeñas and Buendía reservoirs and the inflow to the system in the previous 12 months, with a maximum water transfer of 650 hm^3 in each hydrological year. Moreover, the rule establishes a maximum monthly release to the Tagus river that includes the urban and irrigation water demand downstream of the Bolarque dam as well as the environmental flow.

The operating rule has often been contested by stakeholders and has undergone several modifications over the years (Table 1). The infrastructure was intended to transfer 'surplus' Tagus water, i.e. resources in excess of water demand for urban water supply, irrigation, hydroelectric production and environmental flow maintenance in the donor basin (Hernández-Mora and del Moral, 2015), as defined by Law 21/2015. However, the estimation of surplus resources in the donor basin has been long questioned, arguing that the environmental effects have been not rigorously taken into account (Hernández-Mora et al., 2014; Rey et al., 2016). According to WWF (2009), the reduced stream flows have affected riparian vegetation along the Tagus River and have limited the river capacity to dilute the polluted flows produced by the Madrid region, resulting in water quality problems between Aranjuez and Toledo (Bolinches et al., 2020; Hernández-Mora and del Moral, 2015).

The high frequency of situations in which the system falls into level 3 or even in level 4 (where no transfer is allowed) was brought to the attention of the Ministry in charge of setting the rules. This circumstance creates negative impacts on the population living on the shores of the reservoirs in the area of origin, limiting tourism and recreational activities (San-Martín et al., 2018), as well as in the Segura basin due to the instability and irregularity of the water transfer (CEDEX, 2020). Such a situation arises from the combination of

Table 1
Evolution of the 4-level TSA water transfer rule over the years. V is the total storage of Entrepeñas and Buendía reservoirs, and I is the inflow to the system in the 12 previous months. Curve A and Curve B are reported in Table S1, Supplementary Material.

	1997 Rule (ER 1997[a])		2014 Rule (Royal Decree 773/2014[b])		2021 Rule (Royal Decree 638/2021[c])	
Level	**Condition**	**V transfer (hm^3/month)**	**Condition**	**V transfer (hm^3/month)**	**Condition**	**V transfer (hm^3/month)**
1	V > 1500 hm^3 I > 1000 hm^3	68	V > 1300 hm^3 I > 1200 hm^3	60	V > 1300 hm^3 I > 1400 hm^3	60
2	V < 1500 hm^3 I < 1000 hm^3	38	V < 1300 hm^3 I < 1200 hm^3	38	V < 1300 hm^3 I < 1400 hm^3	27
3	V < Curve A	Up to 23	V < Curve B	Up to 20	V < Curve B	Up to 20
4	V < 240 hm^3	0	V < 400 hm^3	0	V < 400 hm^3	0

[a] Operating rules adopted internally, for guidance purposes, by the Central Commission for the Exploitation of the Tagus-Segura Aqueduct, in November 1997.
[b] https://www.boe.es/buscar/doc.php?id=BOE-A-2014-9336
[c] https://www.boe.es/diario_boe/txt.php?id=BOE-A-2021-12610

two elements: the reduction of the natural runoff registered in the basin since the 1980s and the choice of certain control parameters in the operating rule. Since the design of the transfer in the 1960s, the Tagus headwater suffered a reduction of natural inflows by 47% (San-Martín et al., 2020), thus leading to the under-exploitation of the infrastructure with respect to the design targets. Specifically, annual transferred volumes have averaged about 350 hm^3 since 1979 instead of the projected 600 hm^3 (Senent-Aparicio et al., 2021). At the same time, some studies consider the transferred volume at level 2 to be unsustainable (de Lucas, 2019; Cabezas, 2013) and the storage and inflow thresholds for entering in level 1 too low (de Lucas, 2019; Larraz et al., 2020). In 2021, the water transfer rule was revised to lower the probability of occurrence of levels 3 and 4 (CEDEX, 2020): the volume to be transferred in level 2 was decreased to 27 $hm^3/month$, while the inflow threshold for entering level 1 was increased to 1400 hm^3. However, other studies propose even smaller values for the transferred volume at level 2 and suggest an increase also in the storage threshold (de Lucas, 2019; Larraz et al., 2020).

A further critical issue is the environmental flow (EF) to be ensured in the Tagus river, which directly influences the maximum monthly release target. Until the entry into force of the 2021–2027 Tagus River Basin Management Plan (RBMP), the legislation required a constant flow of 6 m^3/s at the Aranjuez gauge, the first monitoring point for the control of the environmental flow requirements located 100 km downstream of the Bolarque dam. This value was not technically supported and has been long contested. A sentence of the Spanish Supreme Court 309/2019, which repealed several articles of the Tagus RBMP for not containing an adequate determination of the EF in Aranjuez and in other three strategic water bodies (Molina, 2019), forced the modification of the original value of the EF. The 2021–2027 Tagus RBMP foresees a gradual increase of the EF, up to an average value of 8.6 m^3/s in 2027. While, from the Tagus perspective, this value has been judged as insufficient (Baeza, 2021), SCRATS argued that this value will significantly compromise the annual volume transferred to the Segura basin (SCRATS, 2020).

2.2. Model description

The model developed in this work consists of three main components: Entrepeñas reservoir (Tagus river), Buendía reservoir (Guadiela river) and the aqueduct (Fig. 1b). Since Entrepeñas reservoir has a lower storage capacity with respect to Buendía (802 hm^3 vs 1638 hm^3), but a higher inflow, a tunnel connects the two reservoirs. The modelled system was simplified excluding the Bolarque reservoir (Tagus river, just downstream of Entrepeñas and Buendía), given its very low storage capacity and its main use for daily regulation and hydropower production. The monthly dynamics of Entrepeñas and Buendía reservoirs are described through the following water mass balance equations:

$$s_{t+1}^{E} = s_t^{E} + i_{t+1}^{E} - r_{t+1}^{E} - t_{t+1}^{E} - e_t^{E} \cdot A_t^{E} \tag{1}$$

$$s_{t+1}^{B} = s_t^{B} + i_{t+1}^{B} + t_{t+1}^{E} - r_{t+1}^{B} - e_t^{B} \cdot A_t^{B} \tag{2}$$

where $s_t^{E,B}$ is the storage at the beginning of month t, $i_{t+1}^{E,B}$ is the inflow to the reservoir, t_{t+1}^{E} is the volume of water eventually transferred from Entrepeñas to Buendía through the connecting tunnel, $r_{t+1}^{E,B}$ is the volume of water released, and $e_t^{E,B} \cdot A_t^{E,B}$ is the water evaporated in the time interval [t, t + 1). In particular, $e_t^{E,B}$ is the mean monthly evaporation rate, while $A_t^{E,B}$ is the reservoir surface area uniquely defined by a nonlinear relation given the storage $s_t^{E,B}$. The actual release $r_{t+1}^{E,B}$ depends on the monthly release decision $u_t^{E,B}$ provided by the operating policy, which is forced within a certain operational zone by the maximum and minimum feasible release due to some physical (e.g., activation of the spillways) and normative (e.g. minimum environmental flow maintenance) limitations.

The volume transferred to the Segura river basin (QS_{t+1}) is then established by applying a water transfer rule dependent on the total storage of Entrepeñas and Buendía reservoirs and the inflow to the system in the previous 12 months i_t^{TOT12} (see Table 1 for details about the current rule, which will be adjusted by determining the optimal time-invariant volume v_{l2} to be transferred in level 2 as described in Section 3.1), subject to the environmental flow requirements (EF_t) in the Tagus river:

$$QS_{t+1} = watertransferrule(r_{t+1}^{B} + r_{t+1}^{E} - EF_t, S_t^{E}, S_t^{B}, i_t^{TOT12}, v_{l2}) \tag{3}$$

Consequently, the total volume flowing to the Tagus river (QT_{t+1}) will be equal to:

$$QT_{t+1} = r_{t+1}^{B} + r_{t+1}^{E} - QS_{t+1} \tag{4}$$

The four conflicting interests in the system are evaluated over a simulation time horizon H of 20 years (1998–2018) and are modelled using the following objectives formulations:

1. Tagus river deficit (J_{tag}) $[(m^3/s)^2]$: the monthly average squared deficit with respect to the monthly Tagus water demand W_t^{Tagus} (including urban, agricultural and environmental needs), to be minimized, defined as

$$J_{tag} = \frac{1}{H}\sum_{t=0}^{H-1}\left(\left(W_t^{Tagus} - QT_{t+1}\right)^{+}\right)^2 \tag{5}$$

The squared deficit aims to numerically favour several small deficits over a small number of large deficits (Hashimoto et al., 1982).

The plus sign in the equation means that only positive differences are counted as deficits. Accordingly, a release to the Tagus river higher than W_t^{Tagus} is allowed and not penalized not to impose restrictions on the discharge flowing in the donor river while still respecting the maximum release defined by the operational zone of Entrepeñas and Buendía reservoirs.

2. Aqueduct deficit (J_{aq}) [$(m^3/s)^2$]: the monthly squared average deficit with respect to the maximum monthly discharge that can be transferred to the Segura river basin $W_{\max}^{aq} = 60\ hm^3$, to be minimized, defined as:

$$J_{aq} = \frac{1}{H}\sum_{t=0}^{H-1}\left(\left(W_{\max}^{aq} - QS_{t+1}\right)^+\right)^2 \tag{6}$$

3. Storage deficit (J_{st}) [m^3]: the monthly average difference between the total storage of Entrepeñas and Buendía reservoirs (S_{t+1}^{tot}) and $S^{\lim} = 1000\ hm^3$, i.e. the volume that can ensure the development of tourism and recreational activities in the areas on the shores of the reservoirs (San-Martín et al., 2018), to be minimized, defined as

$$J_{st} = \frac{1}{H}\sum_{t=0}^{H-1}\left(S^{\lim} - S_{t+1}^{tot}\right)^+ \tag{7}$$

4. Hydropower production (J_{hyd}) [kWh/month]: the monthly average production at the Entrepeñas and Buendía hydropower plants (${HP_{t+1}}^{E,B}$), to be maximized, defined as

$$J_{hyd} = \frac{1}{H}\sum_{t=0}^{H-1}\left({HP_{t+1}}^{E} + {HP_{t+1}}^{B}\right) \tag{8}$$

where ${HP_{t+1}}^{E,B}$ is estimated from an abacus that relates the hydraulic jump, the turbined flow and the power retrieved from official design documents (Eptisa, 2000b, 2000a).

3. Methods and tools

The approach adopted in this study focuses on addressing two main issues of the debated implementation of the TSA water transfer rule (see Section 2.1): the best volume to be transferred in level 2, and the impact that the 2027 EF will produce on the system. The aim is to design an operating policy that could guarantee a workable compromise between the main stakeholders involved and be sufficiently robust in the near future scenario of reduced water resources availability.

The purpose of this work is not to estimate the water needs of the donor and receiving basins. Indeed, the domestic and irrigation water demand in the Tagus and Segura basins, as well as the non-transferable reserve in the headwaters, are assumed to be those specified in the 2021 water transfer rule. We keep the same 4-level scheme currently used, but we do not impose the Tagus water demand as the maximum possible release to the Tagus river. This avoids limiting the discharge flowing into the donor basin.

3.1. Evolutionary multi-objective direct policy search (EMODPS)

The framework adopted in this study foresees the generation of decision alternatives, i.e. candidate operating policies with associated alternative volume v_{l2} to be transferred at level 2, via multi-objective optimization. Specifically, according to Giuliani et al. (2021) the multi-objective optimization problem can be formulated as follows:

$$\pi^* = \underset{\pi}{\operatorname{argmin}} J_\pi \tag{9}$$

where $J_\pi = \left|J_{tag}, J_{aq}, J_{st}, -J_{hyd}\right|$ subject to Eqs. (1), (2).

The objective J_{hyd} is multiplied by -1 to ensure the correct direction of optimization. Finding $\pi^* = |p^*, {v_{l2}}^*|$ means finding both the optimal operating policy p^* and the optimal time-invariant volume ${v_{l2}}^*$ to be transferred in level 2 that minimize the four-dimensional objective function J_π. We solve this optimal control and planning problem using the evolutionary multi-objective direct policy search approach (EMODPS), that transforms the optimal control problem into a planning one by parameterizing the control policy p_ϑ within a predefined class of functions and exploring the parameter space through multi-objective evolutionary algorithms in order to identify a set of Pareto approximate policies (Giuliani et al., 2016). A solution is defined as Pareto-optimal if there is no other solution that presents a better value for one objective without worsening the performance in at least one other objective. Using the EMODPS approach, the above planning and control problem can be solved by jointly evolving solutions in a complex search space, formed by the parameters of the control policy and the volume v_{l2}, within a single optimization process (Bertoni et al., 2019; Giudici et al., 2019). Specifically, a random set of initial parameters is defined and used as input to run a system simulation over the time horizon H. Starting from the simulation outputs, the objective functions are computed and used by the optimization algorithm to update the parameter set. The new parameter set is then introduced into the simulation again and the process is repeated until the maximum number of function evaluations is reached (Giuliani et al., 2016; Macian-Sorribes and Pulido-Velazquez, 2020).

In this study, we parameterize the water reservoir operating policy by means of nonlinear approximating networks, using Gaussian radial basis functions (RBFs). The release decision u_t^k for the kth of K reservoirs at time t is therefore calculated as follows:

$$u_t^k = \sum_{i=1}^{N} w_i^k \varphi_i(I_t) \tag{10}$$

where N is the number of RBFs $\varphi_i(\cdot)$ and w_i^k is the weight of the *i-th* RBF. The weights are formulated such that they sum to one ($\sum_{i=1}^{N} w_i^k = 1$) and are nonnegative ($w_i^k \geq 0, \forall_{i,k}$). As for the single RBF, it is defined as follows:

$$\varphi_i(I_t) = \exp\left[-\sum_{j=1}^{M} \frac{\left[(I_t)_j - c_{i,j}\right]^2}{b_{i,j}^{\,2}}\right] \tag{11}$$

where M is the number of policy inputs I_t, c_i and b_i are the M-dimensional centre and radius vectors of the *i-th* RBF. The centres must lie within the input bounded space and the radii must be strictly positive (i.e., for normalized variables, $c_{i,j} \in [-1, 1]$ and $b_{i,j} \in (0, 1]$). As a result, the parameters vector employed for the parametrization of the operating policy is defined as $\vartheta = \left[c_{i,j}, b_{i,j}, w_i^k\right] \in R^{n_\vartheta}$ where $i = 1,\ldots,N$, $j = 1,\ldots,M$, $n_\vartheta = N(2M + K)$, and K= number of policy outputs. In this work, the input vector I_t includes the following four elements: the time t expressed as a combination of sine and cosine functions ($\sin(2\pi t)/365$ and $\cos(2\pi t)/365$) and the storage in the Entrepeñas and Buendía reservoirs (s_t^E *and* s_t^B). The number of policy outputs is 2, i.e. the release decisions for the two reservoirs. Considering N = 8, M= 4 and K= 2, the total number of parameters to be optimized is equal to 81 (i.e., 80 parameters of the control policy and 1 parameter representing the volume v_{l2} to be transferred in the level 2). This latter parameter can vary between 0 and 40 $hm^3/month$.

In order to explore the parameter space and discover optimal values, we employ multi-objective evolutionary algorithms (MOEAs). Specifically, we adopted the self-adaptive Borg MOEA algorithm (Hadka and Reed, 2013), since it is highly robust across a wide number of challenging multi-objective problems by meeting or exceeding the performance of other state-of-the-art MOEAs (R. Gupta et al., 2020; Zatarain Salazar et al., 2016).

The Borg MOEA is based on an epsilon dominance archiving, requiring the users to specify a numerical threshold on each optimization objective below which they are insensitive to changes in performance. In this study, we adopt epsilon-dominance values equal to 10 for J^{aq}, 2 for J^{tagus}, 7500 for J^{hydr} and 10,000,000 for $J^{storage}$. These epsilon values represent the significance of precision that is considered consequential in evaluating decision trade-offs. Each optimization was run for ten random seeds to improve solution diversity and avoid randomness dependence. In addition, each seed was run up to 500,000 function evaluations, which proved to be sufficient by visual inspection of search progress. The final set of Pareto approximate system configurations for each computational experiment was computed as the reference set of non-dominated solutions obtained across the ten optimization trials.

According to the most recent reviews (Dobson et al., 2019; Giuliani et al., 2021; Macian-Sorribes and Pulido-Velazquez, 2020), the use of EMODPS to design closed-loop operating policies presents substantial advantages over the methods traditionally adopted in the literature. Its ability to overcome the curses of dimensionality, modelling, and multiple objectives (Giuliani et al., 2016) allows handling systems with more than three reservoirs, widening the number and complexity of objectives and directly using exogenous information. This is particularly relevant in today's complex context, where the operational decision making should balance multi-sectoral human pressures and environmental degradation, and consider a wide range of hydroclimatic uncertainties arising by climate change (Giuliani et al., 2021).

3.2. Scenarios setting

We run the optimization on the 1998–2018 inflows and estimated evaporation rates. As water transfer parameters, we chose the ones established in the 2021 rule (see Table 1), except for the volume v_{l2} to be transferred in level 2, which is optimized by the model. We tested the optimization under two scenarios of EF implementation in the Tagus river. The baseline scenario (Sc0) considers the EF required by the 2015–2021 Tagus RBMP, while the second scenario (Sc1) considers the increased EF to be implemented by 2027. The EF is included in the Tagus water demand objective, which then varies across scenarios, as shown in Table 2.

Scenario Sc1, which implies an increased discharge flowing in the Tagus river, is expected to exacerbate tensions among stakeholders further. We thus explore whether increasing the degree of freedom of the current rule could allow exploring a more comprehensive range of solutions, raising the chance of finding a compromise policy. De Lucas (2019) and Larraz et al. (2020) found by trial-and-error tests that a rule without level 1 could significantly favour the storage objective: the high water volume that can be transferred in level 1 prevents the recovery of the reservoir's level and jeopardise the state of the system in the following months. Following this insight, we tested a modified version of the second scenario (Sc1_mod), where we set a high volume threshold for

Table 2
Tagus water demand ($hm^3/month$) in the different scenarios of environmental flow.

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Sc0	25	18	19	19	18	23	23	31	42	60	51	36
Sc1/ Sc1_mod	30	23	24	31	29	35	31	39	50	63	54	39

entering level 1 (2000 hm^3 instead of 1300 hm^3). This allows eliminating level 1 without modifying the framework of the water transfer rule, as prescribed by Law 21/2015. Moreover, the volume to be transferred in level 3 was also lowered to the minimum possible water supply, i.e. emergency irrigation and domestic water supply (de Lucas, 2019), in order to better balance the water transfer in the different levels.

The Pareto-optimal solutions are compared with the historical policy, estimated from historical time series of levels and releases. Since the historical water transfer rule underwent several modifications over the years (see Table 1 above), we also consider the performance of the policies obtained by applying the 2014 and the 2021 water transfer rule to the 1998–2018 inflow series (henceforth 2014 and 2021 policy). These rules simplify the system by assuming a unique conceptual reservoir, without specifying how volume and release are distributed between the two reservoirs. Consequently, it is impossible to distinguish between the single hydropower production in Entrepeñas and Buendía dams.

4. Results and discussion

4.1. Baseline scenario Sc0

Parallel plots are used to show the Pareto-optimal policies retrieved by solving the optimization problem defined in Eq. (9). The general structure of a parallel plot is shown in Fig. 2a: each polyline is a different policy, each parallel axis represents an optimization objective, and the crossing points identify the performance of a certain policy in the different objectives. For example, the policy represented by the grey line presents an aqueduct deficit equal to 400 $(m^3/s)^2$, while the Tagus deficit is 10 $(m^3/s)^2$. The axes are oriented so that the highest level of achievement of each objective is always at the bottom (i.e., minimum deficit for aqueduct, Tagus and storage and maximum hydropower production). This means that the green line represents the ideal solution, while the red line corresponds to the worst one. Conflicts are designated as diagonal lines between two adjacent axes, and the extent of the conflicts is proportional to their slope. For example, comparing the grey and the pink lines, a clear conflict between aqueduct and Tagus objectives emerges, while both policies show similar performance in storage and hydropower objectives.

The optimal solutions obtained in the baseline scenario are shown in Fig. 2b. All lines have been coloured according to their performance on the Tagus objective, with dark green representing a smaller deficit. Unsurprisingly, Tagus and aqueduct are the most conflicting objectives, as shown by the inversion of the colour gradients along the two respective axes in Fig. 2b. This conflict results because the total release from the headwaters dams at the diversion point is split between the Tagus and the Segura basins.

The performance of the Pareto-optimal policies is compared with the historical, 2014 and 2021 policies (red, yellow and light blue line in Fig. 2b). The historical system operation minimizes the Tagus deficit and simultaneously demonstrates good performance in aqueduct and hydropower objectives. This is coherent with the fulfilment of the Tagus water demand having the highest priority, followed by domestic and agricultural water needs of the Segura river basin, while the hydropower production has the lowest priority. At the same time, the historical policy generates high storage deficit, which is in line with the historical records of low water levels

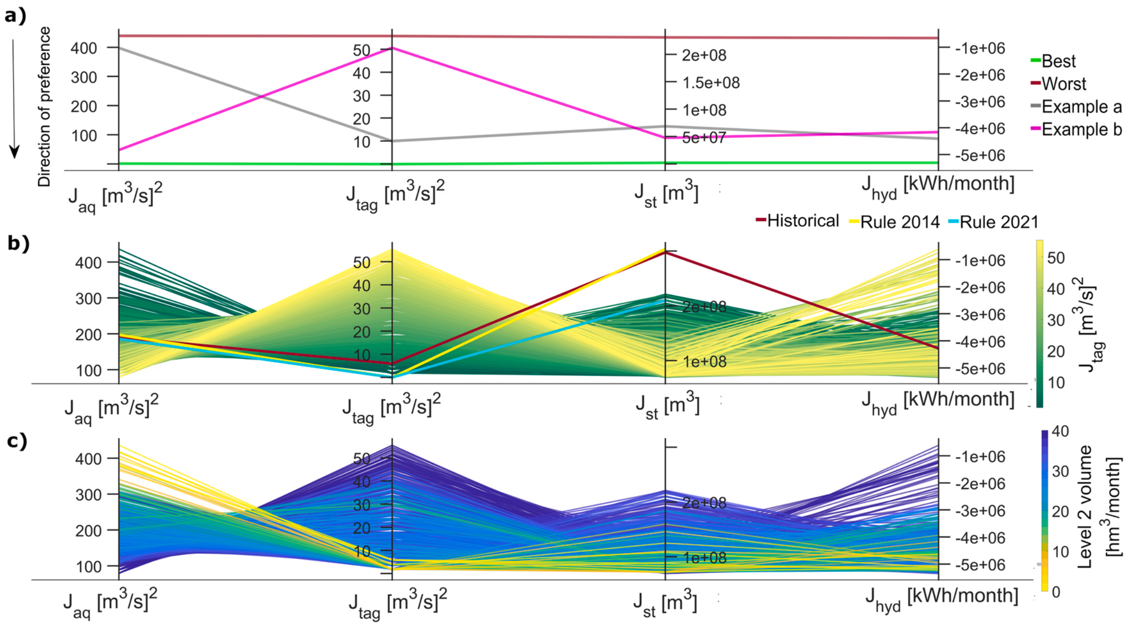

Fig. 2. (a) General structure of a parallel plot. (b) Pareto-optimal solutions obtained via multi-objective optimization and comparison with three different policies: historical policy (red line), the policy obtained by applying the 2014 water transfer rule (yellow line) and policy obtained by applying the 2021 water transfer rule (light blue line). (c) Pareto-optimal solutions are coloured according to the associated optimal volume to be transferred in level 2.

registered in Entrepeñas and Buendía reservoirs. The scant attention given to the recreational objective has been questioned since it contradicts the priority that should be given to the entire donor basin, not only to the river stretch downstream of the TSA diversion (San-Martín et al., 2018). The objective values obtained by applying the 2014 and the 2021 water transfer rule are similar to those derived from the implementation of the historical policy, except for the storage deficit, which presents a 38% reduction by applying the 2021 policy. All the optimized solutions strongly improve the storage objective compared to the historical and 2014 policies, with a deficit reduction ranging between 30% and 98%. The 2021 policy is outperformed by the optimized solutions in 99% of cases.

Each Pareto-optimal solution is associated with an optimal monthly volume v_{l2} to be transferred in the level 2, represented by the colour of the polylines in Fig. 2c, where maximum values are blue and minimum are yellow. Operating policies with high volume v_{l2} dominate the set of solutions, and a colour pattern can be identified: high values of v_{l2} (between 27 and 40 $hm^3/month$) are associated with low aqueduct deficit, while values lower than 27 $hm^3/month$ are limited to those policies that produce little Tagus and storage deficits.

Since by law the water use priority has to be ensured to the donor basin, we focused only on the subset of solutions that minimize the Tagus deficit (i.e., with performance equal to or better than the historical solution). Within this subset, two groups of solutions with a conflicting behaviour can be identified: a) the solutions that minimize the aqueduct deficit and b) the ones that minimize the storage deficit. The distribution of their performance in each objective is shown by two groups of box plots (A and B) in Fig. 3. A significant conflict between aqueduct and storage objective is detected. In the first group, by imposing a deficit in the aqueduct lower than the historical value, the minimum storage deficit is about $5 * 10^7 m^3$. In the second group, this value can be further minimized until a near-zero deficit, but a higher aqueduct deficit must be assumed. The scatter plots in Fig. 3 show the individual solutions coloured according to the associated optimal value of volume v_{l2}. In the first group, v_{l2} values lie in the range between 26.3 and 36.8 $hm^3/month$. These values are in line with the ones adopted in the 2014 and 2021 water transfer rules (i.e., 38 and 27$hm^3/month$). Lower values in this range enable a lower storage deficit: a volume v_{l2} equal to 26.3 $hm^3/month$ corresponds to the solution that maximizes the storage deficit reduction (−86%) in the first group. The second group of solutions generally presents low values of volume v_{l2}: 80% of optimized solutions present a volume to be transferred in level 2 lower than 30 $hm^3/month$.

Among the subset of solutions with minimum Tagus deficit (equal or lower than the historical value), we identified the best policy for each objective (see coloured lines in Fig. 4a). The relative trajectories of total reservoir's storage, water transfer and Tagus release in the hydrological years 2012–2014 are plotted in Fig. 4b as an example. Table 3 reports the volume v_{l2} associated to each best policy, as well as the mean annual water transfer and the percentage of times the total reservoir's level falls into level 1 or 2 in the studied period. Under the minimum Tagus deficit constraint, the aqueduct deficit could be further minimized with respect to the historical performance, but the improvement is limited by the strong conflict with the Tagus objective. Specifically, the aqueduct deficit can be reduced by 21% at most (blue line in Fig. 4a), leading to a mean annual water transfer of 359 hm^3, but implying a quite high cost for the storage objective (almost 26% of the time the total reservoir's level falls into level 3 or 4). A near-zero deficit for Tagus, storage and hydropower objectives can be achieved at the expense of the aqueduct objective, leading to a mean annual water transfer minor than 300 hm^3 (see green, pink and orange lines in Fig. 4a).

In order to select a possible compromise policy, we first identified the solutions that perform better than the historical policy in all the four objectives. Within this subset, we then selected the policy with the lowest Tagus and storage deficit, giving priority to the

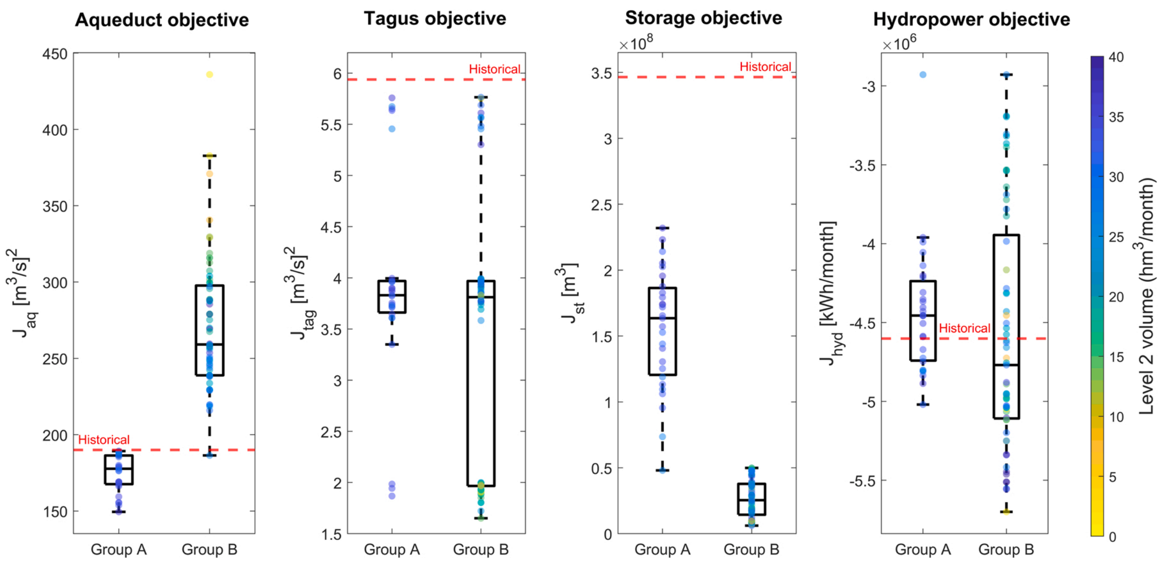

Fig. 3. Distribution of performance of group A (solutions with minimum Tagus and aqueduct deficit) and group B (solutions with minimum Tagus and storage deficit) in each objective. The scatter plots show the individual solutions coloured according to the associated optimal volume to be transferred in level 2.

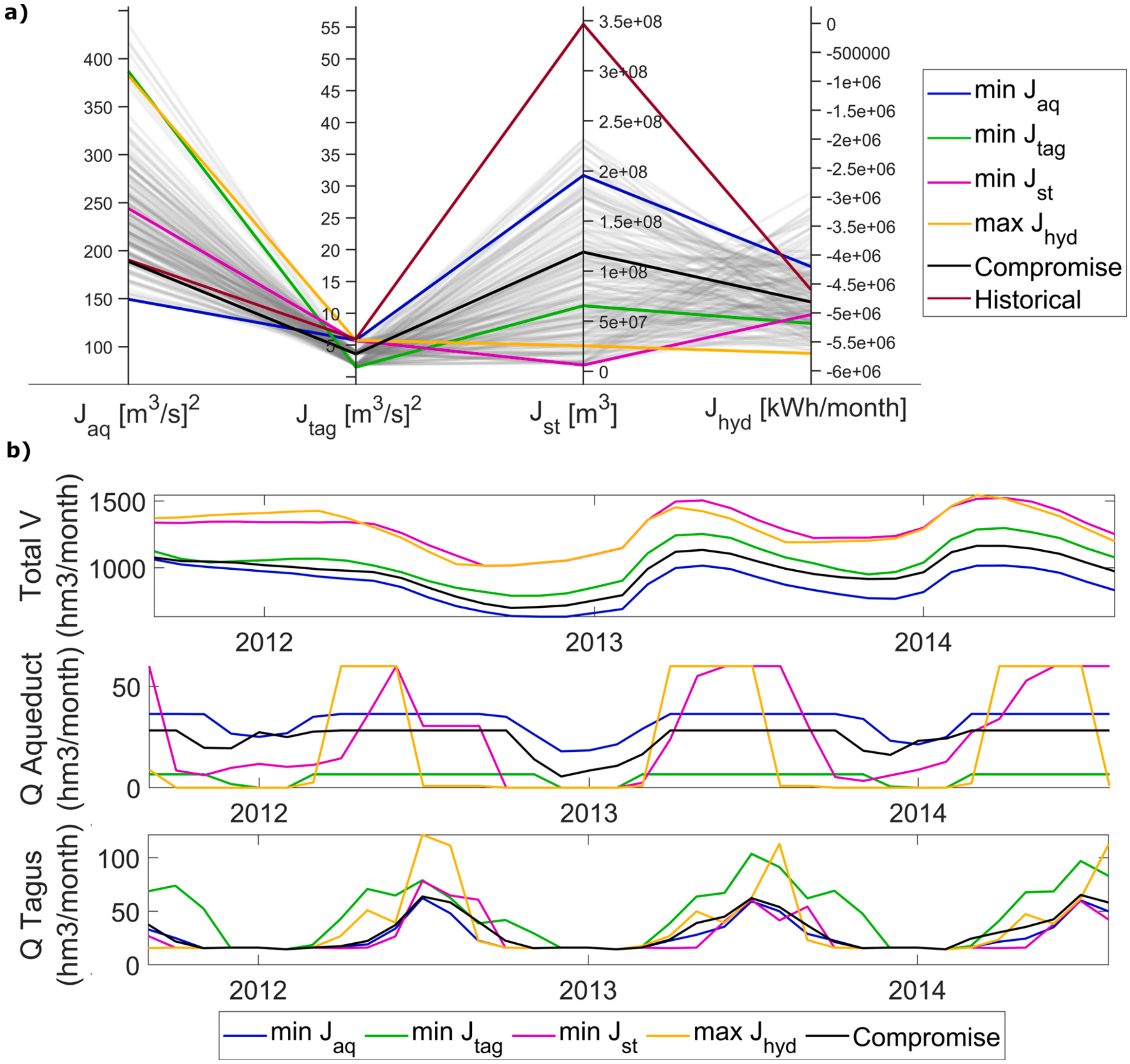

Fig. 4. (a) Policies that minimize each objective and the compromise policy within the subset of Pareto-optimal solutions with minimum Tagus deficit. (b) Trajectories of the total reservoir's storage, water transfer and Tagus release for the policies that minimize each objective and for the compromise solution in the hydrological years 2012–2014.

Table 3

For the optimal policies that minimize each objective and for the compromise policy, the table reports: the associated volume v_{l2} to be transferred in level 2, the mean annual water transfer and the percentage of times the total reservoir's level falls into level 1 or 2. The comparison with the historical policy is also shown.

Optimal policy	Volume v_{l2} (hm^3/month)	Mean annual transfer (hm^3/year)	Occurrence level 1 or 2 (%)
Historical	27/38	374.4	50.4
Min J_{aq}	36.4	359	74.16
Min J_{tag}	6.6	138.8	100
Min J_{st}	30.4	296.8	100
Max J_{hydr}	0.9	180.6	99.5
Compromise	28.2	311.3	93

donor basin. We thus ended up with the compromise policy represented by the black line in Fig. 4a. The same result would be obtained also by applying the technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon, 1981) to the subset of solutions exceeding the historical performance, with equal weights assigned to all the objectives. The performance of the compromise solution in terms of aqueduct, Tagus and hydropower deficit is slightly better than the historical solution, while the storage deficit is reduced by 66%. As shown in Table 3, the mean annual transfer is 311.2 hm^3 and the total reservoir's level falls into level 1 or 2 for the vast majority of the time (93%). The storage deficit varies throughout the year, with a better performance in winter and spring, as shown in Fig. S1. This solution is obtained with a volume v_{l2} to be transferred in level 2 equal to 28.2 $hm^3/month$. It is important to underline that other compromise operating policies could be chosen. The Pareto-optimal solutions shown in Fig. 4a are the starting point for a negotiation process among the stakeholders that will end up with a set of compromise alternatives to be submitted to the decision maker for the final political decision (see Castelletti and Soncini-Sessa, 2006 for details).

Even in cases where the values of the volume v_{l2} are close to the ones adopted in the 2014 and 2021 water transfer rule (i.e., 38 and 27 $hm^3/month$), the model is able to generate optimized policies with improved performance with respect to the 2014 and 2021 solutions, especially in terms of storage deficit. This is due to the fact that the optimized policies introduce a novelty with respect to the existing rule, generating water transfers that cyclically vary according to the hydrological period of the year. For example, if we compare the solution obtained by applying the 2021 water transfer rule with an optimized solution presenting the same volume v_{l2} (27 $hm^3/month$), the water transfer trajectories differ from each other (see Fig. S2). The 2021 water transfer rule only depends on storage levels. This means that whenever the total storage falls into level 1 or 2, the maximum monthly water volume allowed at that level is transferred. Conversely, in some cases where the storage level falls into level 1 or 2, the transfer volume prescribed by the optimized operating policy is lower than that allowed.

The re-operation of Entrepeñas and Buendía dams and the water transfer rule are jointly optimized. This implies that the modelled water transfer trajectory presents the same cyclostationary behaviour as the total release from the headwaters reservoirs, with storage accumulation in winter and higher release in summer to meet the downstream Tagus demand (see blue line in the second panel of Fig. S2). Coupling the 4-level water transfer rule with the cyclostationary time index allows for expanding the search for solutions and significantly improving the storage objective.

Other studies seem to support the idea of a water transfer operating rule that varies according to the period of the year. Different water transfer triggering mechanisms have been proposed to decide when to transfer a certain water volume from the donor to the recipient basin. Water transfer decisions can be determined by the water transfer rule curve based on the storage of the recipient reservoir (Xi et al., 2010), on storage of donor reservoir, or on storage of both (Guo et al., 2012; Zeng et al., 2014). In all cases, the water transfer rule curve presents a seasonal trend according to flood and dry periods. Zhu et al. (2014) proposed an optimised water transfer rule with diversion flows that vary at different periods of hydrological stage and reservoir water level zones. For the TSA system, Villarrubia (2018) demonstrated that an inter-annual water transfer rule that also considers inflows to the Segura basin would be able to store volume in wet years and meet the water demand in dry years.

4.2. Increased EF scenarios

We run the optimization under the scenario Sc1, which simulates the situation that will occur in 2027 with the implementation of the increased EF established in the 2021–2027 Tagus RBMP. The obtained Pareto-optimal policies are plotted in Fig. 5 (light blue polylines). As expected, the solutions are shifted towards a higher aqueduct deficit with respect to the baseline scenario, as there are no solutions with an aqueduct deficit lower than 119 $(m^3/s)^2$ (corresponding to a mean annual water transfer of 387.9 $hm^3/year$). The storage deficit also increases in a subset of solutions. The pattern of volume v_{l2} is similar to the one observed in the baseline, with low values leading to low Tagus and storage deficits (Fig. S3a, Supplementary material).

For the subset of solutions that presents a minimum deficit in the Tagus river, the aqueduct deficit is always higher than the historical one, and equal to 214 $(m^3/s)^2$ (corresponding to a mean annual water transfer of 275.5 $hm^3/year$) in the best case. This suggests that the current controversy between the donor and the receiving basin would be further exacerbated in the scenario Sc1. Moreover, the conflict between the aqueduct and storage objective is even more acute than the one observed in the baseline scenario. If we want to keep the aqueduct deficit as small as possible (e.g. lower than 250 $(m^3/s)^2$), the minimum storage deficit is about 10^8 m^3 (group A, Fig. 6a). This value can be further minimized only by generating a higher aqueduct deficit (group B, Fig. 6a). As shown by the

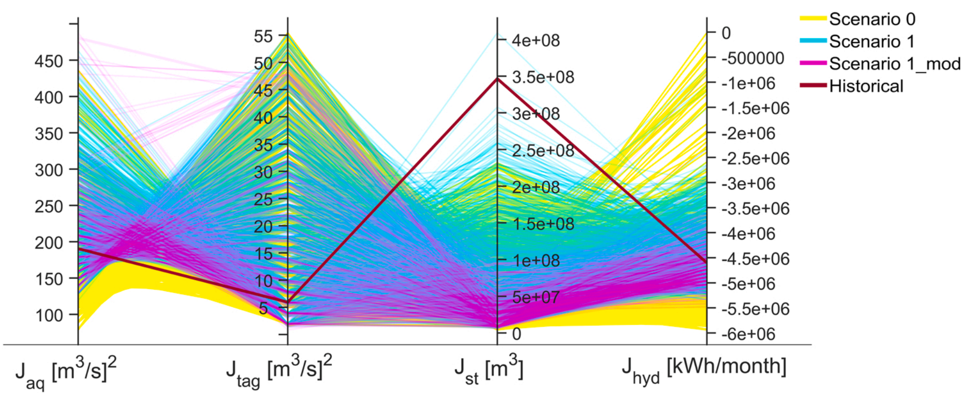

Fig. 5. Comparison of Pareto-optimal solutions obtained in each scenario.

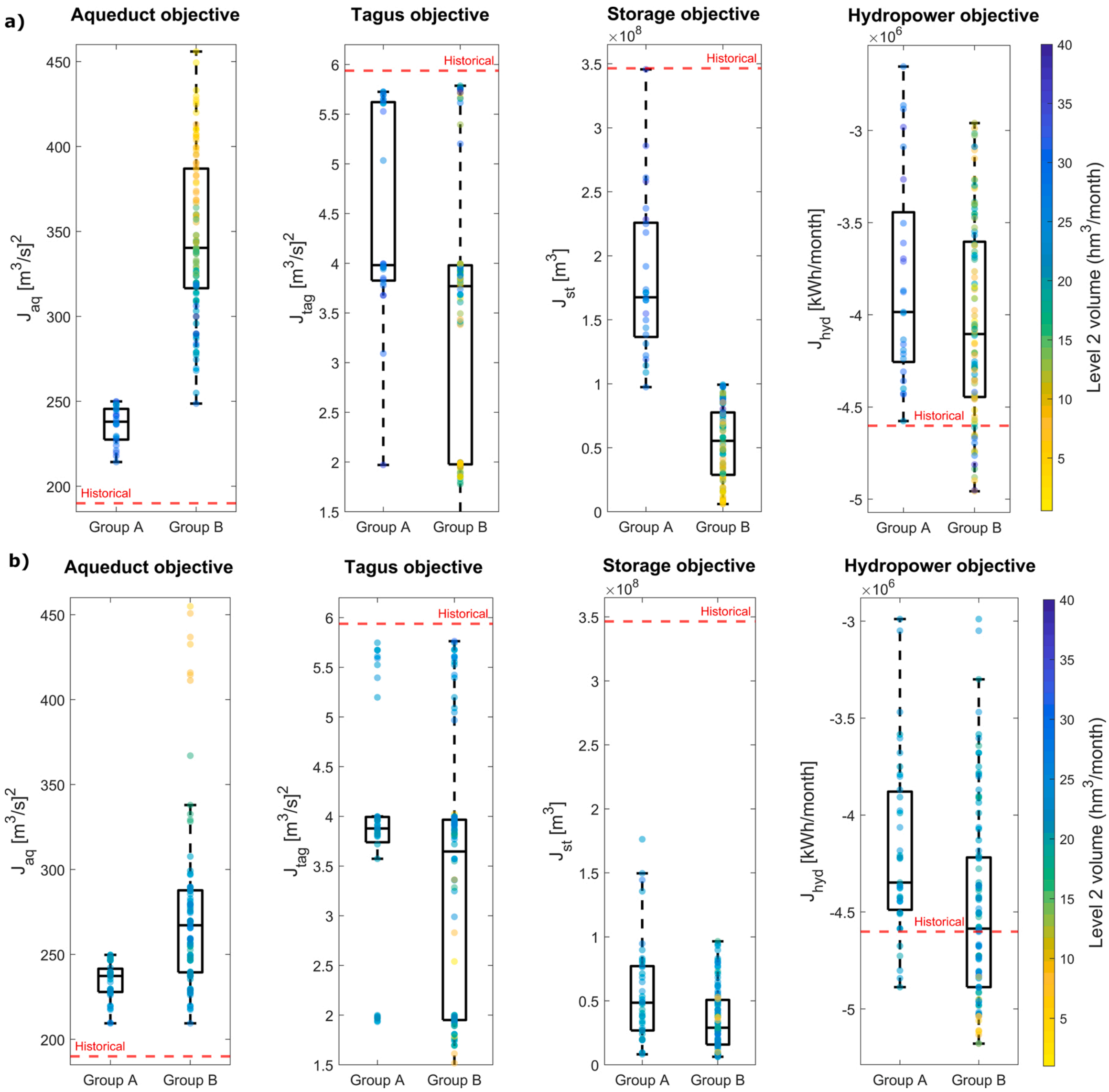

Fig. 6. Distribution of performance of group A (solutions with minimum Tagus and aqueduct deficit) and group B (solutions with minimum Tagus and storage deficit) in each objective for Sc1 (a) and for Sc1_mod (b). The scatter plots show the individual solutions coloured according to the associated optimal volume to be transferred in level 2.

scatter plots in Fig. 6a, this scenario reinforces the positive association between low values of volume v_{l2} and low storage deficit.

Climate change is expected to exacerbarte this situation, with a reduction in the transferred volume by more than 60% (Senent-Aparicio et al., 2021) or even up to 79% (Pellicer-Martínez and Martínez-Paz, 2018). Moreover, Sondermann and de Oliveira (2021) proved that the implementation of planned environmental flow requirements will decrease the ability of the system to satisfy the demands of the agriculture sector in the Tagus river. In such an alarming context, complementary strategies have to be considered in the Segura basin, such as desalinization and treated reused water (Morote et al., 2017), or new water markets options and insurance policies (Rey et al., 2016).

Unlike the baseline scenario, imposing a higher EF in the Tagus river limits the chance of finding an optimized solution with a good trade-off between the different objectives. We thus introduced the hypothesis that a rule with a higher degree of freedom (no level 1) could expand the solutions space and tested the optimization under the scenario Sc1_mod.

The number of solutions significantly decreases, thus suggesting that the model is able to find a smaller subset of optimized solutions. The pattern of values of volume v_{l2} is more marked and shifted to values equal or minor than 25 $hm^3/month$, as shown in Fig. S3b, Supplementary material.

The Pareto front between the aqueduct and Tagus deficit does not change across Sc1 and Sc1_mod, while the Pareto front between storage and Tagus objective is confined to the area of low storage deficit (see pink polylines in Fig. 5). This implies that, for the subset of solutions with a minimum Tagus deficit and under the same constraints considered above (i.e., an aqueduct deficit lower than 250 $(m^3/s)^2$), the model is now able to outperform Sc1 in the storage objective, generating policies with a storage deficit lower than 10^8 m^3 (group A, Fig. 6b). The values of v_{l2} associated with these solutions are mainly between 20 and 24 $hm^3/month$. Unlike the previous scenarios, the solutions that minimize Tagus, aqueduct and storage objectives do not belong to two different conflicting groups, but rather overlap (see groups A-B, Fig. 6b).

The removal of level 1 in the water transfer rule, together with low values of the volume to be transferred in level 2, leads to a significant improvement in the system performance in the scenario of increased EF and enables finding a good trade-off between aqueduct and storage objectives under the constraint of a minimum Tagus deficit. For example, the solution with the lowest increase in the aqueduct deficit compared to the historical policy (+10%) presents a strong storage deficit reduction (−73%).

5. Conclusions

This paper explores the potential of EMODPS to improve the historical management of the Tagus Segura aqueduct (TSA), a controversial interbasin water transfer in Spain. The re-operation of Entrepeñas and Buendía reservoirs and the existing water transfer policy (specifically the monthly volume to be transferred in level 2) are jointly optimized under two scenarios of environmental flow implementation in the Tagus river.

Among the wide range of Pareto-optimal solutions generated in the baseline scenario, we could identify a possible compromise policy which is able to perform as well as the historical solution in the objectives of water releases to the Tagus river, water transfers through the aqueduct and hydropower generation, while strongly improving the objective of ensuring a certain level of storage in the headwaters reservoirs for recreational uses. The associated optimized water transfer policy presents control parameters in line with the ones currently defined by law (the optimal volume to be transferred in level 2 turns out to be 28.2 hm^3/month), but introduces a novelty in the mechanism triggering the water transfer to the Segura basin. The transferred volume depends not only on the volume stored in the headwaters reservoirs and on the inflow to the system, but also on the hydrological stage of the year. The resulting cyclostationary behaviour of the water transfer allows for minimising the occurrence of situations with low storage level (level 3 and 4), benefiting the populations living on the shores of the reservoirs, and also ensuring more stability to the TSA functioning.

We also assessed the effect that the environmental flow to be implemented by 2027 in the Tagus river will have on the entire system. The results show that the current tensions between the donor and the receiving basin will be further exacerbated in this scenario. According to the model, the aqueduct deficit will increase by at least 10% with respect to the historical performance, thus suggesting that complementary strategies for meeting the water demand in the Segura basin have to be considered. Moreover, an increased conflict between the aqueduct and storage objective limits the chance of finding a compromise solution in this scenario. The elimination of level 1 in the water transfer rule would enable obtaining optimal solutions that keep the aqueduct deficit as small as possible and at the same time present good performance in the storage objective. Such solutions are associated with low volumes to be transferred in level 2 (mainly between 20 and 24 hm^3/month). Increasing the degree of freedom of the water transfer rule, coupled with a lower value of volume v_{l2}, seems then a promising approach to widen the solutions space and design a compromise policy also in this more complex scenario of increased EF.

The model proposed in this paper considers the main stakeholders involved in the TSA system and offers compromise solutions looking at the present and future of this infrastructure. The operating policies identified are in line with current legislation, since we set up the model in order to respect the criteria specified in Law 21/2015. The cyclostationary variation of the transferred volume in level 2 would be the novelty aspect of the rule.

The pressing need for recovering the good status of the freshwater ecosystems and the expected reduction in water resources availability in the near future make it necessary to design alternative and sustainable operating rules of water transfers, able to assuage tensions between recipient and donor regions and fulfil the environmental needs in the donor basin. By applying EMODPS to an emblematic case study, this paper confirms the potential of this method for managing trade-offs in water transfer operations.

CRediT authorship contribution statement

Carlotta Valerio: Conceptualization, Formal analysis, Visualization, Writing – original draft. **Matteo Giuliani:** Methodology, Supervision, Writing – review & editing. **Andrea Castelletti:** Methodology, Funding acquisition, Writing – review & editing. **Alberto Garrido:** Conceptualization, Funding acquisition, Writing – review & editing. **Lucia De Stefano:** Conceptualization, Supervision, Funding acquisition, Writing - review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Carlotta Valerio reports financial support was provided by Botín Foundation. Carlotta Valerio reports financial support was provided by Fundación Tatiana Pérez de Guzmán El Bueno. Carlotta Valerio reports financial support was provided by Complutense University of Madrid. Carlotta Valerio reports financial support was provided by Technical University of Madrid.

Data Availability

Data will be made available on request.

Acknowledgments

This study was supported by a research grant provided by the Botín Foundation and Fundación Tatiana Pérez de Guzmán El Bueno and by two projectes funded by School of Geological Sciences, Complutense University of Madrid and by the Research Centre for the Management of Agricultural and Environmental Risks (CEIGRAM), Technical University of Madrid. The authors thank the Tagus River Basin Authority (Confederación Hidrográfica del Tajo) for providing part of the data used in this study. They are also thankful to two anonymous reviewers for their thorough and constructive feedback.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2023.101339.

References

Aldaya, M.M., Custodio, E., Llamas, R., Fernández, M.F., García, J., Ródenas, M.Á., 2019. An academic analysis with recommendations for water management and planning at the basin scale: a review of water planning in the Segura River Basin. Sci. Total Environ. 662, 755–768. https://doi.org/10.1016/j.scitotenv.2019.01.266.

Allison, M.A., Meselhe, E.A., 2010. The use of large water and sediment diversions in the lower Mississippi River (Louisiana) for coastal restoration. J. Hydrol. 387 (3–4), 346–360. https://doi.org/10.1016/j.jhydrol.2010.04.001.

de Andrade, J.G.P., Barbosa, P.S.F., Souza, L.C.A., Makino, D.L., 2011. Interbasin water transfers: The Brazilian experience and international case comparisons. Water Resour. Manag. 25 (8), 1915–1934. https://doi.org/10.1007/s11269-011-9781-6.

Aparicio, E., Carmona-Catot, G., Kottelat, M., Perea, S., Doadrio, I., 2013. Identification of gobio populations in the northeastern iberian peninsula: first record of the non-native languedoc gudgeon gobio occitaniae (Teleostei, Cyprinidae). BioInvasions Rec. 2 (2), 163–166. https://doi.org/10.3391/bir.2013.2.2.13.

Baeza, D., 2021. Observaciones al borrador del plan hidrológico de la demarcación del Tajo en relación con el régimen de caudales ecológicos. Fundación Nueva Cultura del Agua.

Bertoni, F., Castelletti, A., Giuliani, M., Reed, P.M., 2019. Discovering dependencies, trade-offs, and robustness in joint dam design and operation: an ex-post assessment of the Kariba Dam. Earth's Future 7 (12), 1367–1390. https://doi.org/10.1029/2019EF001235.

Bolinches, A., De Stefano, L., Paredes-Arquiola, J., 2020. Designing river water quality policy interventions with scarce data: the case of the Middle Tagus Basin, Spain. Hydrol. Sci. J. 65 (5), 749–762. https://doi.org/10.1080/02626667.2019.1708915.

Cabezas, F., 2013. El sistema de cabecera del Tajo y el trasvase Tajo-Segura. Anejo técnico. Consulta pública del RD 773/2014. Madrid.

Castelletti, A., Soncini-Sessa, R., 2006. A procedural approach to strengthening integration and participation in water resource planning. Environ. Model. Softw. 21 (10), 1455–1470. https://doi.org/10.1016/j.envsoft.2005.07.013.

CEDEX, 2020. Nota técnica sobre la propuesta de actualización parcial de la regla de explotación del trasvase Tajo-Segura. Centro de estudios y experimentación de obras públicas.

CHS, 2015. Plan Hidrológico de la Cuenca del Segura 2015–2021. Confederación Hidrográfica del Segura.

de Lucas, A., 2019. Concepto, análisis histórico y determinación de excedentes de la cuenca del Tajo: aplicación al trasvase Tajo-Segura, PhD thesis. Universidad de Alcalá de Henares, Madrid.

Dobson, B., Wagener, T., Pianosi, F., 2019. An argument-driven classification and comparison of reservoir operation optimization methods. Adv. Water Resour. 128 (April), 74–86. https://doi.org/10.1016/j.advwatres.2019.04.012.

Dolan, F., Lamontagne, J., Link, R., Hejazi, M., Reed, P., Edmonds, J., 2021. Evaluating the economic impact of water scarcity in a changing world. Nat. Commun. 12 (1), 1–10. https://doi.org/10.1038/s41467-021-22194-0.

Duan, K., Caldwell, P.V., Sun, G., McNulty, S.G., Qin, Y., Chen, X., Liu, N., 2022. Climate change challenges efficiency of inter-basin water transfers in alleviating water stress. Environ. Res. Lett. 17 (4), 044050 https://doi.org/10.1088/1748-9326/ac5e68.

Eptisa, 2000a. Documento XYZT de la presa de Buendía.

Eptisa, 2000b. Documento XYZT de la presa de Entrepeñas.

Giudici, F., Castelletti, A., Garofalo, E., Giuliani, M., Maier, H.R., 2019. Dynamic, multi-objective optimal design and operation of water-energy systems for small, off-grid islands. Appl. Energy 250 (May), 605–616. https://doi.org/10.1016/j.apenergy.2019.05.084.

Giuliani, M., Castelletti, A., Pianosi, F., Mason, E., Reed, P., 2016. Curses, tradeoffs, and scalable management: advancing evolutionary multiobjective direct policy search to improve water reservoir operations. J. Water Resour. Plan. Manag. 142 (2), 04015050, 10.1061/(ASCE)WR.19435452.0000570.

Giuliani, M., Quinn, J.D., Herman, J.D., Castelletti, A., Reed, P.M., 2018. Scalable multiobjective control for large-scale water resources systems under uncertainty. IEEE Trans. Control Syst. Technol. 26 (4), 1492–1499. https://doi.org/10.1109/TCST.2017.2705162.

Giuliani, M., Lamontagne, J.R., Reed, P.M., Castelletti, A., 2021. A state-of-the-art review of optimal reservoir control for managing conflicting demands in a changing world. Water Resour. Res. 57 (12) https://doi.org/10.1029/2021WR029927.

Grant, E.H.C., Lynch, H.J., Muneepeerakul, R., Arunachalam, M., Rodríguez-Iturbe, I., Fagan, W.F., 2012. Interbasin water transfer, riverine connectivity, and spatial controls on fish biodiversity. PLoS One 7 (3). https://doi.org/10.1371/journal.pone.0034170.

Gu, W., Shao, D., Tan, X., Shu, C., Wu, Z., 2017. Simulation and optimization of multi-reservoir operation in inter-basin water transfer system. Water Resour. Manag. 31 (11), 3401–3412. https://doi.org/10.1007/s11269-017-1675-9.

Guo, X., Hu, T., Zhang, T., Lv, Y., 2012. Bilevel model for multi-reservoir operating policy in inter-basin water transfer-supply project. J. Hydrol. 424–425, 252–263. https://doi.org/10.1016/j.jhydrol.2012.01.006.

Gupta, J., van der Zaag, P., 2008. Interbasin water transfers and integrated water resources management: Where engineering, science and politics interlock. Phys. Chem. Earth 33 (1–2), 28–40. https://doi.org/10.1016/j.pce.2007.04.003.

Gupta, R.S., Hamilton, A.L., Reed, P.M., Characklis, G.W., 2020. Can modern multi-objective evolutionary algorithms discover high-dimensional financial risk portfolio tradeoffs for snow-dominated water-energy systems? Adv. Water Resour. 145 (August) https://doi.org/10.1016/j.advwatres.2020.103718.

Hadka, D., Reed, P.M., 2013. Borg: an auto-adaptive many-objective evolutionary computing framework (http://www.mitpressjournals.org/doi/abs/). Evolut. Comput. 2004. https://doi.org/10.1162/EVCO_a_00075.

Hashimoto, T., Stedinger, J.R., Loucks, D.P., 1982. Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. Water Resour. Res. 18 (1), 14–20. https://doi.org/10.1029/WR018i001p00014.

Heinz, I., Pulido-Velazquez, M., Lund, J.R., Andreu, J., 2007. Hydro-economic modeling in river basin management: implications and applications for the European water framework directive. Water Resour. Manag. 21 (7), 1103–1125. https://doi.org/10.1007/s11269-006-9101-8.

Hernández-Mora, N., del Moral, L., 2015. Developing markets for water reallocation: revisiting the experience of Spanish water mercantilización. Geoforum 62, 143–155. https://doi.org/10.1016/j.geoforum.2015.04.011.

Hernández-Mora, N., Del Moral Ituarte, L., La-Roca, F., La Calle, A., Schmidt, G., 2014. Interbasin water transfers in Spain: interregional conflicts and governance responses. Glob. Water.: A Quest. Gov. 9789400773 (October), 175–194. https://doi.org/10.1007/978-94-007-7323-3_13.

Hwang, C.L., Yoon, K., 1981. Multiple attribute decision making. In: Lecture Notes in Economics and Mathematical Systems, Vol. 186. Springer-Verlag.

Larraz, B., Ciencias, F. De, Martín, E.S., Ciencias, F. De, Baeza, D., Ciencias, F. De, Sánchez, M.Á., Amreeb, T. (2020). Propuesta AMREEB de mejora de las reglas de explotación del trasvase tajo-Segura. Universidad de Castilla La Mancha.

Lobanova, A., Liersch, S., Tàbara, J.D., Koch, H., Hattermann, F.F., Krysanova, V., 2017. Harmonizing human-hydrological system under climate change: a scenario-based approach for the case of the headwaters of the Tagus River. J. Hydrol. 548, 436–447. https://doi.org/10.1016/j.jhydrol.2017.03.015.

Ma, Y., Chang, J., Guo, A., Wu, L., Yang, J., Chen, L., 2020. Optimizing Inter-basin water transfers from multiple sources among interconnected River basins. J. Hydrol. 590 (June), 125461 https://doi.org/10.1016/j.jhydrol.2020.125461.

Macian-Sorribes, H., Pulido-Velazquez, M., 2020. Inferring efficient operating rules in multireservoir water resource systems: a review. WIREs Water 7 (1), 1–24. https://doi.org/10.1002/wat2.1400.

Maier, H.R., Kapelan, Z., Kasprzyk, J., Kollat, J., Matott, L.S., Cunha, M.C., Dandy, G.C., Gibbs, M.S., Keedwell, E., Marchi, A., Ostfeld, A., Savic, D., Solomatine, D.P., Vrugt, J.A., Zecchin, A.C., Minsker, B.S., Barbour, E.J., Kuczera, G., Pasha, F., Reed, P.M., 2014. Evolutionary algorithms and other metaheuristics in water resources: current status, research challenges and future directions. Environ. Model. Softw. 62, 271–299. https://doi.org/10.1016/j.envsoft.2014.09.013.

Martin-Gorriz, B., Martínez-Alvarez, V., Maestre-Valero, J.F., Gallego-Elvira, B., 2021. Influence of the water source on the carbon footprint of irrigated agriculture: a regional study in South-Eastern Spain. Agronomy 11 (2). https://doi.org/10.3390/agronomy11020351.

Melgarejo-Moreno, J., López-Ortiz, M.I., Fernández-Aracil, P., 2019. Water distribution management in South-East Spain: a guaranteed system in a context of scarce resources. Sci. Total Environ. 648, 1384–1393. https://doi.org/10.1016/j.scitotenv.2018.08.263.

Ming, B., Liu, P., Chang, J., Wang, Y., Huang, Q., 2017. Deriving operating rules of pumped water storage using multiobjective optimization: case study of the Han to Wei Interbasin Water Transfer Project, China. J. Water Resour. Plan. Manag. 143 (10), 05017012, 10.1061/(asce)wr.1943-5452.0000828.

Molina, A., 2019. Los caudales ecológicos en la planificación hidrológica. Reflexiones a la luz de la Sentencia del Tribunal Supremo 309/2019 de 11 de marzo, relativa al plan hidrológico del Tajo y sus posibles impactos en el Trasvase Tajo-Segura. Sostenibilidad: Económica, Soc. Y. Ambient. 1, 13–30. https://doi.org/10.14198/sostenibilidad2019.1.02.

Morote, A.F., Hernández, M., Rico, A.M., Eslamian, S., 2020. Inter-basin water transfer conflicts. The case of the Tagus-Segura Aqueduct (Spain). Int. J. Hydrol. Sci. Technol. 10 (4), 364–391. https://doi.org/10.1504/IJHST.2020.108267.

Morote, Á.-F., Olcina, J., Rico, A.M., 2017. Challenges and proposals for socio-ecological sustainability of the Tagus-Segura Aqueduct (Spain) under climate change. Sustainable 9 (11). https://doi.org/10.3390/su9112058.

Pellicer-Martínez, F., Martínez-Paz, J.M., 2018. Climate change effects on the hydrology of the headwaters of the Tagus River: implications for the management of the Tagus-Segura transfer. Hydrol. Earth Syst. Sci. 22 (12), 6473–6491. https://doi.org/10.5194/hess-22-6473-2018.

Rasmussen, J. , 2002. The Cal-Sag and Chicago Sanitary and Ship Canal: a perspective on the spread and control of selected aquatic nuisance fish species. US Fish and Wildlife Service, Region, 1–26. http://www.micrarivers.org/wp-content/uploads/2018/04/ConnectingChannelsPaperFinal.pdf.

Ren, K., Huang, S., Huang, Q., Wang, H., Leng, G., Wu, Y., 2019. Defining the robust operating rule for multi-purpose water reservoirs under deep uncertainties. J. Hydrol. 578 (July), 124134 https://doi.org/10.1016/j.jhydrol.2019.124134.

Rey, D., Garrido, A., Calatrava, J., 2016. An innovative option contract for allocating water in inter-basin transfers: the case of the Tagus-Segura Transfer in Spain. Water Resour. Manag. 30 (3), 1165–1182. https://doi.org/10.1007/s11269-015-1219-0.

Rupérez-Moreno, C., Senent-Aparicio, J., Martinez-Vicente, D., García-Aróstegui, J.L., Calvo-Rubio, F.C., Pérez-Sánchez, J., 2017. Sustainability of irrigated agriculture with overexploited aquifers: the case of Segura basin (SE, Spain). Agric. Water Manag. 182, 67–76. https://doi.org/10.1016/j.agwat.2016.12.008.

Sahouri, N.F., 2014. Transboundary Water Management under Climate Change-The Tagus River Basin, Master thesis. Universidad Politécnica de Madrid.

San-Martín, E., Larraz-Iribas, B., Hernandez-Mora, N., 2018. *Estudio de los impactos socioeconómicos del Trasvase Tajo-Segura sobre los municipios ribereños de los embalses de Entrepeñas y Buendía*. Universidad de Castilla La Mancha.

San-Martín, E., Larraz, B., Gallego, M.S., 2020. When the river does not naturally flow: a case study of unsustainable management in the Tagus River (Spain). Water Int. 45 (3), 189–221. https://doi.org/10.1080/02508060.2020.1753395.

SCRATS, 2020. The economic impact of the Tajo-Segura aqueduct on Alicante *, Almería and Murcia* . Sindicato Central de Regantes del Acueducto Tajo-Segura.

Senent-Aparicio, J., López-Ballesteros, A., Cabezas, F., Pérez-Sánchez, J., Molina-Navarro, E., 2021. A modelling approach to forecast the effect of climate change on the Tagus-Segura interbasin water transfer. Water Resour. Manag. 35 (11), 3791–3808. https://doi.org/10.1007/s11269-021-02919-y.

Shumilova, O., Tockner, K., Thieme, M., Koska, A., Zarfl, C., 2018. Global water transfer megaprojects: a potential solution for the water-food-energy nexus? Front. Environ. Sci. 6 (DEC), 1–11. https://doi.org/10.3389/fenvs.2018.00150.

Sondermann, M.N., de Oliveira, R.P., 2021. A shared vision on the transboundary water management challenges of the Tagus River Basin. Water Resour. Manag. 35 (13), 4647–4664. https://doi.org/10.1007/s11269-021-02973-6.

Veena, S., Singh, R., Gold, D., Reed, P., Bhave, A., 2021. Improving information-based coordinated operations in interbasin water transfer megaprojects: case study in Southern India. J. Water Resour. Plan. Manag. 147 (11), 04021075, 10.1061/(asce)wr.1943-5452.0001456.

Villarrubia, F.P., 2018. Diseño de una nueva regla de explotación hiperanual para los embalses de cabecera del Tajo, Master thesis. Universidad de Zaragoza, Escuela Politécnica Superior (Huesca).

WWAP, 2020. The United Nations World Water Development Report 2020: Water and climate change. UNESCO Publishing, Paris.

WWF, 2009. Interbasin water transfers and water scarcity in a changing world - a solution or a pipedream? WWF Germany.

Xi, S., Wang, B., Liang, G., Li, X., Lou, L., 2010. Inter-basin water transfer-supply model and risk analysis with consideration of rainfall forecast information. Sci. China Technol. Sci. 53 (12), 3316–3323. https://doi.org/10.1007/s11431-010-4170-6.

Zatarain Salazar, J., Reed, P.M., Herman, J.D., Giuliani, M., Castelletti, A., 2016. A diagnostic assessment of evolutionary algorithms for multi-objective surface water reservoir control. Adv. Water Resour. 92, 172–185. https://doi.org/10.1016/j.advwatres.2016.04.006.

Zeng, X., Hu, T., Guo, X., Li, X., 2014. Water transfer triggering mechanism for multi-reservoir operation in Inter-Basin water transfer-supply project. Water Resour. Manag. 28 (5), 1293–1308. https://doi.org/10.1007/s11269-014-0541-2.

Zhang, L., Li, S., Loáiciga, H.A., Zhuang, Y., Du, Y., 2015. Opportunities and challenges of interbasin water transfers: a literature review with bibliometric analysis. Scientometrics 105 (1), 279–294. https://doi.org/10.1007/s11192-015-1656-9.

Zhu, X., Zhang, C., Yin, J., Zhou, H., Jiang, Y., 2014. Optimization of water diversion based on reservoir operating rules: analysis of the Biliu River Reservoir, China. J. Hydrol. Eng. 19 (2), 411–421. https://doi.org/10.1061/(asce)he.1943-5584.0000805.

Zhuang, W., 2016. Eco-environmental impact of inter-basin water transfer projects: a review. Environ. Sci. Pollut. Res. 23 (13), 12867–12879. https://doi.org/10.1007/s11356-016-6854-3.