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A Generalized Dynamic Programming Modelling Approach for Integrated Reservoir Operation

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Abstract
In water resource systems, the demands at each reservoir are generally known. However, in the integrated operation of a system involving inter-basin water transfers, the import/export of water among various reservoirs also plays an important role in the sustainable and optimal management of available water. Generally, a trial and error approach is adopted to simulate a system for integrated operation. Prior information on water resettlements among reservoirs would be helpful for facilitating the integrated management of these systems. In the present study, a generalized inventory-based dynamic programming model is developed to evaluate the water transfers between reservoirs in the Alqueva subsystem. The model offers guidelines on water transfers among reservoirs and estimates the overall amount of water to be pumped from the Alqueva reservoir to subsidize the shortfalls in the Alqueva subsystem. The proposed methodology may be adapted to other complex systems to promote integrated operations, and the model may be useful for design and operational purposes.

Keywords Dynamic Programming · Hydrological modeling · Irrigation · Water transfer

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1 Introduction

During water transfer projects, inter-basin water transfers are performed to transfer water from a basin with abundant water resources to basins with shortages, thereby adjusting the water quantity between basins and meeting the water demand of water-deficient areas. Reservoir systems play an important role in storing and importing or exporting water within these projects. A number of inter-basin water transfer schemes have been developed worldwide; however, few studies have focused on the transferral of water among reservoirs in such projects (Guo et al. 2012). In the inter-basin water transfer schemes, reservoirs are operated in an integrated manner in which a deficit at a given reservoir is met by the exporting (upstream) reservoir, which releases water via a river or transfers water via a channel, tunnel or a pipe. In certain situations, water is pumped back from a downstream reservoir to an upstream reservoir to meet deficits. In general, optimization or simulation models are used for the integrated operation of reservoirs (Labadie 2004; Rani and Moreira 2010).

The difference in the total flow and demand is calculated via simulation approaches. This information is then used as an additional demand of the structure from which this deficit can be met, and then a trial and error approach is used. Estimating water transfer between reservoirs using this method may ignore some important factors, such as losses through evaporation and transport and the total water availability at a given time period. These factors should also be taken into account when determining the amount of water import.

For reservoir operation problems, dynamic programming (DP) has been considered a suitable optimization technique since such problem can be easily fitted into a DP framework. DP can provide an optimal global solution for an initial estimate, making it useful if combined with other optimization techniques or simulations (Rani and Moreira 2010). Even if it is not ideal due to computational requirements, DP can guide the determination of the best solution. Many examples are available in the literature on the use of DP for single- and multiple-reservoir operations (Feng et al. 2017; Giles and Wunderlich 1981; Hall et al. 1969; Yi et al. 2003; Yurtal et al. 2005; Zhao et al. 2017).

The idea of developing water transfer policies among reservoirs was introduced by Rani et al. (2005), although few studies have focused on the development of these policies. Zeng et al. (2014) mentioned that water transfer and water supply problems are correlated; therefore, water transfer rule curves and water supply rules should be considered together in inter-basin water transfer projects. The authors used storage-based water transfer rule curves for integrated reservoir operation using an optimization approach. A set of operating rules that consider both water transfer and water supply in an inter-basin water transfer-supply system for guiding the number of multi-reservoir systems was also developed (Guo et al. 2012; Wang et al. 2015; Peng et al. 2015). Gu et al. (2017) proposed a new set of operation curves among reservoirs in a system with multiple exporting reservoirs and a single importing reservoir. In most of the papers cited above, water transfer targets, which are generally established at the planning stage, were used in the development of the water transfer policies. Rani et al. (2016) used a set of linked optimization models to plan the water transfers of an inter-basin water transfer link project using an inventory-based DP model to evaluate the water transfers between reservoirs. That approach is extended in the present paper for estimating water transfers between the reservoirs in the Alqueva subsystem, which is the main component of the Multipurpose Alqueva Project (MAP) in Portugal. The model developed in this study is generalized and innovative in the sense that it can be applied to any complex system involving multiple exporting reservoirs.

The MAP is a structural project in southern Portugal, designed for the social and economic development of the Alentejo region. The Alqueva dam is the restorative feature of the project, and it guarantees a future source of water for the region. The Alentejo region is a drought-prone area of the country that has experienced a shortage of water in the past and is likely to suffer droughts in the future as per climate change projections (Boken et al. 2005; Mourato et al. 2015; Rani et al. 2008). The MAP aims to utilize the water from the Guadiana basin to meet the deficits of the Alentejo region through storage at the Alqueva project. There are three independent hydraulic subsystems within the MAP, namely, the Alqueva, Pedrógão, and Ardila subsystems. The Alqueva reservoir pumps water to the Alqueva subsystem, where it undergoes inter-basin water transfer from the Guadiana to the Sado basin.

At this stage, information about the crops grown in the region can be based on the planned project design, although the actual scenario may be different from the planned one. In addition, for newly developed storage projects, observed historical data may not be available and may need to be estimated for planning purposes. Therefore, the allocation of acreages to particular crops and their corresponding water requirements may also be unknown and need to be estimated before developing the operating policies for these projects. The choice of crops depends on meeting the food requirements of the region and optimizing the economic return from production; thus, the proper management of irrigation areas must include an optimal allocation of land and water resources. Researchers have used conventional and non-conventional optimization techniques in irrigation planning and management models (Fallah-Mehdipour et al. 2012; Mohammad 2017; Pant et al. 2010; Raju and Kumar 2004; Zhou et al. 2007). Linear programming (LP) is capable of handling a large number of constraints and variables; therefore, it has been used as a convenient tool in crop planning (Paudyal and Gupta 1990; Sethi et al. 2006; Singh et al. 2001). The LP-based approach has been used for the projection of irrigation water requirements considering water availability and crop area allocations as decision variables in the crop planning model of Rani et al. (2016). Recently, Khandelwal and Dhiman (2018) formulated deterministic LP and chance-constrained LP models to maximize net returns from a canal command area while simultaneously mitigating waterlogging conditions. At the planning stage of a project, the land occupied by the crops, the amount of water available for irrigation, and/or the irrigation requirement for the cropped areas may change up to the exploration stage. In such cases, the projection of water requirements/availability for an optimal crop plan may be achieved with the help of a crop planning model.

Physically based hydrological models allow for a better representation of watershed hydrological processes (Abbott et al. 1986; Bathurst and O'connell 1992). Their grid-to-grid flow routing structure and kinematic representations of lateral soil drainage, surface, and subsurface runoff and channel flow make them naturally suited for area-wide hydrological forecasting of flows from an ungauged location. In terms of strategic and operational planning, the use of such models provides major advantages to those responsible for the management of water resources in large river basins, as well as to those responsible for local planning and management. These advantages are particularly significant in terms of the ability to assess the spatial variability of water resources with a smaller spatial resolution than that provided by the recorded data, and the ability to verify the effects of changes in land use and climate over larger geographical areas. SHETRAN has been applied for a range of hydrological features (Ewen and Parkin's 1996; Ewen et al. 2000; Zhang et al. 2019), and the results provide an encouraging demonstration of SHETRAN's fitness for the predictive modeling of hypothetical future basins. Mourato et al. (2015) also undertook a multi-basin, multi-location and multi-response calibration approach using the SHETRAN model.

Considering the stage of the Alqueva subsystem, it was essential to have updated information about the irrigation requirement for the developing irrigation areas, information of inflows at all the reservoirs and water transferral among reservoirs, for integrated operation of the system. Therefore, in this paper, hydrological modelling was combined with an optimization approach for the integrated management of the multi-reservoir system, with the CROPWAT model used to determine the crop water demands, the LP model used for the optimal allocation of crop areas and corresponding monthly irrigation water requirement projections, the SHETRAN model used to evaluate the runoff contribution to the reservoirs, and a generalized DP-based water import model used to estimate the water import/export flow information among reservoirs. The proposed methodology that integrates hydrological modeling and optimization was designed to improve system manager decision-making about water transfers between reservoirs in a multi-reservoir system and subsequent inter-basin water transfers between river basins. The approach may contribute to strategic planning for agricultural practices in a year.

2 Description of the Study Area

2.1 Multipurpose Alqueva Project

The MAP was designed to enhance the social and economic development of the Alentejo region in Portugal. For this, an approximately 120,000 ha agriculture area was planned for development, in which MAP will be the primary water source for irrigation. In addition to providing hydropower, flood control, tourism, and fishing activities, the MAP will also deliver water to municipal and industrial users. To meet the region's demands, the Guadiana River basin transfers water to the Sado River basin via storage at the Alqueva and Pedrógão reservoirs. There are three independent hydraulic subsystems of the MAP: Alqueva (62,595 ha), Pedrógão (21,860 ha), and Ardila (30,125 ha).

The Alqueva subsystem (Fig. 1) begins at the Alqueva dam and benefits approximately 10,000 ha of land in the Guadiana River basin, and 52,000 ha in the Sado River basin. It consists of 11 reservoirs (Alqueva, Álamos, Loureiro, Monte Novo, Alvito, Odivelas, Vale de Gaio, Pisão, Cinco Reis, Penedrão and Roxo), several kilometers of linking channels/tunnels/pipes, 2 power generating plants, and 1 pumping station. The system begins at the Alqueva reservoir, where the Álamos station (42 MW) pumps water to the Álamos reservoir. The water from the Álamos reservoir is delivered to the Loureiro reservoir.

The Loureiro reservoir has two diversions; the Loureiro-Monte Novo channel, which links the Monte Novo reservoir, and the Loureiro-Alvito tunnel, which transfers water to the Alvito reservoir. The Loureiro-Monte Novo channel will irrigate 7824 ha of Monte Novo. Originating from the Alvito dam, the Alvito-Pisão channel arrives near the Pisão dam permits a gravity-fed water supply to all the blocks between Cuba and Pisão (10,000 ha). From Pisão, the channel continues to the Roxo dam. One branch of the channel originates from the Alvito-Pisão channel, i.e., the Odivelas-Vale de Gaio channel, and feeds the Vale de Gaio reservoir through gravity. It transfers water to Odivelas and Vale de Gaio reservoirs to irrigate the Odivelas and Vale de Gaio blocks. Water for irrigation to infrastructure 12 (6845 ha) is supplied from the Odivelas reservoir. At the time of this study, the Cinco-Reis, Pisão, Penedrão, and Roxo dams, and their corresponding irrigation areas and links were in the preliminary study phase.

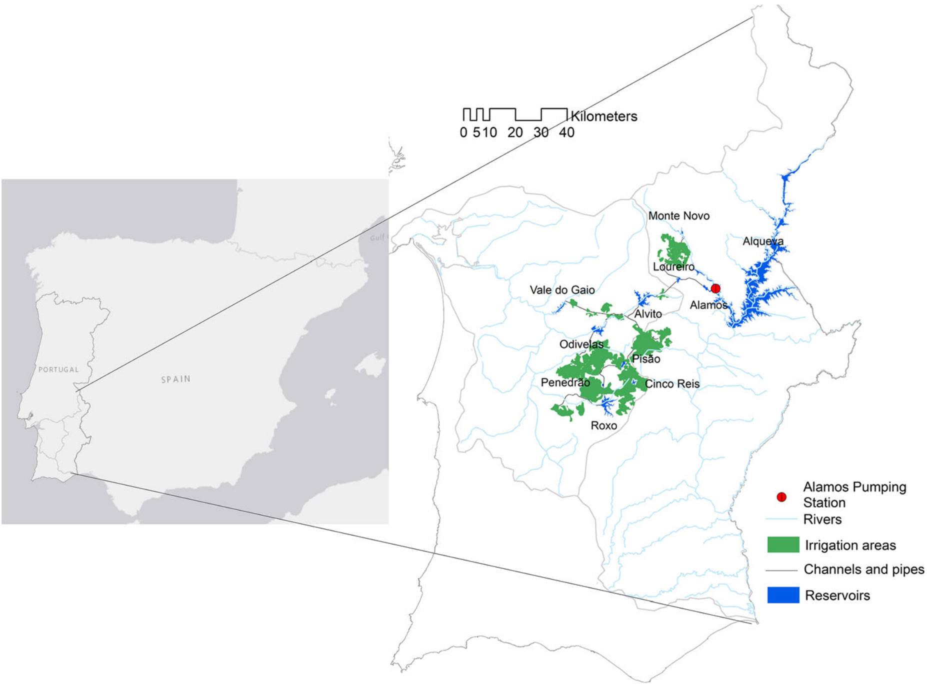

Fig. 1 Map showing location and components of Alqueva Sub-system

2.2 Study System

This study is focused on the Alvito-Odivelas system, in which water is transferred from the Guadiana to the Sado River basin. The Loureiro-Monte Novo channel irrigates 7824 ha of Monte Novo, and the Loureiro-Alvito channel and partially built Alvito-Pisão channel irrigate 10,000 ha of Alvito-Pisão and 6845 ha of Infrastructure-12 by the Odivelas reservoir. The Alvito-Pisão irrigation area consists of the irrigation blocks Cuba Este, Cuba Oeste, Faro, and Vidigueira. In this case, the water is imported at the Alvito reservoir from the Loureiro reservoir through the Loureiro-Alvito tunnel to meet shortages at the Alvito and Odivelas reservoirs. The overall water transfer is performed from the Alqueva reservoir through Álamos up to Loureiro. The Loureiro reservoir also supplies water to the Monte Novo irrigation area through the Loureiro-Monte Novo link channel, in addition to water transfer for the Alvito reservoir.

The study system considers 5 reservoirs (Odivelas, Alvito, Loureiro, Álamos, and Alqueva) in the Alqueva subsystem. The relevant features of these reservoirs and their purposes are given in Table 1. Any deficit occurring at a reservoir can be met by importing water from the Alqueva reservoir through the subsystem.

3 Methodology

This study was carried out in three steps. In the first step, for the reservoirs at which historical records were not available, the hydrological model SHETRAN was used to estimate inflows.

Table 1 Salient features of the reservoirs in the study system

	Alqueva	Alamos	Loureiro	Alvito	Odivelas
River	Guadiana	Guadiana	Loureiro	Odivelas	Odivelas
Basin	Guadiana	Guadiana	Degebe	Sado	Sado
Gross Storage Capacity (10^3 m^3)	4,150,000	17,600	6980	132,500	96,000
Useful Storage(10^3 m^3)	3,117,000	4400	2480	130,000	70,000
Dead Storage(10^3 m^3)	1,033,000	13,200	4500	2500	26,000
Normal Max. Water Level (m)	152	227.5	222.0	197.5	103
Flood Water Level (m)	152.8	228.1	223.10	198.55	104.55
Minimum Water Level (m)	130	225.9	219.0	172	91.3
Reservoir Purpose	Irrigation, municipal, industrial water supply, hydropower and recreation	Pumping and storing water from Alqueva for export	Irrigation and municipal water supply	Irrigation and municipal water supply	Irrigation and municipal water supply

In the second step, the CROPWAT model was used to estimate the crop water demands, and the LP model was used to estimate the area allocations for each crop and project the corresponding monthly irrigation water requirements for the irrigation areas. Finally, in the third step, a generalized DP-based water-import (WIDP) model was used to quantify the amount of water required to meet various demands at a reservoir from its upstream reservoirs.

These steps are discussed in detail in the following subsections.

3.1 Estimation of the Monthly Inflows at the Álamos and Loureiro Reservoirs

The inflow data for the Álamos and Loureiro reservoirs were simulated using the observed meteorological series from 1961 to 1990. The SHETRAN model was chosen to estimate the runoff series because it is a physically-based spatially distributed hydrological model. The model uses physics-based governing partial differential equations for the flow and transport, which are solved on a three-dimensional grid. SHETRAN represents the spatial distribution of catchment properties (topography, channel network, soils, and land use), rainfall input, and hydrological response in the horizontal direction, in an orthogonal grid network, and in the vertical direction. SHETRAN was calibrated and validated against daily runoff measurements at the outlet and internal sections and against phreatic surfaces using a multi-basin, multi-location and multi-response approach (Mourato et al. 2015). The model calibration was conducted against the daily flow for the period 1/10/1980 to 30/9/1984. Validation was performed for the period 1/10/1984 to 30/9/1990. The observed and simulated daily flows were compared using the correlation coefficient (R), the percentage of volume deviation (Vd), and the Nash Sutcliffe coefficient (NS).

The Álamos and Loureiro basins cover an area between 10 and 262 km^2 of predominantly sandy loam soils and forest or non-irrigated arable land use. The climate regime is representative of the climate conditions throughout southern Portugal. Precipitation data were obtained from the Portuguese hydrological monitoring network (www.snirh.pt) using the rainfall stations of São Manços and Reguengos. The temperature observations are from the Viana do Alentejo meteorological station of the Portuguese Institute of Meteorology (www.ipma.pt).

The spatial distribution of soil type was taken from 1:25000 Portuguese soil cartography maps (www.dgadr.pt). Pedo-transfer functions were used to estimate missing soil data (Saxton and Rawls 2006). The land use was obtained from the Corine Land Cover map (CLC00) at a scale of 1:100000 (www.eea.europa.eu). The topography was characterized using a digital elevation model from Portuguese military maps at a scale of 1:25000 (www.igeoe.pt).

3.2 Projections of Monthly Irrigation Water Demands and Optimal Cropping Pattern

The cropping pattern considered in this study was based on the information available from EDIA (EDIA 2003). The crops considered in this study were the major crops grown in the region, which are usually adapted to the region's soil and climate. The 8 crops considered in this study were as follows: wheat, maize, forage maize, conservation forage, sunflower, pasture (8 years), tomato (industrial crop), and tomato (horticulture).

The monthly crop water requirement for each crop was obtained using the FAO CROPWAT 4 W model (Clarke et al. 1998)). The model calculates the reference crop evapotranspiration using the FAO Penman-Monteith method (Allen et al. 1998) and gives values compatible with the actual crop water needs worldwide. The mean monthly climate data for the period 1951–1980 (I.N.M.G. 1991) and the soil and crop data were from FAO. The CROPWAT model estimates the monthly crop water and, subsequently, the irrigation requirements. The monthly on-farm irrigation requirements were obtained using 80% application efficiency (EDIA 2003). The estimation of expenditure on crop cultivation, including irrigation charges, expenses for seeds, fertilizers, pesticides, machinery and equipment, energy, etc., and benefits from crop production were obtained with the help of agriculture experts. All this information was used in the LP model to project the monthly irrigation requirements for optimal area allocation to each crop. The proportional area allocations are given in the EDIA report (EDIA 2003) were considered as much as possible to form the upper and lower bounds for the crops.

The crop planning model was solved using the LINGO package (LINDO Systems Inc). The objective of the model is to maximize the net benefits from crops subject to water and land availability constraints. Parameters that include the cost of cultivation of each crop and the relative benefits from crop production were used within the objective function to maximize the net income from crop production. Since the amount of water available was unknown for the irrigation areas of Monte Novo and Alvito-Pisão, the model itself was utilized to project the irrigation water requirements of these areas and the respective optimal crop plan by considering water availability as a decision variable (water requirement) along with area allocation. The LP model is given below in Eqs. (1) to (5):

$$\max \sum_{i=1}^{N_c} b_i A_i \tag{1}$$

where i = index for i^{th} crop; N_c = number of the crops; A_i = area allocation to i^{th} crop and b_i= net benefit from the i^{th} crop.

This model is subject to the following constraints:

(i) Surface water availability/requirement constraints

$$\sum_{i=1}^{N_c} w_{i,t} A_i \leq R_t \quad \forall t \tag{2}$$

where $w_{i,\,t}$ = the farm irrigation water requirement for the i^{th} crop, during time period t in terms of depth and R_t = the water supply/demand during the time period t for the given irrigation area.

(ii) Land availability constraints

$$\sum_{i=1}^{N_c} A_i \leq A_T \quad \forall t \tag{3}$$

$$\sum_{i=1}^{N_c} \lambda_{i,t} A_i \leq A_T \quad \forall t \tag{4}$$

where A_T = the total area occupied by the crops; $\lambda_{i,\,t}$ is the land occupation constant, with $\lambda_{i,\,t}$ = 0 if the i^{th} crop does not occupy land in month t and $\lambda_{i,\,t} = 1$ otherwise.

(iii) Limits on area allocation

$$A_{i,min} \leq A_i \leq A_{i,\ max} \quad \forall t \tag{5}$$

where $A_{i,\ max}$ and $A_{i,\ min}$ are the upper and lower limits on the area allocation for the i^{th} crop.

3.3 Projection of Water Import Requirements in the System

In general, the integrated operation of a reservoir system is meant to achieve the best utilization of the available water in the system. Due to the interdependence within the system, it is usually necessary to simulate the system to determine a practical operating plan that generates an impartial supply of water. Commonly, an iterative process is used to create operation rules that can achieve these objectives. However, the optimization technique can help reduce the computational requirements by providing an initial estimate or refining policies while optimizing the overall performance of the system. The main purpose of water transfer projects is to reduce water deficits but not at the cost of water losses, which may happen without prior information about when and how much water is to be transferred from an exporting reservoir to an importing reservoir. The WIDP model developed by Rani et al. (2016) has been enhanced to a generalized form in this study, which can be applied to more complex reservoir systems. The original model was inspired by Haimes' inventory-based procurement DP model (Haimes 1977), which can be applied for an importing reservoir to estimate the amount of water import required from another source to fully meet its water demands (Rani et al. 2016). It is presumed that an unlimited amount of water is available at another source and that water can be procured to meet the importing reservoir's demands fully from the available reservoir storage and procured water, while the inflow to the importing reservoir is also available for use in addition to the imported water. In the present model, there may be several exporting sources, and water procurement would be done in such a way that the demand could be met fully from the available water at the importing reservoir (storage plus inflow) and the procured water from exporting reservoirs (Fig. 2). This eventually provides a projection of the water import requirement at a reservoir from single or multiple sources (reservoirs) located upstream in a multi-reservoir system. When an importing reservoir experiences water import from multiple sources (upstream reservoirs), the model estimates the total amount of water import needed at the reservoir. The total amount is further disaggregated proportionately among the exporting reservoirs as per their storage capacity or water transfer cost to specify the water releases from each contributing reservoir; which subsequently becomes their respective demand ($DT_{i,\,t}$) when they are treated as the importing reservoir since the model is applied successively, starting from the most downstream reservoir to the most upstream reservoir(s). The model is formulated as follows:

The overall objective function to be minimized is given as follows:

$$Min \sum_{t=1}^{N} C_t \times WIM_t \tag{6}$$

where C_t is the cost of water import during time period t and WIM_t is the total amount of water import from upstream reservoirs required to completely meet the demands at the importing reservoir during time period t. All the volume units in the model are in $10^3 m^3$. For the present study, the water transfer cost is assumed to be constant for each time period. In other words, the objective function minimizes the total water imports. Therefore, the objective function may be rewritten as follows:

$$Min \sum_{t=1}^{N} WIM_t \tag{7}$$

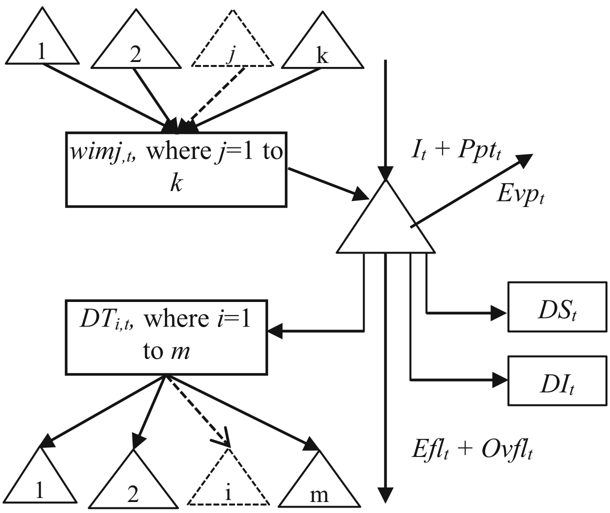

Fig. 2 Schematic of the generalized water import dynamic programming Model applied to a reservoir importing water from multiple exporting reservoirs (Here, $wimj_{,t}$= water import entailed from *jth* exporting reservoir; $DT_{i,t}$, = water transfer demand/shortage of reservoir(s) in downstream; I_t = inflow to the reservoir; Ppt_t = *precipitation over reservoir;* Evp_t = *evaporation losses from reservoir;* DS_t = municipal water supply demand at reservoir; DI_t = target irrigation demand at reservoir; Efl_t = *release required for ecological flow;* $Ovfl_t$ = *overflow from the reservoir)*

where

$$WIM_t = \sum_{j=1}^{k} wim_{j,t}$$

$t = 1, \ldots, N$; N is the total number of time periods of operation; $j = 1, \ldots, k$, k is the total number of exporting reservoirs and $wim_{j,\,t}$ is the amount of water import from the jth reservoir in time period t. The recursive equation to minimize the above function is given as follows:

$$f_t(S_t) = \frac{Min}{} WIM_t[WIM_t + f_{t-1}(S_{t-1})], \;\; f_0(S_0) = 0 \tag{8}$$

where S_{t-1} is the initial storage in the importing reservoir, at the beginning of time period t; S_t is the final storage in the importing reservoir at the end of time period t and $f_t(S_t)$ is the recursive function.

The constraints of the model are as follows:

(i) Continuity Equation:

$$S_t = S_{t-1} + I_t + Ppt_t + WIM_t - Efl_t - D_t - Evp_t - Ovfl_t \tag{9}$$

Where, I_t is catchment flow/inflow into the importing reservoir during time period t; $D_t = \sum\left(DS_t + DI_t + \sum_{i=1}^{m} DT_{i,t}\right)$, is the total demand at the importing reservoir during time period t. DS_t is target municipal water supply demand at the importing reservoir during time period t; DI_t is the target irrigation demand at the importing reservoir during time period t; $DT_{i,\,t}$ is the water transfer demand/shortage of water at the reservoir(s) downstream, which needs to be fulfilled from the importing reservoir during time period t, (where $i = 1$ *to* m, the number of reservoirs linked to the importing reservoir, which may need water from the importing reservoir to fulfil their demands); Efl_t is the ecological flow requirement at the importing reservoir during time period t; Ppt_t is precipitation into the importing reservoir during time period t; Evp_t is the evaporation loss from the importing reservoir during time period t; and $Ovfl_t$ is the overflow from the importing reservoir, if any, during time period t.

(ii) Storage Limits:

$$0 \le S_t \le K \tag{10}$$

where K is the live storage capacity of the reservoir.

(iii) Water import limits:

$$WIM_t \ge 0 \tag{11}$$

Substituting Eq. (9) in (10) gives the upper and lower limit on water imports for each time t:

$$Ecfl_t + D_t + Evp_t - S_{t-1} - I_t - Ppt_t \leq WIM_t \leq K + Ecfl_t + D_t + Evp_t - S_{t-1} - I_t - Ppt_t \quad (12)$$

(iv) Overflow definition

$$\begin{aligned} Ovfl_t &= 0, if\ WIM_t > 0 \\ &= S_{t-1} + I_t + Ppt_t - Ecfl_t - D_t - Evp_t - S_t \text{ if } WIM_t = 0 \text{ and } S_t = K \text{ in this case} \end{aligned} \quad (13)$$

The WIDP was first applied to Odivelas because it is the most downstream reservoir in the study system. The model was further applied to the reservoirs upstream one by one, and the cumulative results were obtained for the downstream reservoirs. The observed inflow data from 1952–53 to 1972–73 were available for the Alvito and Odivelas reservoirs. However, the inflow data for the Álamos and Loureiro reservoirs obtained using the hydrological model SHETRAN were available from 1961–62 to 1990–91. Therefore, the common period for all the reservoirs, i.e., 1961–62 to 1972–73, was used for the water import analysis. The evaporation values were estimated using the *Thornthwaite* equation.

4 Results and Discussion

The SHETRAN calibration and validation processes can be considered successful. The daily Nash-Sutcliff efficiency, volume deviation and coefficient of determination ranged, from 0.58 to 0.76, −9% to 15% and 0.59 to 0.79 in the calibration period, respectively, and from 0.54 to 0.75, −14% to 12% and 0.54 to 0.77 in the validation period, respectively. The monthly results of the NS efficiency coefficient ranged between 0.98 and 0.84, and the R^2 ranged from 0.98 and 0.92 (Zhang et al. 2015; Op de Hipt et al. 2017).

The monthly irrigation requirement of each crop using the CROPWAT model and the optimal area allocation to each crop using the LP model are given in Table 2. The monthly irrigation water demands of the Alvito-Pisão, Monte Novo, and Infrastructure-12 irrigation areas are stated in Table 3. The annual irrigation water requirement projected through LP for the Alvito-Pisão irrigation area was 51,765 10^3m^3, which is nearly 66% of the value as per EDIA (77,917 10^3m^3, EDIA 2003). It is worth mentioning here that the optimal allocation of area has had a significant impact on the water used by the crops. For example, pasture, which has the highest water requirement with less revenue, occupies a smaller area (5% of the total) based on the LP model compared to EDIA (6.1% of the total) while tomato (industrial) which is being a higher revenue crop with high water demand, occupies a larger area based on the LP model.

Starting from Odivelas, the WIDP model was successively applied to all reservoirs upstream. The results revealed that on average Odivelas needs to import 19,833.39 10^3m^3 (34% of its demand) water annually from Alvito to meet the irrigation requirement of Infrastucture-12. Further, to meet the import demand of Odivelas and its own demands for the municipal supply and irrigation of the Alvito-Pisão irrigation area, Alvito requires 43,129.90 10^3m^3 water yearly. Annually, 60% of the irrigation demands of Alvito and

Table 2 Monthly on farm water/irrigation requirement (10^3 m^3/ha) of the crops and Optimal cropping pattern for Alvito-Pisão and M. Novo Irrigation areas

Crop period	Wheat Nov-Jun	Maize Apr-Sep	Forage Maize Apr-Sep	Cons. forage Oct-Apr	Sunflower Apr-Aug	Pasture (8 years) Oct-Nov	Tomato (industrial) May-Sep	Tomato (Horticulture) May-Sep
Irrigation demand (10^3 m^3/ha)								
Jan	0.00	...	...	0.00	...	0.00	...	...
Feb	0.00	...	...	...	...	0.00	...	...
Mar	0.15	...	...	...	...	0.13	...	...
Apr	0.80	0.01	0.01	...	0.04	0.62	...	...
May	0.65	0.39	0.39	...	0.59	1.29	0.68	0.68
Jun	0.00	1.54	1.54	...	1.73	1.71	1.55	1.55
Jul	...	2.55	2.55	0.00	0.80	2.03	2.61	2.61
Aug	...	2.09	2.09	0.00	0.00	1.88	2.33	2.33
Sep	...	0.76	0.76	0.00	...	1.14	1.04	1.04
Oct	...	...	...	0.00	...	0.37	...	...
Nov	0.00	...	...	0.00	...	0.00	...	...
Dec	0.00	...	...	0.00	...	0.00	...	...
Annual	1.61	7.33	7.33	0.00	3.16	9.16	8.21	8.21
Optimal area allocation to each crop (ha)								
Alvito--Pisão	2500	2000	1000	500	1500	500	1500	500
M. Novo	1956	1565	782	391	1174	391	1174	391

Odivelas need to be met by importing water at Alvito from Loureiro. The average monthly results show that in general, a substantial amount of water needs to be imported from June to September (Fig. 3). The evaporation rates are very high during these months, which results in higher crop water needs. A large amount of water is also lost

Table 3 Monthly irrigation water requirement (10^3 m^3) at Alvito-Pisão, M. Novo and Infrastructure-12 irrigation areas

Month	Irrigation area (ha)		
	Alvito-Pisão[a]	M. Novo[a]	Infrastucture-12[b]
Oct	185.00	144.67	542.81
Nov	0	0	118.42
Dec	0	0	6.85
Jan	0	0	28.06
Feb	0	0	8.90
Mar	440.00	344.23	1802.97
Apr	2400.00	1877.65	3346.52
May	5685.00	4447.98	6341.21
Jun	11,170.00	8739.76	9668.56
Jul	15,085.00	11,802.43	15,160.31
Aug	11,870.00	9286.76	11,334.64
Sep	4930.00	3857.06	2446.40
Annual	51,765.00	40,500.54	50,805.64

[a] Projected with the help of LP model

[b] Available from report EDIA (2003)

through evaporation from the reservoirs, which results in high water import requirements. However, in dry years, water may need to be imported during October–November and April–May (Fig. 4).

The Loureiro reservoir supplies water for the Monte Novo irrigation area's demands (estimated from LP model) and exports water to Alvito for its shortages (available from

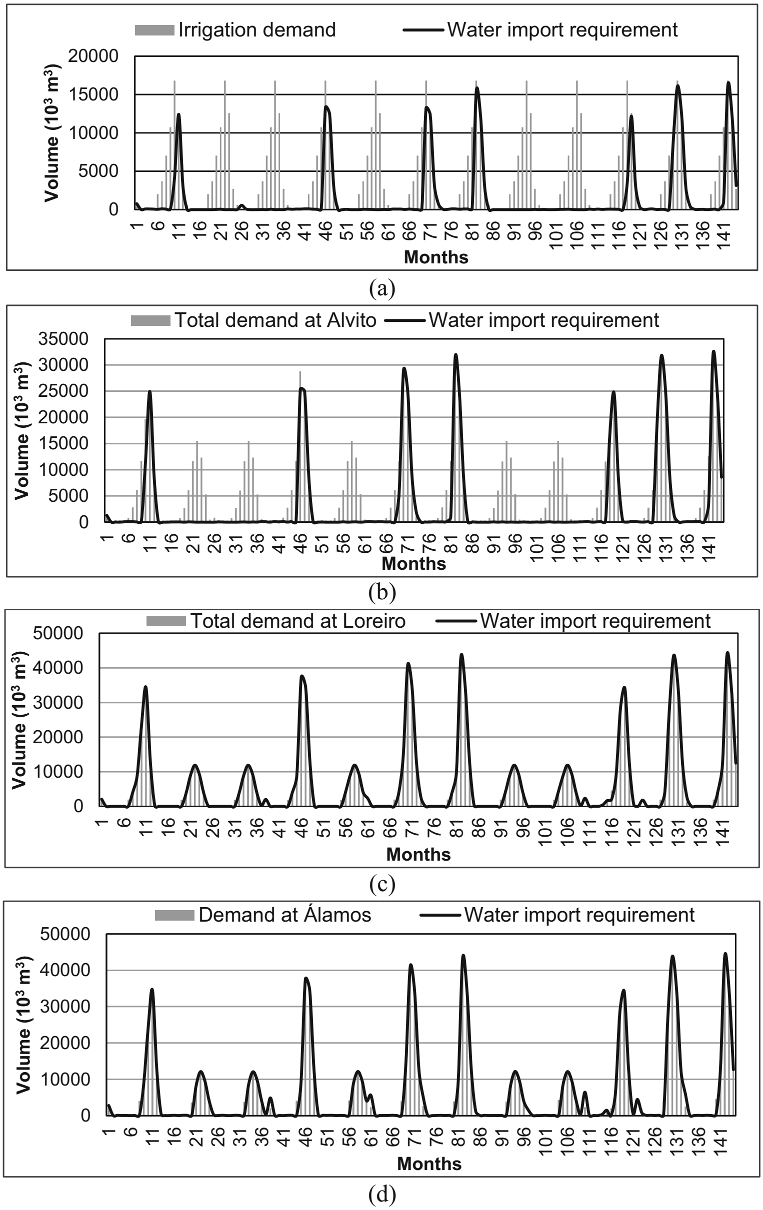

Fig. 3 Monthly water import requirement at each reservoirs (**a**) at Odivelas from Alvito (**b**) at Alvito from Loureiro (**c**) at Loureiro from Álamos (**d**) at Álamos from Alqueva

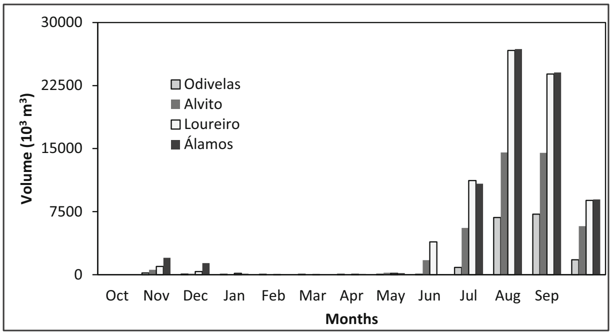

Fig. 4 Average monthly water import requirement at each reservoir in the system

the import model results) through the Loureiro-Alvito tunnel. The monthly inflow data for the Loureiro reservoir were obtained using the hydrological model SHETRAN. The results showed that Loureiro needs 76,175.53$10^3 m^3$ water per year. Interestingly, at the Monte Novo irrigation area, all the irrigation needs are satisfied only by the imported water. In other words, Loureiro will store the water imported from Alqueva and allocate it for various purposes.

Finally, the water import model was applied to the Álamos reservoir, where the water import requirement of the Loureiro reservoir is the only demand to be met. The monthly water import results are given in Fig. 2, which shows that at Álamos and Loureiro, the demands are mostly met by imported water.

The results show that to fulfill the water demands of the system considered in this study, an average of 74,529.43$10^3$ m^3/annum of water will need to be pumped from the Alqueva reservoir to Álamos; this value represents nearly 50% of the total demand of the system considered in this study, and accounts for approximately 30% of total irrigation area under the Alqueva subsystem (EDIA 2017; Barrona and Oliveira 2015). However, this amount is less than the water import required at Loureiro, which further shows the importance of using an optimization approach. Annually, this amount may vary from 34,529.64 $10^3 m^3$/annum to 124,013.08 $10^3 m^3$/annum. The overall average annual amount of pumped water from Alqueva to fulfil the water demands is only 2.5%, and the maximum amount that may be needed from Alqueva is 4% of the active storage capacity, in the presented scenario. This amount of water can always be expected to be available from Alqueva (Barrona and Oliveira 2015). Therefore, for the system scenario considered in the study, sufficient water will be available to meet all the irrigation and municipal requirements.

Systems similar to the Alqueva subsystem allow for great water use flexibility, which can further be strengthened via the application of optimal water transfer policies that diminish the waste of water while minimizing water deficits in the overall system. For instance, during the real-time operation of the Alqueva subsystem, the water import requirement of each reservoir must be provided to the system manager at the beginning of the agriculture year, and irrigation associations need to pay for water they need for irrigation from Alqueva. However, if the conditions of the hydrological year would are not known, then crop unsustainability may occur or they may pay for water that they do not need in the future. The proposed integrated approach is capable of facilitating decisions regarding the volume to release for each reservoir because patterns can be determined for water release (import) for each reservoir in the system.

5 Summary and Conclusions

In this study, the necessary inflow series were acquired using the physically based simulation model SHETRAN for ungauged watersheds. Projections were performed of the monthly irrigation requirements for the developing irrigation areas under study, and the corresponding optimal cropping patterns were obtained using the LP-based crop planning model. A generalized water import model evaluates inter−/intra-basin water transfer requirements at reservoirs in the Alqueva subsystem to meet water shortages while considering evaporation losses and storage of the importing reservoir, and the objective function is to minimize water import to reduce water wastage. This concept is unique because the minimization of water shortage is considered an objective function (Guo et al. 2012). The inclusion of water transfer costs in the objective function may further improve the quality of the results. The model described herein can provide guidance about how much water Alqueva should release for the system considered in this study. The simulation of the whole system, including Alqueva, using these guidelines, would be required to determine the operation policies for the entire subsystem. In the present scenario, Alqueva is already in operation and has enough water to meet all demands of the system under study; thus, the simulation provides reliable results. In the future when all the components of the MAP are functioning, operation policies may be developed using this approach, which may be quite useful for determining 'when and how much water' from the Alqueva reservoir is separately needed for the three MAP subsystems (Alqueva, Pedrógão and Ardila subsystems) and the proportionate overall amount of water transferred from Alqueva. The generalized WIDP model is applicable to systems with more than one exporting reservoir, and this concept is a novel aspect of the approach applied in this study. Here, the total amount of water import may be distributed proportionately based on the cost of the transfer or storage capacity of each source. However, in such cases, the amount of water would be a multi-decision variable problem, which will increase computational requirement of DP; therefore, the use of an unconventional optimization technique would be a better approach and can be recommended for future research. Additionally, the joint application of an optimization approach, a hydrological model and an optimum crop plan provides the minimum amount of water required to be pumped from Alqueva, which in turn can minimize the wastage of water and save energy required to pump extra water compared with values that are not estimated optimally. The use of these tools in an integrated way can be used by decision-makers to provide real-time information, such as irrigation demands based on optimal cropping patterns of existing crops and reservoir inflow based on hydrological model results, which are used to estimate the water import requirements at each reservoir. Therefore, any change in crop plan or climate may be incorporated in the model to obtain updated results, which is another advancement of the proposed method. The proposed procedure may be applied with future climate model projections to enable assessments of the impact of climate change on water availability and crop water requirements and definitions of new water transfer policies between reservoirs.

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Compliance with Ethical Standards

Conflict of Interest None.

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