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Reusing wastewater for agricultural irrigation: a water-energy-food Nexus assessment in the North Western Sahara Aquifer System

C Ramirez, Y Almulla and F Fuso Nerini

Department of Energy Technology, KTH Royal Institute of Technology, Brinellvägen 68, Stockholm 10044, Sweden

E-mail: camilorg@kth.se

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Abstract

The North Western Sahara Aquifer System stands out as one of the water scarcest regions in the world. Moreover, in recent decades agriculture activity has grown exacerbating the pressure on groundwater resources and pumping energy requirements. In this study, a water-energy-food Nexus approach was used to assess the effect of capturing, treating and reusing wastewater for irrigation. GIS-based tools were used to capture the systems spatial dimension, enabling to match wastewater supply and water demand points, identify demand hotspots and evaluate techno-economically viable wastewater treatment options. Moreover, the minimum energy requirements for brackish water desalination were estimated. Seven domestic wastewater treatment technologies and one irrigation tailwater treatment technology were evaluated, making use of a levelized cost of Water methodology to identify the least-cost system. Four scenarios were constructed based on water-consumption behaviour of farmers towards changes in irrigation water pricing. The identified least-cost wastewater treatment technologies showed clear trade-offs, as different technologies were more cost-effective depending on treatment capacity requirements of the spatially distributed agglomerations. The reuse of treated wastewater/tailwater in agricultural irrigation, showed improvement of groundwater stress, reducing on about 49% water abstractions and groundwater stress levels in the best case scenario. However, groundwater stress still fell on the extremely high category, highlighting the critical condition of the aquifer. Furthermore, reuse of wastewater/tailwater decreased dependency on groundwater pumping and the overall energy-for-water requirements, reducing by about 15% the total energy requirements in the best case scenario. However, to effectively preserve water resources and act holistically towards the sustainable development agenda, measures as better water pricing mechanisms, management strategies to improve water productivity and adoption of more efficient irrigation schemes may be needed.

1. Introduction

Nexus approaches have been widely used for evaluating interlinkages between resource systems, trying to identify challenges, synergies, trade-offs and assess holistic solutions [1, 2]. Nexus thinking is also gaining attention in transboundary resources settings [2, 3]. Such is the case of the North Western Sahara Aquifer System (NWSAS). The NWSAS is located in North Africa covering large parts of Algeria, Tunisia and Libya, and it holds invaluable groundwater resources to maintain livelihood in the region [4].

Its large extension over an area of more than 1 million km^2, makes the NWSAS one of the largest groundwater sources in the world. NWSAS is the main source of water for all socio-economic activities in the region, such as agriculture, industry and domestic use [5]. Therefore, the growth in the agricultural activities in the past years increased the water abstraction levels significantly. The cropland area reached about 470 000 ha in 2014 [6] of which 60% are irrigated by NWSAS water [5]. The water abstractions, as result, jumped from around 0.6 billion cubic meters (BCM) in 1970 [4] to 3.2 BCM in 2018 [5] which is three times higher than the average annual recharge rate of 1 billion $m^3 yr^{-1}$ [7]. This overexploitation is pushing for urgent and coordinated actions to safeguard this essential groundwater resource for 4.8 million people [8]. Moreover, the NWSAS has suffered improper disposal of non-treated wastewater and irrigation drainage (i.e. tailwater), resulting in excessive rise of surface water tables, as the case for Ouargla and El Oued, leading to soil and water salinization [4].

The main scientific studies on the NWSAS have been conducted in the form of joint efforts between Algeria, Tunisia, and Libya [9]. Such efforts have identified challenges and risks that the NWSAS has been facing mainly in terms of water scarcity and utilization [4]. Research outcomes have achieved common databases containing over 9000 water extraction points, developed hydraulic models to assess impacts of water withdrawals, consultation mechanisms for joint management of water resources, identified the inefficiency of irrigation, the inadequate valorization of water and the degradation of soil quality in the region [4, 6, 9, 10].

Moreover, Almulla *et al* [5] developed the first water-energy-food (WEF) Nexus analysis in the NWSAS, capturing dynamics between the agricultural, water and energy sectors. The main outcomes of the study are helpful to inform policy making in the three countries and enhance synergies between sectors. However, the aim of the study was not on identifying measures to ease water scarcity, rather than to quantify the WEF Nexus perspective and evaluate options to transition to clean energy sources in agriculture. Most recently, the United Nations Economic Commission for Europe (UNECE) [8] conducted a basin-wide water-food-energy-ecosystems Nexus study in the NWSAS, in the form of a participatory assessment. The study yielded high-priority, implementable solutions aligned with the Sustainable Development Agenda. The solutions ranged from governance and international cooperation, to economic and policy instruments, infrastructure and innovation.

Within the solutions identified in [8], two are of concern of the present study: (1) to set up dedicated policies and related incentives for wastewater reuse in agriculture and urban areas, and (2) to upscale the use of non-conventional water resources through desalination and wastewater and drainage treatment. Such solutions are aligned with international recognition on treated wastewater/tailwater reuse as one of the best measures to ease water scarcity [11, 12], as it could substantially increase availability of clean water resources for all uses not available otherwise. Furthermore, non-treated wastewater that runs freely to the environment, often poses severe environmental and health consequences, polluting groundwater aquifers, rivers, lakes, soils and food, among others [11].

The potential of reusing treated wastewater has not yet been explored in the basin, neither the synergies and trade-offs it may have with the energy, water and agricultural sectors. In general, wastewater treatment and reuse has been commonly evaluated with water, food and health centred approaches, often overlooking energy requirements and its implications [11, 13–15]. On the other hand, wastewater-related nexus approaches, have usually focused on the energy and nutrients recovery potential from wastewater [11, 16, 17]. To date, a research gap was found into how to determine the potential of wastewater treatment and reuse, assessing possible treatment technologies, the energy demand implications and the effects on the water system. To address that gap, the objective of this study was to develop a novel exploratory WEF Nexus approach to asses the impact that reclaiming, treating and reusing domestic wastewater/agricultural drainage (i.e. in agricultural irrigation), may have in the water, food and energy systems. Tailored geographic information systems (GIS) methods were used with a levelized cost of water (LCOW) methodology [18] to capture key special characteristics of the Nexus system. Furthermore, the methodology was applied to the NWSAS in the context of sustainable development.

2. Methodology

GIS-based methods were selected to model the current state of the basin and evaluate treated wastewater reuse scenarios. By incorporating the spatial distribution of resources in WEF Nexus modelling and preventing aggregation of spatial scales, more robust analytical analysis tackling the intersection of all three resources can be achieved, providing better insights for planning and decision making [19, 20]. This concept gains even more importance in the context of the transboundary nature of the NWSAS basin.

The analysis was performed for a baseline year around 2015, using the most up-to-date open source demographic, irrigated area, water quality and groundwater depth data. Moreover, monthly-average climatic data available for the period 1970–2000 was used to estimate crop water needs based on evapotraspiration. The relevant layers are identified and described in section 1 of the supplementary information (available online at stacks.iop.org/ERL/16/044052/mmedia). A general model and case study runner for the NWSAS were developed using Python and hosted in an open-source Github repository which ensures the complete reproducibility of the results.

Throughout this section, the methods used to characterise the current state of the aquifer (Baseline scenario) are presented. Then, descriptions of the treated wastewater reuse scenarios are provided along with the methods used and a schematic representation of the overall system. Finally, detailed explanations of key modelling processes are given.

Table 1. Brief description and enumeration of methods used for the Baseline scenario (in order of execution).

#	Method	Systems involved	Description
1.	Data calibration	Residential and agriculture	Geospatial population count and irrigated cropland extend calibrated according to provincial statistics
2.	Clustering	Residential and agricultural sectors	Clusters of population and cropland extent points are identified
3.	Water demand	Residential and agriculture	Based on population water consumption per capita and spatial irrigation water needs per hectare according to provincial statistics
4.	Water withdrawals	Groundwater aquifer, residential and agriculture	Calculate water withdrawals from the groundwater aquifer, based on demand from the residential and agricultural sectors. No water reuse is accounted here
5.	Groundwater stress indicator	Groundwater aquifer	Estimate geospatially the current groundwater stress indicator based on the water extractions, the recharge rate of the aquifer and the areal extent of each cluster and the basin
6.	Pumping energy	Groundwater aquifer	Based on total water withdrawals from the aquifer and the depth to groundwater of each spatial location

2.1. Characterizing the baseline scenario

Water requirements for domestic and irrigation use were assumed to be supplied by the groundwater aquifer, whereas other water uses (e.g. industrial) were excluded due to unavailability of data [8]. The recharge rate R for the entire aquifer was taken as 1.1 billion cubic meters of water per year, which for the area of the aquifer, is an equivalent water column of 1.06 mm per year [4]. Furthermore, no environmental flow, wastewater treatment or reuse were considered. Water demand for domestic use was estimated using a water demand per capita level of 55 m^3 yr^{-1} [21], based on medium consumption values recommended by the World Health Organization to prevent health risks. Current population was set according to statistics from population count within each country area inside the basin [4]. Agricultural irrigation requirements were taken from provincial specific data derived from [6], and irrigated area from [4–6]. Details of all input layers are provided in the supplementary information.

Table 1 presents the six main steps performed in order to characterize the current state of the basin.

2.2. Wastewater treatment and reuse scenarios

Four wastewater/tailwater treatment and reuse scenarios were analysed, evaluating current irrigation water pricing regimes and wastewater/tailwater reuse (see figure 1). Irrigation water pricing regimes were taken from [6], were it was found that the irrigation water demand per hectare throughout the NWSAS basin is heavily dependent on the supply water cost. Moreover, the same population water demand of 55 m^3 per capita was used for all scenarios:

Scenario 1: Assumes the same behaviour as the baseline, but accounts for wastewater treatment and reuse in irrigation.

Scenario 2: Private farmers that pay the full price of water. The average level of water demand is around 10 512 m^3 ha^{-1} [6]. The Sahara and Sahel Observatory (OSS) [6] found that farmers belonging to this regime have higher water productivity.

Scenario 3: Users that have access to water subsidized to some extent ('collective' networks). The average water demand is 15 334 m^3 ha^{-1} [6].

Scenario 4: Farmers that have free access to water, meaning that the government fully subsidize the price of water and that the resource can be utilized without limitations. The average irrigation water demand is 21 215 m^3 ha^{-1} [6].

It is worth noting that the large irrigation water demand increase seen in the subsidized and free regimes compared to the private regime, suggests a strong price elasticity of the irrigation water demand and/or the use of lower efficiency irrigation technologies in such regimes [6].

Although the majority of farmers in the NWSAS are currently under the private water regime, the three water regimes were used as central point of the scenarios with the aim of exploring extremes and highlighting the WEF Nexus implications that certain water use behaviours may pose.

The same six steps used to characterize the Baseline were applied to the treated wastewater reuse

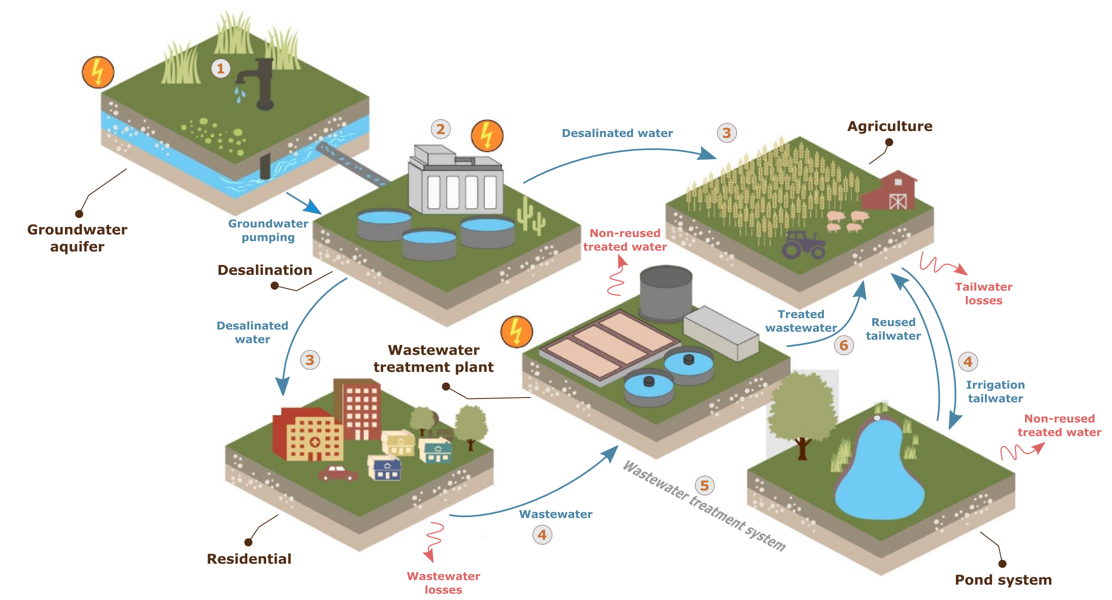

Figure 1. NWSAS systems, energy and water resource flows. The blocks represent the different systems, the arrows the water flows, the voltage icons the systems that require energy, and the numbers the order of processes: (1) extracting water from groundwater resources, (2) desalinating brackish water when needed, (3) supplying water demand for domestic and agricultural irrigation purposes, (4) reclaiming domestic wastewater and agricultural drainage (i.e. tailwater), (5) treating reclaimed wastewater, and (6) reusing treated wastewater in agricultural irrigation.

scenarios (see table 1), plus nine additional steps which assessed the WEF impact of reusing treated wastewater on the basin (table 2). Moreover, a lifespan of 35 years was used as the technical life of the system.

2.3. Clustering algorithm

Often, analyses are carried out on an administrative boundaries basis, in which all data is aggregated per defined administrative borders (e.g. provinces). Such approach is problematic when target areas (i.e. populated and irrigated areas) are scattered throughout broad areas, and accounting for proximity between points is important. Therefore, a clustering approach was used in order to identify dense areas where a wastewater treatment system could be implemented, minimizing constraints imposed by existent large distances among scatter population or irrigated lands. A hierarchical clustering algorithm was run using the *Agglomerative* Clustering object from the Python *scikit-learn* package [22].

Forty clusters were created in the process, which succeeded in identifying dense agglomerations. If the sum of the pairwise distance between points within each cluster is calculated, the clustering approach achieved a reduction of 574% on the overall distance between points when compared to a province basis approach (i.e. populated and irrigated areas within each province). This is especially important in larger provinces with substantial population and agricultural activity as Adrar, Ghardaa, Ouargla and el Oued. Detailed maps of the identified clusters are available in the supplementary information.

2.4. Groundwater stress indicator

The groundwater stress indicator (GWS) was used to quantify the current stress of the aquifer [23, 24]. It relates the ratio of water withdrawals due to anthropogenic reasons (i.e. in this case domestic and irrigation uses), and the total recharge rate of the aquifer. The groundwater stress indicator is usually calculated as the ratio of groundwater footprint to aquifer area [23, 25]:

$$\mathrm{GWS} = \frac{\mathrm{GF}}{A_{\mathrm{A}}}, \quad (1)$$

where:

- GWS: groundwater stress indicator. Values below 1 indicate low stress areas, values from 1 to 5 indicate low to middle stressed areas, values from 5 to 10 indicate middle to high stressed areas, values from 10 to 20 indicate high stressed areas and values above 20 indicate extremely high stressed areas.
- GF: groundwater footprint. Identifies the area required to sustain groundwater use and groundwater-dependent ecosystem services [23].
- A_{A}: areal extent of an aquifer throughout a given region.

The groundwater footprint is calculated as:

$$\mathrm{GF} = \frac{C}{R-E} \cdot A, \quad (2)$$

where:

- C: total area-averaged annual withdrawals of groundwater for anthropogenic use.

Table 2. Brief description and enumeration of additional methods used for the wastewater treatment and reuse scenarios (in order of execution).

#	Method	Systems involved	Description
7.	Desalination energy	Desalination system	Minimum energy requirements to desalinate brackish water using the Reverse Osmosis (RO) process. The TDS content of the water and the water withdrawals of each location are used, plus a minimum TDS content threshold of 1000 $mg\,l^{-1}$ to desalinate (a sensitivity analysis on these parameters were performed)
8.	Reclaimed, treated and reused wastewater	Residential, agriculture and wastewater treatment system	Estimates the available wastewater and tailwater to be reclaimed. Losses are subtracted and available treated wastewater/tailwater are computed for each cluster
9.	CAPEX and OPEX estimation	Residential, agriculture and wastewater treatment system	The Capital Expenditure (CAPEX) and the Operational Expenses (OPEX) of each evaluated wastewater treatment system are calculated for each cluster
10.	LCOW estimation	Wastewater treatment system	The levelized Cost of Water (LCOW) is calculated for each wastewater treatment system in each cluster
11.	Least-cost option	Wastewater treatment system	The least-cost wastewater treatment options are identified in each cluster
12.	Recalculate water withdrawals	Groundwater aquifer, residential, agriculture and wastewater treatment system	Based on water demand from the residential and agricultural sectors and the available treated wastewater for reuse in agriculture in each cluster
13.	Recalculate groundwater stress	Groundwater aquifer	New groundwater stress indicator based on new water withdrawals after treated wastewater/tailwater reuse in agriculture
14.	Recalculate pumping and desalination energy	Groundwater aquifer and desalination system	Recalculate pumping and desalination energy requirements for new water withdrawals from the aquifer after treated wastewater reuse in agriculture
15.	Wastewater treatment energy	Wastewater treatment system	Calculate the energy requirements for wastewater treatment of the least-cost treatment systems selected in each cluster

- R: total area-averaged annual recharge rate of water for groundwater aquifer, including natural and anthropogenic sources.
- E: total area-averaged annual environmental stream flow used to sustain ecosystem services (assumed as zero for the NWSAS).
- A: areal extent of a given region where C, R, and E can be defined.

2.5. Irrigation tailwater treatment system

Irrigation tailwater capturing, storing and reusing potential were estimated according to equation (3)

$$\text{water}_{\text{stored}} = 0.8\,\text{water}_{\text{used}} - \text{water}_{\text{crop}} - \text{water}_{\text{loses}}, \quad (3)$$

where:

- $\text{water}_{\text{stored}}$: monthly water used for irrigation based on each scenario water use regime.
- $\text{water}_{\text{crop}}$: monthly water requirements of the croplands, calculated based on the Penman–Monteith method.
- $\text{water}_{\text{loses}}$: monthly water losses due to evaporation in the storage system, leakage and storage capacity.

Crop water requirements ($\text{water}_{\text{crop}}$) were estimated using the FAO-56 Penman–Monteith method for evapotranspiration [26]. Meteorological parameters were calculated from 'WorldClim' monthly data [27] using the Python library 'Pyeto' [28]. For the purpose of this study, date palms and vegetables were assumed to cover in equal shares the cropland area—as they represent the main crops cultivated in the region [5, 6]. The crop coefficients and irrigation calendar were set according to [5]. From this process, the monthly crop water needs throughout the entire basin were obtained.

Furthermore, an on-farm storage pond system was evaluated to account for the potential reusable water ($\text{water}_{\text{stored}}$). For this, a water balance on the on-farm storage was executed following a similar approach to Reinhart *et al* [29]. First, the maximum attainable irrigation efficiency (i.e. crop water requirements over irrigation water used) was set to be

Table 3. Pollutant levels of domestic wastewater and treated wastewater to be reused in agricultural irrigation. Based on [31].

Pollutant type	Domestic ($mg\,l^{-1}$)	Treated ($mg\,l^{-1}$)	Removal (%)
Suspended solids (SS)	700	30	95
Nitrogen (N)	40	30	25
Phosphorus (P)	20	10	50
Biochemical oxygen demand (BOD_5)	500	50	90
Chemical oxygen demand (COD)	1300	120	90

80%, being the remaining 20% non-recoverable loses. If additional water was available, it was recovered and stored. The storage reservoir surface area, was assumed at 2% of the cropland area and a standard depth of 3 m [29]. Leakage losses in the storage system were set to be 0.9 $mm\,d^{-1}$, and evaporation loses were calculated using a modified Penman–Monteith method for an open water body [29]. For this, and albedo, surface height, and surface roughness values of 0.05, 0.002 m, and 0 s m^{-1}, respectively were used [30]. Moreover, energy requirements of 0.19 $kWh\,m^{-3}$ of tailwater conveyed was used.

2.6. Domestic wastewater treatment system

The amount of domestic wastewater generated, was assumed to represent around 70% of the total domestic water used [11]. From that share, an additional 10% was assumed to be lost in the capture, conveyance and treatment processes. Pollutant levels of domestic wastewater were assumed to be constant throughout the basin, using standard values based on studies from FAO [31]. Such levels and the required levels for reused treated wastewater in irrigation are shown in table 3.

One irrigation tailwater treatment technology and seven domestic secondary wastewater treatment technologies (WWTT) were evaluated (table 4). For this, pollutant removal ranges, capital and operational costs were taken into account. Cost functions in terms of wastewater treatment capacity, were used for each technology to estimate capital expenditure (CAPEX) (i.e. includes all capital investments required) and operational expenses (OPEX) (i.e. covers all fix and variable costs needed to operate the plant, including energy requirements) [32–34]. However, technology specific cost functions were not available for the NWSAS basin area, nor statistical data to develop them. Therefore, based on the work of Molinos-Senante *et al* [33] cost functions for different WWTTs in Spain were used to evaluate the competence of selected technologies in the NWSAS. As all technologies evaluated in [33] were derived from data from real cases covering about 274 unit processes, the behaviour of the curves is expected to follow a similar trend in the NWSAS, maintaining a comparable relative cost differences between technologies. Moreover, energy intensity characteristics were added for each technology according to [35, 36]. See section 6 of the supplementary information for specific information of the evaluated technologies.

Table 4. Domestic wastewater treatment systems analysed.

Technology	Usage	Energy ($kWh\,m^{-3}$)
Intermittent sand filter (ISF)	Domestic wastewater	0.2
Trickling filter (TF)	Domestic wastewater	0.3
Moving bed biofilm reactor (MBBR)	Domestic wastewater	0.8
Rotating biological contractors (RBC)	Domestic wastewater	0.8
Membrane bioreactor (MBR)	Domestic wastewater	0.8
Extended aeration (EA)	Domestic wastewater	0.6
Sequencing batch reactor (SBR)	Domestic wastewater	1.0

2.7. Levelized cost of water

A proposed LCOW method was used as a metric to compare cost-effectiveness among WWTTs. The LCOW assesses the life-cycle cost of delivering one unit (e.g. one cubic meter) of treated wastewater, based on all physical assets and resources required [18]. This concept, is inherited from the levelized cost of electricity (LCOE) methodology, which applies the same life-cost analysis for one unit of electricity output [37]. The LCOW method follows the logic of the LCOE method [37, 38], with pertinent adjustments to the variables used in wastewater treatment systems. Then, the LCOW can be expressed as follows:

$$\mathrm{LCOW} = \mathrm{LCOW_{Inv}} + \mathrm{LCOW_{OM}}. \tag{4}$$

The expression presented in equation (4), disaggregates the LCOW ($\$\ m^{-3}$) value in two components: the cost components due to investment $\mathrm{LCOW_{Inv}}$, and operation and maintenance $\mathrm{LCOW_{O\&M}}$. As the CAPEX function comprises all investment components of a wastewater treatment plant, it enables an easy calculation of the $\mathrm{LCOW_{Inv}}$ for each WWTT and each region or cluster. Equation (5) describes the process to calculate the $\mathrm{LCOW_{Inv}}$:

$$\mathrm{LCOW_{Inv}} = \frac{\mathrm{Inv}}{\sum_{t=1}^{T} V_t \cdot \gamma^t} \cdot \Delta, \tag{5}$$

where Inv stands for the CAPEX value, V_t for the treated water flow per year t ($m^3\,yr^{-1}$), Δ for the tax factor (assumed as 1) and γ^t represents the discount factor of the project, calculated for a discount rate of 5%.

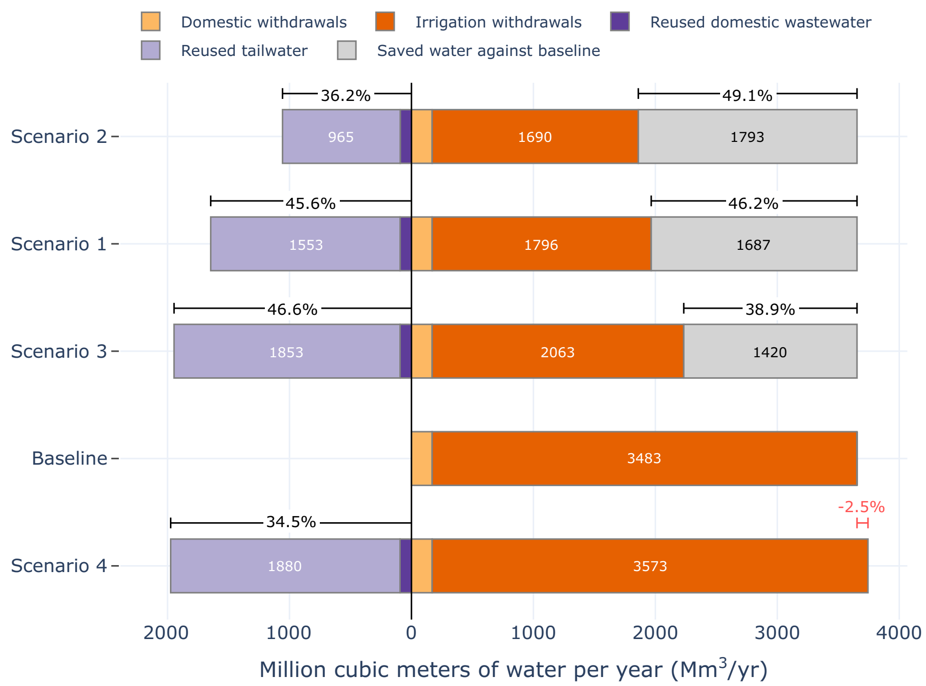

Figure 2. Water usage for all scenarios. At left: reused water after reclaim, treatment and allocation classified by population and irrigation source. Percentage bars indicate the share of reused water against the total demand. At right: overall water extractions classified by population and irrigation use. Percentage bars indicate the percentage of water saved compared to Baseline withdrawals.

The LCOW related to operational costs $\mathrm{LCOW_{O\&m}}$ equation (6) was computed by using the OPEX values ω_t calculated for each year in each cluster and the discount factor γ^t per year

$$\mathrm{LCOW_{O\&m}} = \frac{\sum_{t=1}^{T} \omega_t \cdot \gamma^t}{\sum_{t=1}^{T} V_t \cdot \gamma^t}. \qquad (6)$$

2.8. Sensitivity analysis

Sensitivity analysis were performed on the following key model parameters in order to provide clarity of the contributions of the inputs to the uncertainty in the results: domestic water use per capita, population growth, depth to groundwater levels change, groundwater quality change, irrigated area growth, TDS threshold to desalinate brackish water and discount rate. The complete rationale and results of the sensitivity analysis are reported in section 12 of the supplementary information.

3. Results

3.1. Water demand

Year average water withdrawals in the Baseline scenario were estimated at 3653.7 $\mathrm{mm^3\,yr^{-1}}$, with agricultural irrigation accounting for 95% of the total share (see figure 2). In scenarios 1 and 2, the overall water used was lower than the Baseline scenario (i.e water withdrawals plus water reused), opposite behaviour to scenarios 3 and 4. However, due to reusing treated wastewater/tailwater in irrigation, the overall water withdrawals were also lower in scenario 3 and only 2.5% more in scenario 4 than those of the Baseline. This shows that even in the worst case scenario of water usage (i.e. scenario 4), the total withdrawals can be similar to the Baseline by treating and reusing wastewater/tailwater. Moreover, water withdrawals in scenarios 1 and 2 were very close to each other and lower than that of scenario 3. This suggests that the higher irrigation water price due to the private regime, promotes the use of more efficient irrigation schemes reducing even more water withdrawals compared to wastewater/tailwater reuse only.

The share of reused wastewater/tailwater in the total water used was highest in scenario 3 (46.6%) and lowest in scenario 2 (36.2%). This means, that the available tailwater to reclaim, treat and reuse is much lower in scenario 2. As the overall irrigation efficiency is better in Scenario 2, the available tailwater to reclaim is lower, thus the reused share in the total water used is reduced. However, this is compensated with the reduced water withdrawals due to lower water use. This shows again the importance of using efficient irrigation schemes in reducing total water withdrawals.

On the other hand, wastewater/tailwater reuse share was lower in scenario 4 against scenario 3. This was due to the cap set to the on-farm storage area of maximum 2% share of the cropland area. Therefore,

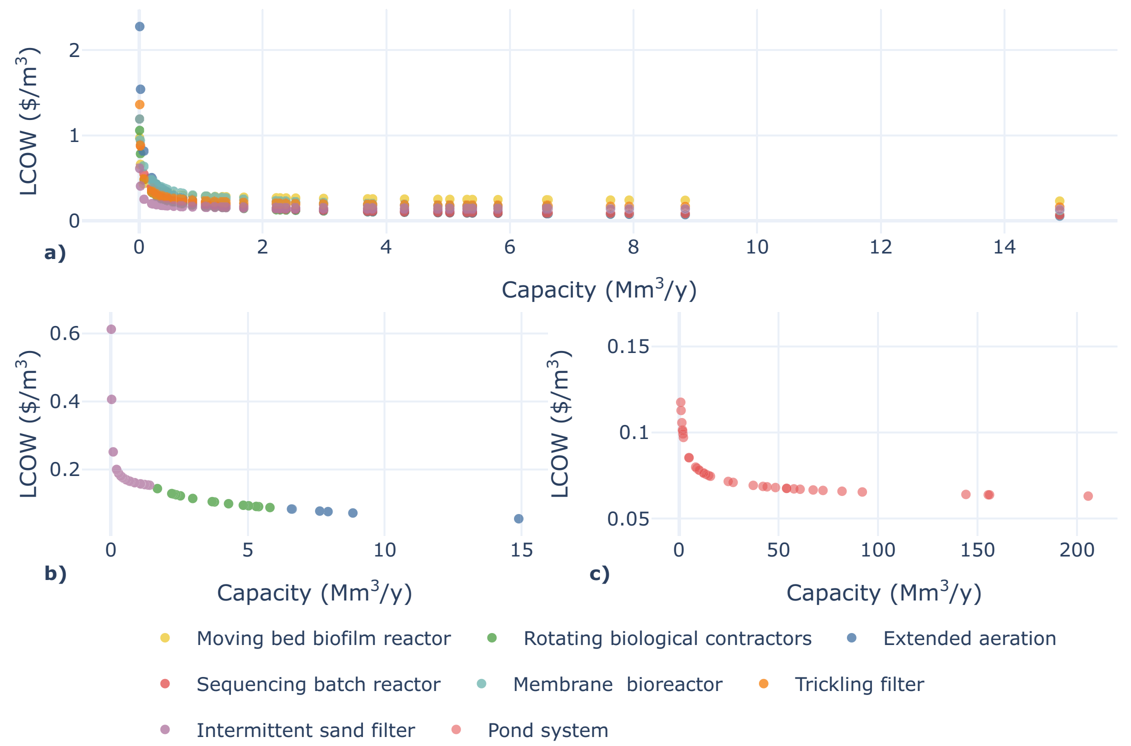

Figure 3. Levelized cost of water (LCOW) against treatment capacity for each cluster in Scenario 1. (a) LCOW for the 7 different technologies evaluated for domestic wastewater treatment. (b) Least-cost technologies for population wastewater treatment. (c) LCOW of the pond systems treatment technology evaluated for irrigation tailwater.

while more recoverable water is available in scenario 4 (i.e. due to the free water regime), the storage system cannot hold everything.

Finally, domestic water withdrawals do not represent large shares in the overall water use, as irrigation water use are much more extensive. Nonetheless, with the use of more efficient irrigation schemes and population growth, recoverable irrigation tailwater decreases, and population treated wastewater share on agricultural water usage increases. Detailed per cluster results are presented in section 10 of the supplementary information.

3.2. Least-cost wastewater treatment systems

Intermittent sand filters, rotating biological contractors and extended aeration were the least-cost technologies identified for domestic wastewater treatment, with 10.7%, 44.5% and 44.8% share respectively. Figure 3, shows the LCOW value comparison of the technologies in evaluation, against the required treatment capacity of each cluster. In general, when lower capacity is required simpler treatment technologies are more cost-effective, as the independent variable of the CAPEX and OPEX cost functions is the available reclaimed wastewater flow.

The previous is important, as the amount of wastewater available from the agglomerations is key for the calculation of the least-cost technology. Therefore, with larger agglomerations, scalable and higher capacity systems could be implemented.

Moreover, the LCOW value for tailwater treatment in pond systems, shows a steep increase in value for very low treatment capacity. This implies that as irrigation efficiency or irrigated area decreases, the cost feasibility of using pond systems also decreases.

Overall, the least-cost treatment systems obtained, showed important trade-offs, as the best solutions are dependent on geospatial factors than can render a specific technology less costly than other in a given region. Parameters as population proximity to irrigated areas, wastewater treatment capacity and irrigation water usage are key for selecting the proper wastewater treatment and reuse systems. Detailed cluster maps on least-cost technologies can be found in section 12 of the supplementary information and sensitivity analysis on discount rate on section 13.

3.3. Energy requirements

The overall energy related outcomes for all scenarios are shown in figure 4. The energy requirements for groundwater pumping represent the major part of all three activities. Desalination energy, although smaller, represent about a half of the pumping energy, while treatment energy between a sixth and a tenth of the pumping energy. All scenarios apart from Scenario 4, reduced or had similar overall energy consumption as the baseline.

Such reductions, are achieved by the reuse of treated wastewater in irrigation, as the energy

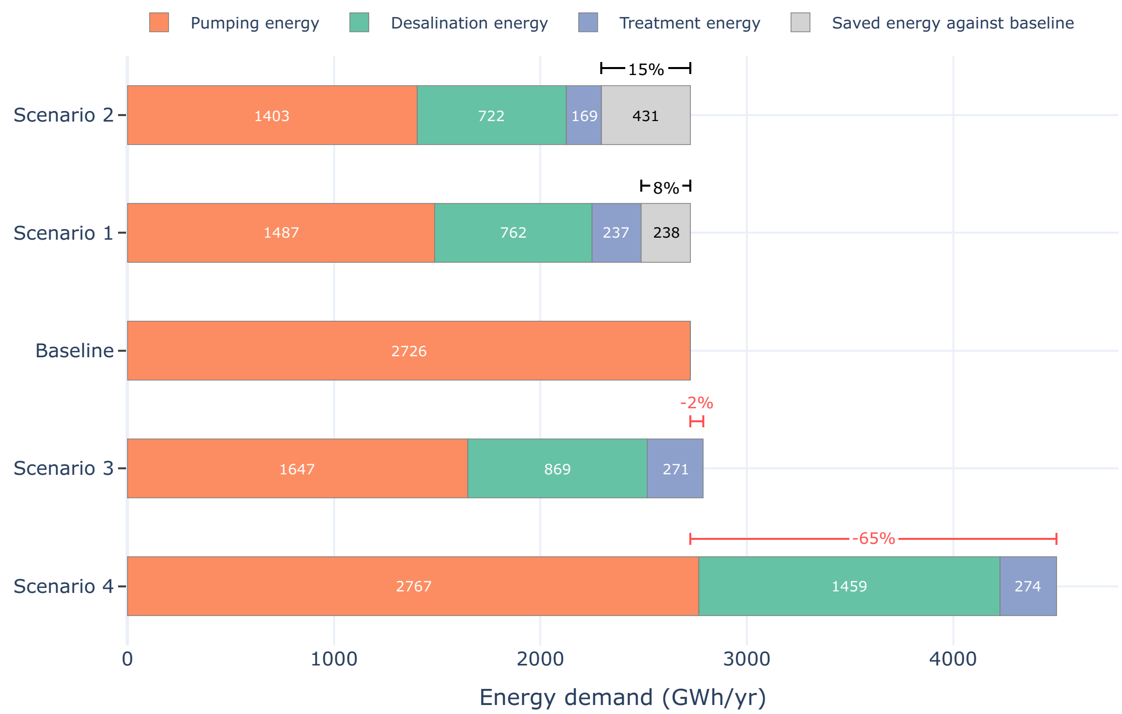

Figure 4. Energy requirements for all scenarios. Percentage bars indicate the share of saved energy against the baseline total.

intensity of treatment is substantially lower than the energy intensity for pumping water from the deep aquifer. This shows synergies between SDG 6, SDG 2 and SDG 7, as when more wastewater is collected and treated it can be made available for reuse in agriculture, supporting sustainable food production and efficient irrigation schemes. Moreover, it can reduce energy intensity of the system and promote the use of clean energy sources. Additional results are presented in section 11 of the supplementary information.

Groundwater depth levels affects most overall energy requirements, increasing substantially pumping needs. This can be seen in figure 5 where all clusters having lower depth values are consistently placed to the right side of the diagonal. The opposite is true for clusters with higher depth levels. On the other hand, TDS content seems to have a much weaker effect as the main driver for energy needs in RO desalination comes from feed water pressurization [39, 40]. Details of the methodology used for estimating desalination energy requirements can be seen section 7 of the supplementary information and section 13 presents sensitivity analysis on TDS content of brackish water.

3.4. Groundwater stress

The overall aquifer GWS for all scenarios, falls inside the extremely high category (table 5 and figure 6). Moreover, the indicator distribution throughout the clusters vary widely, with some clusters falling inside the low and low-to-medium categories. This behaviour is mainly driven by the differences in irrigated area within each cluster and the cluster area. Nonetheless, all scenarios except from scenario 4 achieved a reduction in GWS due to the reduction on total water withdrawals. Scenario 3, 1 and 2 obtained substantial reductions of around 39%, 46% and 49% respectively. Total, min, max, mean, and median values of GWS are presented in table 5.

The GWS can be related to SDG target 6.4.2 on Water Stress, which measures the share of total water withdrawals over the total renewable water resources, subtracting environmental flow requirements. Both indicators are broadly consistent and clearly show the critical condition of the region in terms of water scarcity (see table 5). Synergies and trade-offs of SDG 2 with SDG 6 are clear, specially with targets 6.4 on increasing water-use efficiency and ensuring sustainable withdrawals and supply of freshwater to ease water scarcity, and 6.6 on protect and restore water-related ecosystems.

4. Discussion and broader sustainable development implications

Wastewater reclaim, treatment and reuse, has a clear potential to alleviate water stress in the NWSAS, while supporting sustainable food production and energy efficiency. Supported by a GIS-based quantitative analysis, the use of a Nexus approach sheds light on

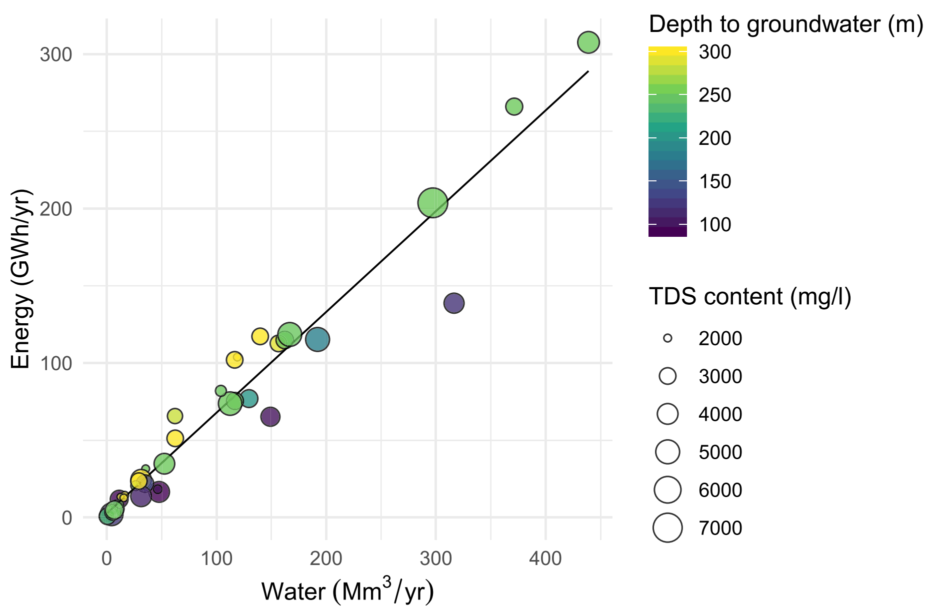

Figure 5. Total energy and water requirements per cluster for Scenario 1. Clusters are represented by the data points. TDS contents of water (mg l^{-1}) are shown as the size parameter of each data point/cluster. Depth to groundwater (m) is represented by the colour ramp. The diagonal represents the trend line of the data points.

Table 5. Summary of GWS results by scenario. The total for the entire aquifer (total), as well as the minimum (min), maximum (max), average (mean) and median values between the clusters are presented.

		Scenario				
Parameter	Value	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4
GWS (—)	Total	155.1	83.4	78.9	94.8	158.9
	Min	4.0	3.8	3.3	3.5	4.0
	Max	447.0	276.2	276.2	276.2	439.3
	Mean	165.0	93.7	90.8	103.5	172.0
	Median	134.3	76.1	76.1	89.4	153.7
Water stress (%)	Total	331.4	178.3	168.7	202.6	339.6
	Min	8.5	8.0	7.1	7.5	8.5
	Max	955.6	590.3	590.3	590.3	939.0
	Mean	352.6	200.2	194.1	221.3	367.6
	Median	287.0	162.6	162.6	191.2	328.6

synergies and trade-offs among selected Sustainable Development targets of interest. Wastewater treatment and reuse could indirectly improve water supply (SDG 6.1) as it can increase water availability, given that proper regulations are adopted to prevent increments in sectoral water usage. Water quality (SDG 6.3) is directly enhanced and water efficiency (SDG 6.4) clearly improved as shown by the GWS. Food security (SDG 2.1/2.2) and agricultural production are directly supported by adopting sustainable practices (e.g. as tailwater reclaim and treatment) and reducing soil salinization (i.e. due to reduction of untreated wastewater/tailwater discharged to the environment). Energy efficiency (SDG 7.3) can be positively affected, as wastewater treatment showed to be less energy intense than pumping water from the groundwater aquifer. Thus, by reusing treated wastewater the overall use of energy per cubic meter delivered could be reduced. This, however, is dependent on the wastewater reclaim and treated wastewater supply system. If large centralized systems are implemented, the need to cover long distances from supply to demand may be inevitable (i.e. wastewater collection points to agricultural irrigation sites), thus large amounts of energy may be required for surface water pumping. Nonetheless, by using decentralized systems (e.g. on-farm treatment and wastewater treatment in small agglomerations), those issues can be lessen. Moreover, by supplying treated wastewater to farmers, on-farm pumping from groundwater aquifers can be reduced, reducing as well the use of fossil fuels and electricity from the grid—the electricity generation mix in the NWSAS countries is heavily dominated by fossil fuel sources, making it an unclean source of energy [41–43]. Accordingly, climate mitigation can also be improved as both the water and the agricultural sectors GHG emissions would be reduced. Moreover, climate resilience (SDG 13.1) also has potential to be improved, as the increase on water availability for agricultural production (and

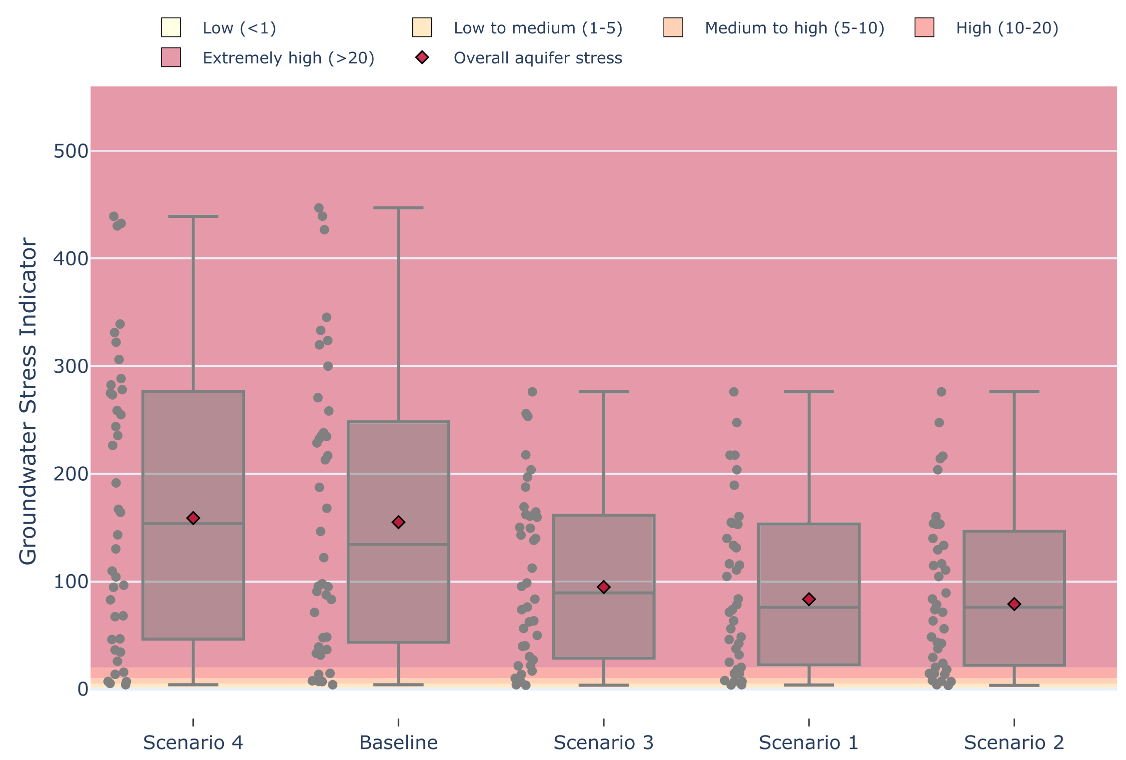

Figure 6. Groundwater stress indicator for all scenarios. The distribution of the indicator throughout the 40 clusters is represented by the points and the boxes, whereas the overall indicator calculated for the entire basin is represented by the red diamonds. The background indicates the scale of stress that the indicator falls into.

indirectly for drinking purposes), would aid on severe drought periods.

Despite the synergies and high potential treated wastewater has in supporting sustainable development and alleviating water scarcity, it can be argued that the measure of increased wastewater reuse alone is not enough. As a matter of facts, none of the scenarios integrating treated wastewater/tailwater reuse achieved a reduction on groundwater stress category. A key parameter affecting such indicator was the water use behaviour of farmers towards price regimes. The inappropriate valourization of water in the NWSAS has been already identified, as well as the inefficiency of irrigation [4]. Therefore, water management strategies and proper pricing mechanisms that ensure the appropriate use of the resource by local farmers are needed. Moreover, the perception of wastewater reuse from local farmers is key on achieving successful strategies, as in some cases this has shown to be an important barrier for treated wastewater reuse [44]. As Mahjoub *et al* [44] analyse 'aspects related to education, knowledge, risk perception, culture, regulation, and communication need to be seriously addressed for a more viable and efficient use of wastewater in agriculture'.

There is great value on having a Nexus approach while evaluating the treated wastewater reuse measure. It enables to identify and potentiate synergies and mitigate or avoid trade-offs. Nexus thinking has the potential to enhance well-being by decoupling it from natural resources degradation. Special attention needs to be put into understanding the cultural and social characteristics from the evaluated region, and the mechanism and strategies needed to create awareness, acceptance and implementation. Thus, articulated policies, regulations, and monitoring mechanisms are needed to properly valuate and manage natural resources holistically rather than in silos and achieve the full potential that treated wastewater reuse poses. Moreover, the use of an enhanced LCOW methodology including tax factors, externalities and specific discount rates, could aid on understanding the efforts required to make treated wastewater/tailwater competitive against local costs of water (what the farmer actually pays).

Finally, limitations exist in the current study. As the CAPEX and OPEX figures used for the different technologies evaluated were taken from the Spanish case in [33], the overall values are expected to vary in the NWSAS. It can be argued that CAPEX figures for all technologies could be higher due to the need for technology imports and transport to the more remote areas of the basin. Whereas OPEX figures could be lower due to the lower wage rates and heavily subsidized energy prices in the three NWSAS countries [8]. Although sensitivity analysis on selected input variables was provided in the supplementary material, uncertainty in other input data exists. Crop water requirements my be very sensible to variations in climatic variables as temperature, wind speed, solar irradiation, and precipitation. Therefore, climatic projections can be used in combination with detailed hydrological models to estimate future water availability, compute water requirements for crop irrigation and estimate groundwater level change. Moreover, inputs related to crops harvested, wastewater treatment costs, water use per capita, coverage of wastewater sanitation, wastewater pollutant composition, energy intensity of treatment technologies, recoverable wastewater and agricultural drainage, among others, can be improved with site-specific data. However, as the aim of this study was to explore, from a Nexus perspective, the sustainable development implications of reusing treated wastewater in irrigation, the authors believe that the present analysis is valuable to promote sustainable and holistic measures to ease water scarcity and could support the execution of more detailed and site-specific developments.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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ORCID iDs

C Ramirez https://orcid.org/0000-0002-7217-3838
Y Almulla https://orcid.org/0000-0003-3015-8610
F Fuso Nerini https://orcid.org/0000-0002-4770-4051

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