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Towards agro-environmentally sustainable irrigation with treated produced water in hyper-arid environments

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Abstract

Produced water (PW) is the main waste stream generated from oil and gas extraction. Nowadays, half of the global PW volume is managed through environmentally controversial and expensive disposal practices, such as re-injection through deep wells. In dry areas such as in the Arabian Peninsula, PW could be reused to irrigate crops, creating environmental, economic and social value. However, the quality of most PWs remains challenging as their high salinity, sodicity and alkalinity can degrade soil fertility and crop yield. Mitigating these negative impacts is costly as it requires specific PW treatment and irrigation management. Thus, the environmental sustainability and the cost of irrigation with PW are uncertain. The aims of this paper was to assess the agro-environmental sustainability of irrigating crops with PW in hot and hyper-arid climate and to estimate the operating cost of reusing PW for irrigation in order to compare this PW management approach to PW disposal in terms of environmental impacts and financial cost. To this end, a soil-water model was used to simulate irrigation of jojoba (*Simmondsia chinensis*) with oilfield-PW. Different irrigation strategies combining over-irrigation, PW blending and desalination were tested to preserve the soil structural stability and the crop yield. The operational costs of identified sustainable scenarios were estimated using a cost analysis. In this case study, the simulations showed that using an irrigation volume up to ~390% of the crop water needs with a blend composed of raw and desalinated PW in a 2:1 ratio could preserve the soil structural stability and the crop yield. However, for irrigation, the least-cost option was to mix raw and desalinated PW in a 1:4 ratio and to reduce the irrigation amount to just meet the crop water needs. Although the cost of managing PW in irrigation remains up to 2.5 times higher than PW disposal, this practice might be competitive considering the crop value generated and the increasing need for sustainable alternatives to PW disposal.

Keywords: arid climate; irrigation water quality; modelling, oil, salinity; SALTIRSOIL

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1 Introduction

The extraction of oil and gas (O&G) is accompanied by massive volumes of produced water (PW), which is composed of formation water initially present in the hydrocarbon reservoir and also water that has been injected during O&G operations and comes back to the surface (such as water injected for enhanced oil recovery and hydraulic fracturing) (Engle et al., 2014). By volume, PW is the main by-product associated with the O&G industry (Veil, 2011) and its volume is increasing (Hedar and Budiyono, 2018; Nasiri et al., 2017). In the southeast Arabian Peninsula, for instance, the volume of PW generated by the O&G industry was estimated at 330,000 m^3/day in 1997 (Al-Muscati et al., 1997), but is predicted to exceed 1 million m^3/day in 2019 (Prabhu, 2018).

In most onshore O&G fields, the PW that is not reused for enhanced oil recovery is usually injected into deep disposal wells (Global Water Intelligence, 2014). This technique is used for disposing of PW worldwide (Van de Hoek et al., 2000; Stefanakis et al., 2018), however, it is energy, and carbon-intensive and expensive (Al-Rawahi et al., 2014). Moreover, injecting PW into deep disposal wells implies environmental risks, such as groundwater contamination (Hagström et al., 2016) and induced seismicity (Walsh and Zoback, 2015). To mitigate these risks, increasingly stringent regulations, requiring extensive PW treatment prior deep-well injection, have been developed in several parts of the world (Al-Sofi, 2014; Folger and Tiemann, 2016). Regulators also impose gradual reductions in the volume of PW that can be disposed of. In the southeast Arabian Peninsula, for instance, PW disposal into shallow geological formations has not been permitted since 2005 and authorities urge O&G firms to reduce the volume of PW injected into deep geological formations (Stefanakis et al., 2018).

Over time, the PW-to-oil ratio of O&G operations increases, and can be as high as 10:1 in mature production zones (Stefanakis et al., 2018). PW management is becoming increasingly costly compared to the revenue obtained from O&G extraction, due to the growth of PW volume (Du et al., 2005), such that the profitability of operating an O&G field can be compromised.

Reusing PW for agricultural irrigation provides an alternative to deep-well injection to reduce the environmental and financial costs of PW management, and the reuse of PW in agricultural irrigation is an opportunity to transform a waste stream into a valuable resource. This concept is particularly relevant in water-scarce regions where agricultural development is limited by water availability. This is in alignment with the ambitious water management and agricultural development policies of Gulf countries, aiming to reinforce their food security through the reuse of marginal water resources (Jaffar Abdul Khaliq et al., 2017; McDonnell, 2016). In theory, the contribution of PW to irrigation in the southeast Arabian Peninsula could be significant as the 365 million m^3/year of PW represents the equivalent of

31% of the annual water volume abstracted by the agricultural sector – the largest water consumer in the local economy (FAO, 2009a).

However, reusing PW in irrigation imposes challenges that are related to agro-environmental sustainability, water consumption and financial viability. The high concentrations of salts, sodium, alkaline ions and heavy metals, which often exceed the threshold values recommended in the FAO guidelines for irrigation water quality (Alley et al., 2011), is the main barrier for its unrestrictive use in agriculture. Even low salinity PW can degrade soil fertility by reducing soil-water infiltration if its sodicity is too high (Ayers and Westcot, 1985). A previous irrigation experiment conducted in Oman showed that the electrical conductivity (EC_e) and the sodium adsorption ratio (SAR_e) of the soil saturation extract rose from 1.6 to 7.1 dS/m and from 2.3 to 68.1, respectively, after only 102 days of irrigation with de-oiled PW (EC = 8 dS/m), resulting in a soil saturated hydraulic conductivity reduction by three orders of magnitude (Hirayama et al., 2002). Such soil degradation from using PW in irrigation is not unique to Oman but has been observed in many dry areas (Echchelh et al., 2018). In the long-term, PW salinity and sodicity can be responsible for the decrease of the soil structural stability and crop productivity (Echchelh et al., 2019).

Techniques aimed at mitigating soil salinity, such as over-irrigation to increase salt leaching (Norvell et al., 2009), PW blending (Atia, 2017; Martel-Valles et al., 2017; Mullins and Hajek, 1998; Sintim et al., 2017), and PW desalination (Sousa et al., 2017; Weber et al., 2017) to reduce salt inputs to the soil, as well as soil and irrigation water amendments to mitigate soil sodicity (Bennett et al., 2016; Johnston et al., 2008), have been tested in field experiments. However, these techniques were used individually, but not in combination to maximise their impacts. Each of these techniques has specific drawbacks. Over-irrigation leads to water losses through drainage whereas PW desalination induces the production of brine, which must be disposed of. The possibility of blending PW with another source of water depends on the availability and quality of other water resources. In many drylands, surface water is virtually non-existent and groundwater is usually fossil, deep and brackish. Therefore, there is no renewable water resource of suitable quality that can be used to dilute PW. Finally, soil gypsum amendments reduce the soil SAR but also increase the soil EC due to the dissociation of gypsum into Ca^{2+} and SO_4^{2-} ions in the soil solution. Gypsum preserves soil structural stability but using a large amount of it negatively affects crop productivity (Hillel, 2000).

There are few data about the economic and financial feasibility of reusing PW in irrigation (Plappally and Lienhard, 2013). Although a techno-economic analysis estimated the cost of reusing raw PW to irrigate crops in Colorado, USA, it did not include any technique to improve the quality of the PWs that were too saline-sodic to be used in irrigation (Dolan et al., 2018). On the contrary, Meng et al (2016) estimated the cost of treating PW in California, USA, up to potable level using desalination, but crops do not require such high water quality. A regional-scale study in Queensland, Australia estimated the cost of treating coalbed methane (CBM)-PW for agricultural irrigation at AU\$1.24/m^3 with an investment of AU\$800 million for building a water treatment plant (Monckton et al., 2017). However, CBM-PW is usually of better quality compared to conventional O&G PW such as PW generated in the Arabian Peninsula (Rice and Nuccio, 2000).

In this context, there is a need to quantify the impacts of irrigation with PW on soil salinity and sodicity to identify potential agro-environmentally sustainable irrigation strategies. This paper aims to assess the agro-environmental sustainability of irrigating crops with PW in a hyper-arid desert and to compare its environmental impacts and financial costs of both PW reuse in irrigation and PW disposal into deep-wells. Alternative agro-ecological mitigation strategies for controlling soil salinisation are simulated using a soil-water model predicting the long-term impacts of irrigation with PW on soil salinity, sodicity, alkalinity, and crop yield. It focuses on a case study where oilfield-PW has been used since 2015 to irrigate halotolerant crops. So far, the crops have been adapting to the PW quality and perennial trees, such as jojoba, showed continuous growth but it is still unknown if the crop performance can be maintained in the long-term without being compromised by excessive soil salinity and sodicity.

2 Material and methods

This paper adopts an integrated approach, comprising modelling the impacts of irrigation with PW on soil salinity and sodicity using a soil-water model and estimating the operating costs of potentially agro-environmentally sustainable irrigation scenarios using a cost analysis (Figure 1).

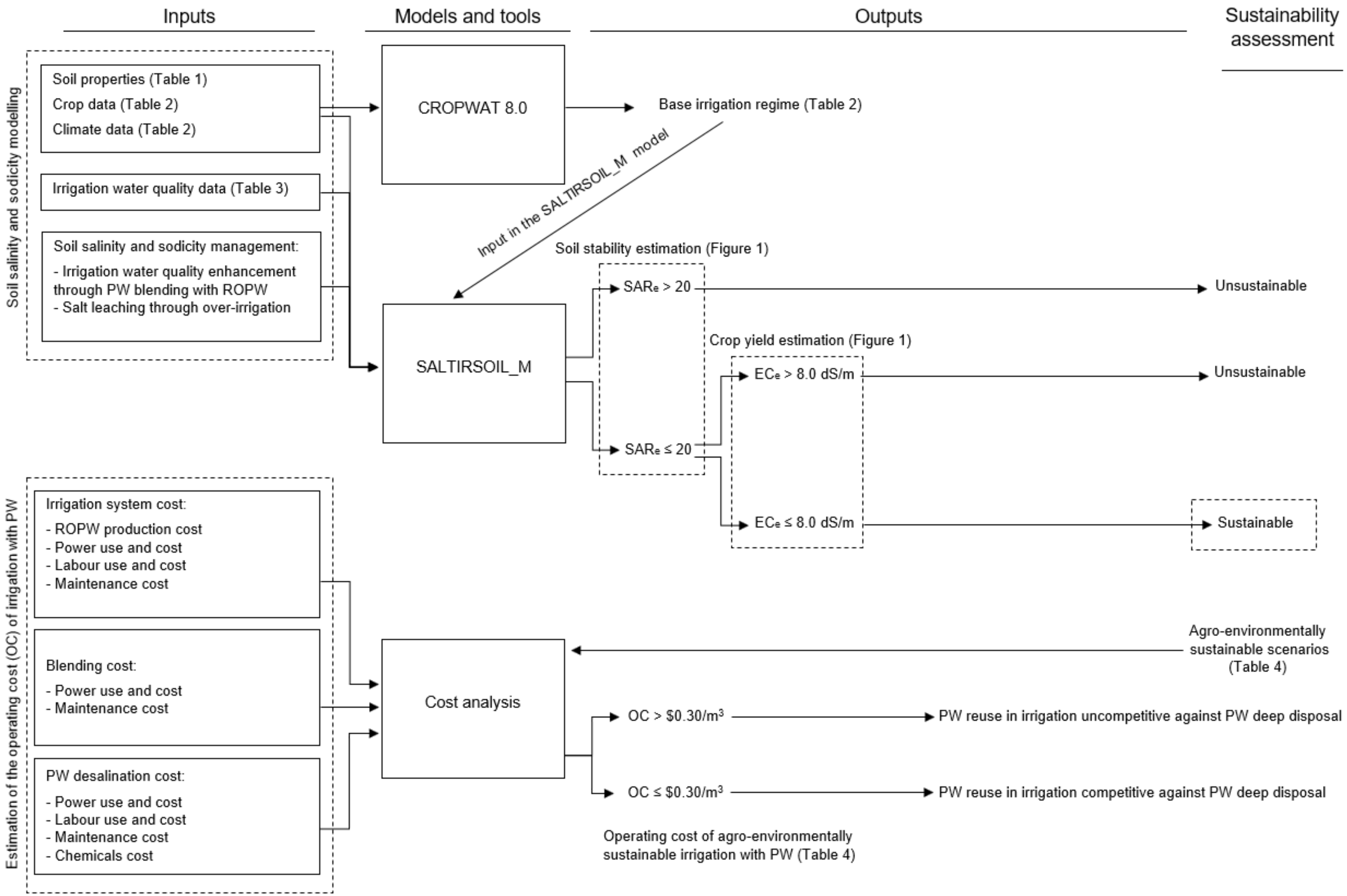

Figure 1. Research methodology flowchart and decision tree for the sustainability assessment.

2.1 Case study site

This case study is located in an oil field in the southeast Arabian Peninsula, where, up to 175,000 m^3/day of PW is treated using constructed wetlands, a sustainable technology applied for oil and fuel hydrocarbons removal from water (Stefanakis et al., 2018; Stefanakis, 2020). Most of the de-oiled PW is eventually discharged to a series of evaporation ponds, but a small volume is used to irrigate 22 hectares of crops as part of a 4-year biosaline agriculture research project (BARP) (Stefanakis et al., 2017). The soil is a shallow Gypsisol-Calcisol (Table 1) typical of this desert region (FAO, 2009b), with bedrock at 50–80 cm below the soil surface. The site is isolated, the soil has poor fertility, and the local climate is hyper-arid with no precipitation and 2,790 mm average annual potential evapotranspiration (Table 2). Because of this harsh environment, the area had never been cultivated. The objective of the BARP was to demonstrate the feasibility of achieving agro-environmentally sustainable irrigation with PW in hyper-arid environments and to encourage similar initiatives to reuse larger volumes of PW in the Gulf region and in drylands worldwide.

2.2 Crop choice

Several halotolerant crops are currently grown in the BARP including tree species such as jojoba (*Simmondsia chinensis*), eucalyptus (*Eucalyptus camaldulensis*), and acacia (*Acacia nilotica*), shrub species namely distichlis grass (*Distichlis spicata*), salt grass (*Paspalum vaginatum*), and dwarf saltwort (*Salicornia bigelovii*) as well as a fibre crop i.e cotton (*Gossypium arboretum*). Jojoba was selected as the focus of this study as it is a salt-tolerant crop with low water requirements which can be irrigated with drip irrigation systems. This crop has shown promising growth results in the field trials and adapted well to the shallow desert soils and harsh climatic conditions in southeast Arabia (Hayder et al., 2012). Jojoba oil has a number of personal (e.g. food, pharmaceuticals and cosmetics) and industrial uses (e.g.

lubricants and biofuels). It thrives in dry areas and on poor soils, and is also used to combat desertification and soil degradation in drylands (Al-Obaidi et al., 2017).

2.3 Definition of agro-environmental sustainability

Sustainability is commonly defined as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” (WCED 1987, p.15). The reuse of PW (which used to be considered as a waste) to create a cultivated soil in a desert environment is assumed to be an environmental enhancement compared to the initial conditions. The reuse of ecologically treated PW for valuable crop irrigation further contributes to a circular water economy paradigm where a previously considered waste (treated PW) is now viewed as a valuable input in a further environmentally and financially beneficial process (irrigation of crops with market value). Moreover, as PW is not injected underground, its reuse contributes to the preservation of the groundwater quality by reducing the risk of aquifer contamination by PW. As surface management of PW is less energy-intensive than deep injection (Stefanakis et al., 2018), it reduces energy consumption and associated greenhouse gas emissions. Furthermore, the emitted greenhouse gases are partially compensated by the carbon sequestered in the crop. It can provide economic and social benefits to the local community through the development of new agricultural land in a previously hyper-arid and unexploited desert area providing jobs and incomes in addition to crops.

The long-term preservation of the environmental, economic and social benefits of the BARP essentially depends on the ability to maintain the crop cultivation on site. This is only possible if the soil fertility is preserved from the high salinity and sodicity of the PW used to irrigate the crop. It is assumed that the aquifer would not be at risk of being altered as the upscaling of the BARP to a commercial-scale project would include a drainage system to capture and dispose the drainage water into the existing lined evaporation ponds. Thus, in this paper, the agro-environmental sustainability of irrigation comprises the preservation of the soil structural stability and the maximum crop yield potential by maintaining safe soil salinity and sodicity levels.

2.4 Quantification of the agro-environmental sustainability indicators

The agro-environmental sustainability indicators were calculated using the soil-water model SALTIRSOIL_M (Visconti, 2013). The SALTIRSOIL_M model is a unidimensional, deterministic, transient-state model with a monthly time step. It has been successfully used to calculate the long-term ionic composition and EC of the soil saturation extract of an irrigated field in semi-arid southeast Spain (Visconti et al., 2014). The SALTIRSOIL_M model is particularly relevant in this study as it has the ability to simulate the equilibrium state of the soil solution, which is the state that would be reached in the long-term under constant irrigation water composition, irrigation management, climate features, soil physical properties, and crop cultivation (Echchelh et al., 2020).

The soil depth selected for the simulation was 0.50 m, as this is the average observed soil depth in the BARP field plot. All results of soil composition were expressed for a saturated extract, which is the standard soil-water ratio for salinity measurements (Rhoades, 1996) and at chemical equilibrium.

2.5 Agro-environmental sustainability indicators and agro-environmental sustainability assessment

The risk of soil structure destabilisation was estimated by comparing the simulated long-term SAR_e to the threshold SAR_e values obtained from the Australian and New Zealand Environment Conservation Council (ANZECC) guidelines (ANZECC, 2000). These inform about the risk of soil structural instability depending on the soil texture and have been used as a reference to study the risks and feasibility of irrigating with PW under dry climates in

Australia and in sub-Saharan Africa (Horner et al., 2011; Mallants et al., 2017; Shaw et al., 2011). The threshold SAR_e was set at 20, as the soil in this case study is a sandy clay loam with a clay content below 24%. Due to the critical importance of the SAR_e for soil stability, no scenario can be considered agro-environmentally sustainable if the simulated soil SAR_e exceeds the ANZECC guidelines threshold value.

The relative crop yield was estimated from its expected response to EC_e. Jojoba has an estimated threshold EC_e of 8 dS/m, but the slope of the yield decrease when the soil EC_e exceeds this threshold remains unknown (Biosalinity Awareness Project, 2019). It was thus assumed that any EC_e value higher than 8 dS/m would make irrigation unsustainable.

Both the SAR_e and the EC_e are commonly used as indicators of soil salinisation and sodification in irrigation studies (Ezlit et al., 2010). Moreover, these indicators were also adopted in environmental assessments addressing the impacts of PW on soil, plants and groundwater (Biggs et al., 2013; Newell and Connor, 2006).

2.6 Simulated irrigation scenarios

Root zone EC_e and SAR_e can be managed by leaching salt out of the root zone through over-irrigation and/or by reducing salt inputs to the soil through the dilution of PW.

The jojoba is presently irrigated with 110 mm/year of PW (Table 2). Although jojoba can grow with less than 120 mm/year of water, its water consumption can exceed 450 mm/year (Ash et al., 2005). Therefore, different irrigation amounts were simulated from 110 mm/year (100% of the crop water needs) up to 450 mm/year (409% of the estimated crop water needs).

Groundwater cannot be used for improving PW quality as the aquifer is very saline (EC = 39.1 dS/m). Alternatively, de-oiled PW can be desalinated using reverse osmosis (RO), and RO-treated PW (ROPW) can be mixed with raw PW to improve irrigation water quality. RO has already been successfully used onsite as well as in other locations for adapting PW to irrigation (Brown et al., 2010; Ersahin et al., 2018). Moreover, RO remains the cheapest commercial technology for PW desalination (Jiménez et al., 2018).

The SALTIRSOIL_M model simulated the long-term EC_e and SAR_e resulting from increasing irrigation amount (from 100% to 409% of the crop water needs) of raw PW and of 99 different blends of PW-ROPW. The blends composition varied from 99% PW–1% ROPW up to 1% PW–99% ROPW.

2.7 Water quality

Table 1 presents the annual average quality of the two effluents (PW and ROPW) used in the irrigation simulations. These data were obtained from the BARP on-site laboratory. Prior to its use for irrigation, the PW is de-oiled (oil in water < 0.5 mg/L) by a constructed wetland facility (Stefanakis et al., 2018). The PW is poor in nutrients, (total nitrogen ~2.5 mg/L, phosphorus ~0.3 mg/L and nitrate ~0.1 mg/L) as they are almost completely removed in the constructed wetland. However, the salt concentration is not affected by the constructed wetland treatment process, and PW remains brackish (EC = 13.9 dS/m) and sodic (SAR = 65). ROPW is not produced under normal operating conditions but it has been generated onsite for testing the possibility of desalinating PW for irrigation purpose.

2.8 Climate

Monthly averages of temperature, relative humidity, precipitation, number of days with precipitation, wind speed and downward solar radiation for the period 2013-2017 were obtained from an on-site Davis Vantage Pro 2 meteorological station. The reference evapotranspiration (ETo) was estimated using the Penman-Monteith equation integrated into SALTIRSOIL_M and the number of sunshine hours was estimated using the adapted equation of Ångström-Prescott (Viswanadham and Ramanadham, 1969).

2.9 Soil

A Dutch auger and a bulk density cylinder were used to collect 30 soil samples representative of two depth ranges 0–0.25 and 0.25–0.50 m. Soil water retention properties, bulk density, texture, calcium carbonate equivalent and soil organic matter were determined according to standard methods (ISO 10693, 1995; ISO 10694, 1995; ISO 11272, 1998; ISO 11274, 1998; ISO 11277, 1998). The soil gypsum content was determined according to Soil Survey Staff (2014). A saturated paste was prepared for each sample, its pH_e was measured, the saturation percentage was calculated, and the saturation extracts were obtained and analysed for EC_e at 25°C, all according to Rhoades (1996). The alkalinity was determined by automatic titration (APHA, 1999) and ionic contents (Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, SO_4^{2-} and NO_3^-) by ion chromatography. Other input parameters used in the soil-water model such as the equilibrium CO_2 partial pressure –which is related to soil pH and alkalinity– and the pH_e of the soil pastes for each soil layer were calculated from the ion contents using the ion speciation software SALSOLCHEMIS (Visconti, 2009).

2.10 Crop growth and irrigation requirements

Model input parameters such as the basal crop coefficients values of jojoba were obtained from the Mallee Catchment Management Authority (2017) while the shaded area was estimated on-site by measuring the surface area shaded by a mature jojoba tree.

Table 1. Soil properties of the BARP field plot.

Soil type	Soil layer (cm)	Hydrophysical			USDA texture			Chemical				
(FAO's RSG)		ρ_b (g/cm^3)	θ_{fc} (%)	θ_{pwp} (%)	Sand (%)	Silt (%)	Clay (%)	pH	Gypsum (%)	CCE (%)	SOM (%)	log pCO_2
Gypsisol-Calcisol	Topsoil 0–25	1.81	23.5	13.9	62	26	11	8.0	12	68	1.3	-3
	Subsoil 25–50	1.93	22.4	14.6	63	26	10	8.1	8	69	1.1	-3

FAO's RSG: FAO's Reference Soil Groups, ρ_b: bulk density; θ_{fc}: soil volumetric water content at field capacity; θ_{pwp}: soil volumetric water content at permanent wilting point; CCE: calcium carbonate equivalent, SOM: soil organic matter, log pCO_2: log value of the CO_2 partial pressure.

Table 2. Climatic, crop development and water quality data used in the simulations.

	Parameter	January	February	March	April	May	June	July	August	September	October	November	December	Total
BARP on-site meteorological station	P (mm)	0	0	0	0	0	0	0	0	0	0	0	0	0
	ETo (mm)	134	162	230	264	301	294	333	325	284	185	145	132	2790
Jojoba	I (mm)	6	6	8	9	11	12	12	12	11	9	8	6	110
	K_{cb}	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	6
	Root depth (cm)	50	50	50	50	50	50	50	50	50	50	50	50	-

P: precipitation; ETo: reference evapotranspiration; I: base irrigation regime covering 100% of the crop water needs; K_{cb}: basal crop coefficient.

Table 3. Quality of the different waters used for irrigation simulations (all ions contents are expressed in mmol/L or mmol$_c$/L of [$CaCO_3$] equivalent for the alkalinity, and the electrical conductivity in dS/m).

	[Na^+]	[K^+]	[Ca^{2+}]	[Mg^{2+}]	[Cl^-]	[NO_3^-]	[SO_4^{2-}]	Alk_w	EC_w	SAR_w	pH_w
PW	123.591	1.082	2.409	1.209	124.524	0.002	5.782	4.753	13.89	65	8.0
ROPW	0.322	0.006	0.010	0.001	0.290	0.008	0.052	0.075	0.04	3	8.7

PW: produced water, ROPW: reverse osmosis-treated produced water, EC_w: water electrical conductivity, SAR_w: sodium adsorption ratio of the water, Alk_w: water alkalinity as [$CaCO_3$] equivalent.

2.11 Cost analysis

A cost analysis was used to estimate the annual operating costs of the identified agro-environmentally sustainable irrigation scenarios. The operating cost is defined as the cost of watering a hectare of jojoba equipped with drip irrigation and calculated as the sum of the costs of associated with PW desalination, PW blending with ROPW and to the irrigation system.

2.11.1 Operational cost of PW desalination

The desalination cost of PW (DC) was estimated at \$0.89/m³ calculated as per Eq. (1) and expressed in \$US/ha/year:

$$DC = WC_{ROPW} + \ PC + MC + LC + CC + other\ costs \tag{1}$$

where WC_{ROPW} is the cost of the volume of ROPW applied in \$US/ha/year and PC is the power cost, in \$US/ha/year, estimated in Eq. (2):

$$PC = Total\ power\ use\ of\ the\ desalination\ unit\ \times electricity\ cost \tag{2}$$

The electricity cost was assumed to be \$0.08/kWh (locally-sourced data).

The estimations of the maintenance cost (MC), labour cost (LC), chemicals cost (CC) and other costs related to PW desalination, all expressed in \$US/ha/year, were based on a pilot-scale treatment train (Ersahin et al., 2018).

The volume of brine generated by RO was estimated at 30% of the inflow PW (Ersahin et al., 2018).

2.11.2 Operational cost of blending PW

Blending PW with ROPW would necessitate a constructed reservoir for mixing both effluents in the right proportion. It was assumed that PW and ROPW were pumped separately (using the same pump type as for the one used for irrigation) and mixed into a constructed reservoir. The PW-ROPW blend was then pumped to irrigate jojoba.

The blending cost (BC) was estimated at \$0.10/m³ and calculated as per Eq. (3) and expressed in \$US/ha/year:

$$BC = PC + \frac{annual\ maintenance\ cost\ of\ the\ reservoir}{annual\ volume\ of\ water\ pumped\ into\ the\ reservoir} \tag{3}$$

The calculation of PC was described previously. The maintenance cost, in \$US/m^3/year, was assumed for a lined reservoir of 75,000 m³ of usable capacity suitable to irrigate an area of 30 ha (after Weatherhead et al., 2014).

2.11.3 Operational cost of the irrigation system

The irrigation system cost (IC), in \$US/m^3/year, was estimated in Equation (4):

$$IC = WC + PC + MC + LC \tag{4}$$

As only ROPW was given a cost while PW was assumed to be delivered free of charge, the water cost (WC), in \$US/m^3/year, was calculated as per Eq. (5):

$$WC = DC \times volume\ of\ ROPW\ applied \tag{5}$$

PC is the power cost, in \$US/m^3/year, estimated in Eq. (6):

$$PC = \frac{volume\ of\ water\ applied}{pump\ flow\ capacity} \times pump\ motor\ power \times electricity\ cost \tag{6}$$

PC is related to pumping irrigation water, with a pump of 48 m³/h flow capacity powered by a 7.5 kW-electric motor (Oosthuizen et al., 2007).

MC is the maintenance cost of the irrigation system, in \$US/m^3/year, estimated in Eq. (7):

$$MC = \frac{annual\ maintenance\ cost\ of\ the\ irrigation\ system}{plot\ area} \tag{7}$$

The annual maintenance cost of a 25 ha-plot equipped with drip irrigation was obtained from Oosthuizen et al. (2007).

LC is the labour cost, in \$US/m^3/year, calculated estimated in Eq (8):

$$LC = \frac{annual\ amount\ of\ hours\ of\ labour\ required}{plot\ area} \times hourly\ mimimum\ wage \quad \textbf{(8)}$$

The annual amount of hours required was obtained from Oosthuizen et al (2007). The hourly minimum wage was estimated at \$15.58/hour for a monthly labour cost of \$1039/month and maximum working hours of 40h per week (locally-sourced data).

2.11.4 Costs not considered

Only the difference in cost between managing PW in irrigation and managing PW through deep-well disposal were considered. Therefore, the cost of de-oiling PW was not included in the cost analysis because PW needs to be de-oiled regardless of its final destination. Also, the cost of evaporating the RO-brine resulting from PW desalination is assumed to be negligible as a much larger volume PW is already sent to ponds to be evaporated after being treated by the constructed wetland.

The capital and investment costs related to the irrigation and drainage system, water conveyance, water blending, PW desalination were not included in the cost analysis. If a commercial-scale irrigation project based on the BARP will be developed, these parameters would be dependent on the project size (e.g. infrastructure dimension) and local financial conditions (e.g. interest rates, subsidies, etc.) which could not be estimated at this early stage of the project.

2.12 Energy consumption

The energy consumption of irrigation with PW (in kWh/m^3) was estimated as the sum of the energy consumed for PW desalination and water pumping.

The RO unit consumes 3.35 kWh/m^3 of ROPW generated (Ersahin et al., 2018). Thus, the energy consumption of the RO in kWh/ha unit was estimated in Eq. 9

$$Energy\ consumed\ for\ PW\ desalination = V_{ROPW} \times 3.35 \quad \textbf{(9)}$$

where V_{ROPW} is the volume of ROPW applied in m^3/ha.

PW and ROPW need to be pumped separately to the blending site from where the PW-ROPW mix is pumped to the irrigated field. The three pumps have the characteristics as the pump described earlier and consumes 0.16 kWh/m^3 (power × pump rate). The energy consumption required for pumping water in kWh/ha was estimated in Eq. 10

$$Energy\ consumed\ by\ pumps = V_{IW} \times 0.16 + V_{PW} \times 0.16 + V_{ROPW} \times 0.16 \quad \textbf{(10)}$$

where V_{IW} and V_{PW} are the total volume of irrigation water and the volume of PW applied in m^3/ha respectively.

3 Results and discussion

3.1 Impact of irrigation on soil structural stability and on crop yield

The results of the simulations showed that irrigation of jojoba with raw PW would be unsustainable, whatever the irrigation amount applied. Indeed, when 110 mm/year of PW was applied, the SAR_e reached 87, which is far in excess of the ANZECC threshold value of 20 for maintaining the soil structural stability. The EC_e reached 28.5 dS/m, which is also much higher than 8 dS/m, the threshold EC_e value of jojoba. Increasing the irrigation amount to 450 mm/year partially leached the excessive salt load out of the root zone, and the SAR_e and the EC_e were 28 and 10.8 dS/m, respectively (Figure 2). These values were still too high to preserve the soil structural stability and a maximal crop yield in the long-term.

Agro-environmentally sustainable irrigation was possible by mixing PW with ROPW. Using irrigation water composed of 65% PW-35% ROPW with an irrigation amount of 425 mm/year (i.e., 386% of the crop water needs) resulted in a long-term SAR_e and EC_e of 19 and 8.0 dS/m, respectively. Approximately the same SAR_e and EC_e could be obtained with an irrigation amount of 110 mm/year (i.e. 100% of the crop water needs) but with a lower PW content in the irrigation water, that is 19% PW-81% ROPW (Figure 2). Both scenarios would be agro-environmentally sustainable by preserving the soil structural stability and the maximal crop yield potential. The long-term application of blended PW to the soil had a limited impact on soil pH, in fact the pH_e slightly decreased compared to the initial conditions (Table 4) remaining within the suitable range for jojoba cultivation excluding risks of nutrient deficiencies.

Conserving irrigation water could only be achieved with high irrigation water quality (i.e., a low PW content in the blend). In fact, when 110 mm/year of irrigation was applied to the soil to cover the crop water needs, almost all the water was used by the crop or evaporated (101 mm out of 110 mm) leaving only 9 mm/year of drainage water. Thus, when irrigation waters with a PW content higher than 19% were used the SAR_e and the EC_e of the soil solution increased above the critical thresholds. Consequently, for an irrigation strategy aiming at using the maximum proportion of PW in the irrigation water (such as 65% PW-35% ROPW), a higher irrigation amount (425 mm/year) had to be applied to leach the excessive salt out of the root zone. However, this strategy reduced the water efficiency of irrigation as the volume of water that was either used by the crop or evaporated remained at 101 mm/year, while the amount of water drained reached 324 mm/year. This lower water efficiency eventually limited the potential area that could be irrigated compared to an irrigation strategy aiming at conserving water (Table 4).

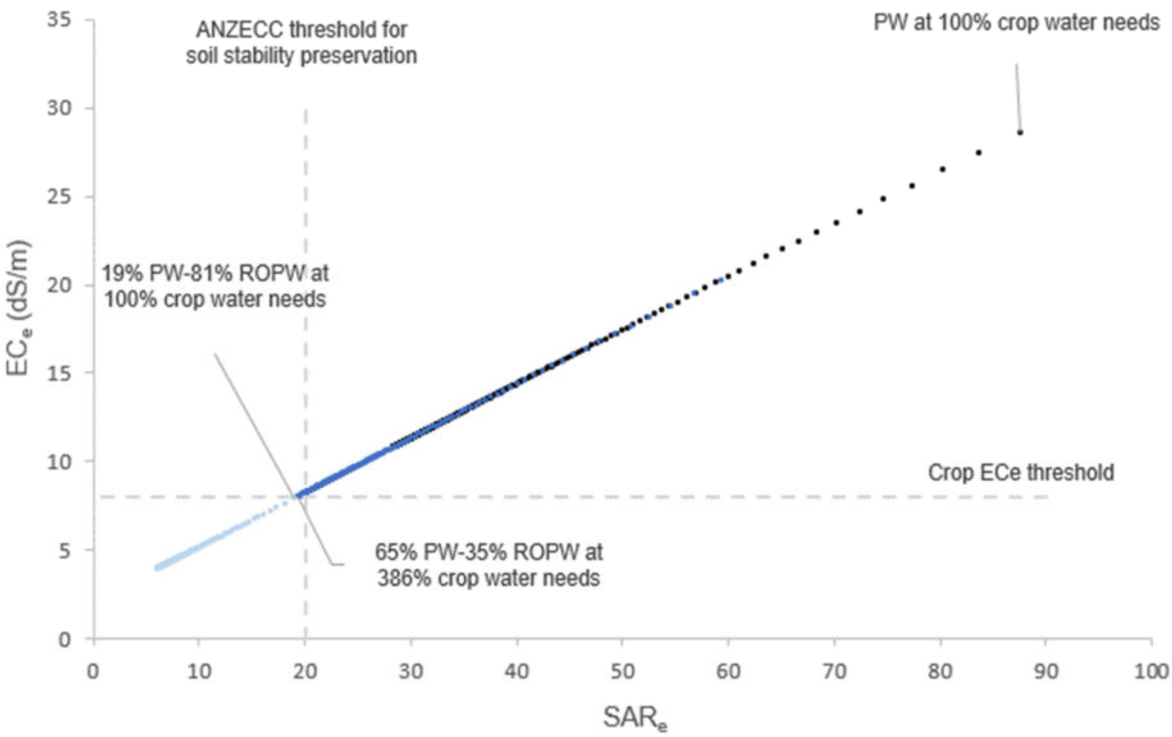

Figure 2. Long-term EC_e and SAR_e following irrigation of jojoba with different blends of PW diluted with ROPW (from 100% PW down to 1% PW + 99% ROPW) and with different irrigation amounts (from 100% up to 300% of the crop water needs).

3.2 The environmental performance of produced water reuse

Although both over-irrigation and PW blending irrigation strategies achieved agro-environmentally sustainable SAR_e and EC_e values, they differ in terms of water use. Indeed, a water conservation approach with 110 mm/year of 19% PW-81% ROPW minimised the volume of water lost through drainage to 91 m³/ha/year, but it also generated 382 m³/ha/year of RO-brine that would be discharged to the evaporation ponds. In addition to having a lower irrigation efficiency, using 65% PW-35% ROPW with an irrigation amount of 449 mm/year generated more RO-brine (664 m³/ha/year) compared to an irrigation strategy with 19% PW-81% ROPW. Actually, even if less desalinated PW had to be added in the 65% PW-35% ROPW blend than in the 19%

PW-81% ROPW blend, more irrigation water had to be applied to maintain sustainable EC_e and SAR_e levels. Therefore using 65% PW-35% ROPW led to a larger volume of ROPW used per hectare than using 19% PW-81% ROPW (Table 4).

Preserving the long-term soil structural stability and a maximal crop yield involves a trade-off between 'wasting' water through drainage for salt leaching and 'wasting' water through RO-brine (generated by the desalination process) to reduce the irrigation water salinity and sodicity. In this study, targeting agro-environmentally sustainable SAR_e and EC_e values, while minimising the water losses, could be achieved by irrigating jojoba at 110 mm/year with a blend composed of 19% PW-81% ROPW (Table 4).

Reusing PW in irrigation would require between 1.5–3.5 kWh/m³ of energy (Table 4). In comparison, injecting PW into deep disposal wells requires between 3.6–5.5 kWh/m³ of energy (Breuer and Al-Asmi, 2010). This comparison between the energy use of PW reuse and the energy use of PW disposal is corroborated by a detailed energy footprint assessment carried out in New Mexico (USA), which demonstrated that reusing PW was far more energy-efficient than transporting and disposing of PW into deep disposal wells (Zemlick et al., 2018). In the current case study, PW deep-injection is relatively cheap because the deep disposal wells are located nearby the oil field, whereas, in several American O&G fields, PW needs to be hauled (sometimes over long distances) to the deep disposal wells, making PW disposal much costlier. Currently, the concept of reusing PW in irrigation in southeast Arabia does not receive as much support by local and/or governmental authorities as in the USA, but there is already an ongoing shift due to the stricter regulation pushing towards the reduction of PW volumes to be re-injected and/or disposed of in the region.

In areas where there are no evaporation ponds to manage saline effluents (i.e., drainage water and RO-brine), these streams could still be managed through deep-well injection. The reuse of PW in irrigation would at least reduce the volume of effluents that need to be injected, save energy, and reduce the cost of PW disposal compared to a situation where all PW is injected into deep disposal wells.

3.3 Cost of produced water reuse in irrigation

The cost of reusing PW in irrigation is very dependent on the cost of pumping water and desalinating PW. As these two factors are themselves dependant on the energy cost and on the irrigation amount, the least-cost irrigation scenario was the one minimising both the energy use and the irrigation amount. For this reason, the less costly irrigation strategy estimated at \$821/ha/year was to use 19% PW-81% ROPW with 110 mm/year of irrigation amount (Table 4).

The operational cost of using PW in irrigation was estimated between 0.32–\$0.75/m³ (Table 4). In comparison, the cost of managing PW through deep-well injection was estimated at \$0.30/m³ in 2010 (Hardisty, 2010). The main operating cost of deep-well injection is related to pumping (\$0.11/m³ in 2004) as this cost component is on an increasing trend, the cost of deep-well injection rises (Schrevel et al., 2004). Although its higher cost compared to PW disposal, the reuse of PW in irrigation benefits both the O&G companies and irrigators. Thus, unlike PW disposal, where O&G firms must bear the disposal cost alone, reusing PW in irrigation would include the contribution of irrigators. The participation of two stakeholders in sharing the cost of PW reuse in irrigation is likely to improve the economic viability of this practice in the future. If the O&G firm prefers to manage the reuse of PW internally, then the revenue generated by the farm would cover the whole or part of the operational cost. Jojoba starts to produce a significant volume of oilseeds four years after planting. The potential value of a jojoba crop was estimated at $1,500/ha/year four years after planting and up to $6,250/ha/year eight years after planting (Khan et al., 2017). The estimated potential revenue, which is greater than the estimated operational cost, needs to be compared to the total financial cost of the project which includes the capital cost. A complete financial analysis of this case study would bring further evidence regarding the financial viability of PW reuse in irrigation. In fact, the financial justification of reusing PW in irrigation in southeast Arabia remains controversial as Hardisty (2010) estimated that the agricultural revenues are not sufficient to cover the PW treatment cost, farm operating cost and project decommissioning cost (including the cost consists of excavating the salt-contaminated soil). However, this significant cost estimated between 10,000–$18,000/ha, would not be necessary if the irrigation scheme includes salinity and sodicity management strategies.

The financial cost of PW management is not the only criterion for selecting a PW management practice. In fact, the local O&G firm is determined to cut the amount of PW injected into deep disposal wells from 52% presently to 22% by 2025 (Prabhu, 2018). These changes in terms of PW management are partly motivated by the increasingly stringent regulation that is likely to further increase the cost of PW disposal practices. As other PW reuse options exist, those must be compared to the reuse of PW in irrigation in terms of environmental and financial cost. Indeed, the range of PW reuse options differ in terms of environmental and social impacts, economic cost and benefits, PW treatment standards and potential volume that can be reused (Table 5).

Table 4. Environmental and financial performance of selected agro-environmentally sustainable irrigation strategies

Scenarios	Irrigation water volume, quality, and water losses						Impact on soil				Water and power consumption		Irrigation operating cost	
	PW (%)	ROPW (%)	Crop needs (%)	Irrigation (m^3/ha)	Brine (m^3/ha)	Drainage (m^3/ha)	Potential area (ha)	EC_e (dS/m)	SAR_e	pH_e	Total PW use (m^3/ha)	Power use in kWh/ha (and in kWh/m^3)	\$/ha	\$/m^3
A	65	35	386	4246	637	3237	8596	8.0	19	7.7	4883	6305 (1.5)	1355	0.32
B	19	81	100	1100	382	91	28326	7.9	19	7.6	1482	3329 (3.0)	821	0.75

A: scenario with the lowest irrigation water quality acceptable, B: scenario with the lowest irrigation amount, water losses, cost and largest potential irrigated area, PW: produced water, ROPW: reverse osmosis-treated produced water, EC_e: electrical conductivity of the soil saturation extract, SAR_e: sodium adsorption ratio of the soil saturation extract.

Table 5. Advantages and disadvantages of several beneficial reuses of PW compared to the reuse of PW in irrigation

Economic sector	Uses of PW	Advantages	Disadvantages	Reference
Agriculture and aquaculture	Irrigation	O&G fields are often surrounded by large farmland areas.	Risks of soil and aquifer contamination; Seasonal variability in irrigation water demand; Costly irrigation management and PW treatment is often needed; Social acceptability remains challenging for food crops.	1, 2, 3, 4
	Livestock watering	O&G fields are sometimes surrounded by large dairy farms and feedlots. No direct impacts on soil, crop and aquifer.	The water quality must be relatively high compared to irrigation standards to avoid livestock exposure to toxic contaminant levels (TDS < 10,000 mg/L).	1, 2, 3, 4
	Aquaculture	Some fish species can tolerate high water salinity (equivalent to seawater), thus the management of PW salinity is likely to be cheaper compared to PW reuse in irrigation.	Although salt-tolerant, fish are sensitive to a myriad of contaminants (organics, heavy metals, acidic or alkaline inputs, etc.); Risk of food chain contamination (e.g. heavy metals) especially for fatty fish species.	3
Environmental restoration	Aquifer recharge	Restore aquifer for multiple groundwater users (agriculture, industry and services). PW of adequate quality can be injected into few wells reducing water conveyance cost.	Risk of aquifer contamination if PW is high in contaminants (i.e. dissolved minerals and organic pollutant).	1

	Stream flow augmentation	Can be a source of indirect PW reuse (e.g. irrigators pumping water into rivers); Prevent low-flow surface streams from drying out, thus, maintaining ecosystems; Limit water conveyance cost.	Risk of surface water contamination (water biological and chemical oxygen demand as well as salinity are critical); Elevated flows accelerate erosion.	1
	Rangeland restoration	O&G fields are sometimes surrounded by extensive rangelands; Restore rangelands damaged by over-grazing and drought; Better social acceptability compared to food crop irrigation.	Risks of soil and aquifer contamination; Lower crop value generated per m^3 of PW used compared to food crop irrigation.	1
	Impoundment into natural or artificial wetland	Support biodiversity and prevent desertification; Better social acceptability compared to food crop irrigation through the creation of leisure areas.	Risk of surface water, soil, aquifer and wildlife contamination (e.g. acute and chronic sodium bicarbonate toxicity to aquatic species).	3
Energy and industry	Reuse in O&G operations (enhanced oil recovery, hydraulic fracturing, well drilling, etc.)	PW is reused onsite limiting water conveyance cost; Social acceptability is not a critical issue.	O&G operations may not be able to reuse the whole volume of PW generated (i.e. well saturation); Hydraulic fracturing requires low-salinity PW to increase O&G reservoir permeability; Risk of aquifer contamination when PW is reused in hydraulic fracturing.	1, 3, 4
	Power generation (steam) and cooling	Reduce freshwater abstraction for power plants and cooling units located in inland areas;	PW must be of suitable quality to avoid equipment scaling.	1, 3, 4, 7

		Social acceptability is not a critical issue.		
Mining	Metal recovery	Valuable metals (e.g. copper and lithium) can be recovered while treating PW whereas these are lost and can contaminated soils, plants and aquifers when PW is used in irrigation.	After metal recovery, PW still has to be managed somehow; Metal recovery from PW remains costly; Although PW contents in heavy metals get reduced, there are other contaminants of concern remaining in PW (e.g. salts).	5
	Dust control	Low quality PW can be used to control dust in coal mining. Better social acceptability compared to food crop irrigation.	High PW conveyance cost unless PW is generated near the mine where PW is reused.	1, 4
Construction and infrastructure maintenance	Drilling	Reduce freshwater abstraction; Better social acceptability compared to food crop irrigation.	Risk of contaminating soil layers and the aquifers crossed by the drill; The volume that can be reused in drilling is limited compared to irrigation.	1, 3
	Snow control and de-icing	Reduce grit salt consumption; Better social acceptability compared to food crop irrigation.	Risks of soil and aquifer contamination; Snow control and de-icing are seasonal activities; High water hauling cost; The volume that can be reused in snow and ice control is limited compared to irrigation.	1, 3

	Dust control	Suppress dust on unpaved roads used by heavy vehicles in dust-prone arid areas; Better social acceptability compared to food crop irrigation.	Risks of soil and aquifer contamination, the volume that can be reused in dust control is limited compared to irrigation.	1
Safety	Fire control	Avoids the use of freshwater for firefighting, The potential environmental degradation caused by PW quality is considered minimal compared to the damages caused by a wildfire. Better social acceptability compared to food crop irrigation.	Risks of soil and aquifer contamination, large PW storage reservoirs have to be built.	1
Domestic	Potable water supply	Reduces freshwater abstraction; Avoids environmental risks for the soil, plant and aquifer; Potable water has a higher value compared to irrigation water.	The treatment of PW up to potable quality grade is costly compared to irrigation quality grade; The social acceptability is likely to be even more challenging than for reusing PW to irrigate food crops.	1, 5, 6

[1](Guerra et al., 2011), [2](Horner, Castle and Rodgers, 2011), [3](Pichtel, 2016), [4](Nghiem et al., 2011), [5](Xu et al., 2008), [6](Meng et al., 2016), [7](Muraleedaaran et al., 2009)

3.4 Limitations

The modelling approach has several advantages as various ‘what-if’ scenarios can be tested, whereas an unmanageable amount of trials would be necessary with an experimental approach. Also, unlike field experiments, extreme scenarios can be simulated with a model without any negative environmental impact (Graves et al., 2002).

On the other hand, the adopted modelling approach has limitations that need to be underlined as the designers of a future irrigation scheme might consider the results of these simulations. Firstly, the SALTIRSOIL_M model has been calibrated and validated against field results in semi-arid Spain with irrigation water of moderate salinity (1.5–2.8 dS/m) (Visconti et al., 2014) but it has not yet been tested and validated in hyper-arid conditions, such as the case study oilfield in the southeast Arabian Peninsula with water of equivalent quality. Therefore, the next step would be to continue the monitoring of the site by analysing soil and water samples on a regular basis. The long-term data collected in the field could be used to test the SALTRISOIL_M model under hyper-arid conditions and to adjust the model assumptions. Also, the potential agro-environmentally sustainable and least-cost scenario (19% PW-81% ROPW with 110 mm/year of irrigation amount) needs to be tested in field conditions and the measured SAR_e and EC_e values compared to the simulated SAR_e and EC_e values. In the long term, the measured values should tend towards the values estimated with the soil-water model.

The agro-environmental sustainability assessment based on threshold SAR_e and EC_e values selected in this study requires further development. Indeed, although the ANZECC guidelines are more specific than the FAO guidelines (Ayers and Westcot, 1985) by taking into account the soil clay content to evaluate the soil vulnerability to dispersion, they lack precision. Recent studies have underlined the risk of using generic standards (Bennett et al., 2019; Dang et al., 2018).

4 Conclusions

The increasing volume of PW is mostly managed through deep-well injection in southeast Arabia. This practice is environmentally controversial and with rising costs because of its energy consumption and the increasing regulatory pressure forcing the development of alternatives to PW disposal. PW reuse in irrigation can reduce the negative impacts of PW disposal while providing a significant volume of water to irrigators. This concept is being tested in an oil field located in the southeast Arabian desert where a biosaline agriculture research project has investigated various appropriate halotolerant crops and irrigation management for reusing large PW volumes. However, PW quality is challenging and agro-environmentally sustainable irrigation can only be achieved by controlling soil salinity and sodicity.

Blending raw PW with desalinated PW in a 2:1 to 1:4 ratio can mitigate the impacts of long-term soil salinisation and sodification on the soil structural stability and on the crop yield. The estimated operational cost per m^3 of this agro-environmentally sustainable irrigation practice ranged between a similar cost and up to twice as much as the cost of disposing of PW into deep wells. Although disposing of PW remains cheaper that managing PW in irrigation, the latter provides environmental benefits such as a reduced energy consumption and carbon emissions compared to PW disposal as well as socio-economic benefits associated to the production of crops.

Paradoxically, although water-efficiency is seen a priority in water-scarce drylands, preserving the soil from long-term salinisation and sodification impose high water losses. Indeed, increasing the irrigation amount to leach salt out of the root zone leads to a loss of water through drainage. On the other hand, improving the irrigation water quality by partially desalinating PW leads to a loss of water though RO-brine. Consequently, there are trade-offs between losing water and consuming energy by either over-irrigating to leach the excessive salt load out of the root zone or by desalinating PW to reduce the salt input to the soil.

Despite the current financial barrier, drivers such as the increasing cost of PW deep disposal, new stringent regulation increasing PW disposal cost, possibility of sharing the cost of producing irrigation water from PW with irrigators, and value generated by the cultivated crop may make the reuse of PW in irrigation financially competitive.

Conflict of interests

None.

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