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Agro-environmental sustainability and financial cost of reusing gasfield-produced water for agricultural irrigation

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Abstract

Produced water (PW) is the largest by-product generated from oil and gas extraction. Currently, half of the total PW volume is managed through environmentally-controverted and costly disposal practices. In dry regions, PW could be beneficially reused to irrigate crops reducing the overexploitation of freshwater resources. However, PW quality, and particularly its high salinity, sodicity and alkalinity, create uncertainties regarding the agro-environmental sustainability and the cost of this practice. The aim of this paper was to identify potential agro-environmentally sustainable irrigation schemes with gasfield-PW in hyper-arid Qatar and to estimate their operating costs. A soil-water model was used to simulate the irrigation of sugar beet with gasfield-PW under the climatic and soil conditions occurring in northern Qatar. Different irrigation strategies combining over-irrigation, PW blending with treated sewage effluent (TSE) and PW desalination were tested in order to protect the soil and the aquifer from salinisation and sodification. The operating costs of identified agro-environmentally sustainable scenarios were estimated through a cost analysis. In the case study, the simulations indicated that using an irrigation volume up to ~300% of the crop water needs with a blend of two-thirds PW and one-third TSE (or desalinated PW) could preserve the soil stability, crop yield and groundwater quality. The least-cost option was to reduce the irrigation amount at a little over the crop water needs and mix PW with an equivalent volume of TSE or four equivalent volumes of desalinated PW which would cost \$0.26/m^3 and \$0.46/m^3 respectively. As traditional PW disposal practices cost between \$0.06–\$16.67/m^3, reusing PW in irrigation is thus potentially a competitive PW management strategy for O&G firms.

Keywords: arid climate, irrigation water quality, modelling, Qatar, salinity, sodicity.

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1 Introduction

Oil and gas (O&G) exploitation generates large volumes of 'produced water' (PW) which is the main waste stream derived from this industry (Veil, 2011). PW is naturally present in the hydrocarbon-bearing strata and flows up to the surface when O&G are extracted. PW also includes water returning to the surface after being artificially injected to enhance O&G production (Engle et al., 2014). Whereas half of global PW volume is beneficially reused to increase hydrocarbon recovery, the other half is managed through injection into deep disposal wells or treated and discharged onto the surface without being reused (Echchelh et al., 2018). This is problematic because deep-well injection is energy-intensive and carbon-intensive, and therefore is costly (Arthur et al., 2011). Besides, this practice is environmentally risky, as it can contaminate aquifers (Hagström et al., 2016) and induce earthquakes (Walsh and Zoback, 2015). Surface discharge is also controversial due to the risks of soil and water pollution (Christie, 2012; Konkel, 2016). Consequently, harsher environmental regulations are being developed demanding advanced PW treatment before discharging (Fakhru'l-Razi et al., 2009) or simply banning it completely (Igunnu and Chen, 2014).

In this context, sustainable alternatives to existing PW management practices are needed. Reusing PW to irrigate crops is an opportunity to reduce the dependence of the O&G industry on traditional disposal techniques while providing significant volumes of water to croplands located in O&G basins (Echchelh et al., 2018). Qatar is an example of how the O&G industry's quest for reducing PW disposal could help meet a country's environmental and agricultural ambitions (Raja and El-Hadi, 2012). Qatar has a hyper-arid climate and limited freshwater resources which are almost totally located in its aquifers. Groundwater reserves and quality have been constantly declining since 1998, mainly because of overexploitation by the agricultural sector which accounts for 92% of groundwater abstraction (Ministry of Development Planning and Statistics, 2017). The government aims to restore aquifers by limiting the volume of groundwater extracted and by developing the reuse of treated sewage effluent (TSE) in irrigation (Jasim et al., 2016). In the meantime, Qatar operates the largest gas reservoir in the world known as North Field (Fulks and Kumar, 2015). North Field generates about 1.4 million m^3/year of PW, representing the largest wastewater stream in the country (Al-Kaabi, 2016), 3.2% of Qatar's average annual water balance, and 0.6% of the annual groundwater volume used in agriculture (Ministry of Development Planning and Statistics, 2017). This potential supply of irrigation water could help Qatar to reduce groundwater abstraction while increasing crop production and achieve its food security plan (Qatar e-government, 2019a). Short-term political risks such as the regional economic blockade on Qatar as well as longer-term trends such as population growth and climate change reinforce the need for developing local non-conventional irrigation water resources (Miniaoui et al., 2018).

Unfortunately, PW reuse in irrigation is challenging mainly because PW is high in salt, sodium, alkaline ions and heavy metals which frequently exceed the threshold contents for irrigation water (Alley et al., 2011). Indeed, irrigation experiments conducted in dry areas have shown that PW quality was responsible for increased soil salinity and sodicity which negatively affected soil structural stability, soil hydraulic properties, and eventually crop productivity (Beletse et al., 2008; Biggs et al., 2013; Burkhardt et al., 2015; Echchelh et al., 2018). Also, a modelling study considering multiple PW qualities, climates and soil types identified that PW alkalinity increases the pH of soils with low carbonate content (such as Arenosols and Planosols) in the long-term (Echchelh et al., 2019). PW alkalinity negatively affects irrigation sustainability for soils that are poor in calcium as the free alkalinity introduced by PW into the soil decreases the concentration of Ca^{2+} ions dissolved in the soil solution due to the formation of calcite which precipitates and accumulates in deeper soil layers (Mallants et al., 2017). When combined, high soil sodicity and alkalinity are responsible for soil particle dispersion, reduced water infiltration and soil hydraulic conductivity. The crop is directly affected by the specific toxicity of alkaline ions such as HCO_3^- and CO_3^{2-} but also indirectly impacted through reduced water availability and nutrient deficiencies through increased soil pH (Day and Ludeke, 1993).

Techniques, 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), irrigation with reverse osmosis-treated PW (ROPW) (Sousa et al., 2017; Weber et al., 2017), as well as soil and irrigation water amendments (Ali et al., 2018; Bennett et al., 2016; Ganjegunte et al., 2005; Johnston et al., 2008; Vance et al., 2008) have been used in field experiments to mitigate soil salinisation and sodification caused by irrigation with PW. However, these techniques were used individually but not in combination to maximise the mitigation of soil salinity and sodicity. Moreover, these short-term (1–3 years) field experiments do not inform about the environmental sustainability of irrigation with PW, that is, the extent of soil degradation and decline of crop productivity in the long-term (i.e. indefinitely). This information is critical as Qatari gas reserves are projected to last 138 years at the current production level (The Oil & Gas Year, 2019) thus, PW could potentially be used in irrigation and applied to the soil for decades. Furthermore, the majority of the field experiments were carried out in specific locations with climates and soils that are different from those found in Qatar. Ideally, long-term field experiments combined with models could be conducted to provide better predictions of the sustainability of irrigation with PW. Another limit of the field experiments conducted in Qatar is that they were not applicable to large irrigation schemes. Indeed, Atia (2017) diluted PW with tap water to mitigate the negative impacts of PW salinity and sodicity on the soil and on the crop, but this would be extremely costly at a commercial scale. Cheaper water resources, such as TSE or desalinated PW could be used to blend PW and improve irrigation water quality. Besides, other techniques such as over-irrigation to increase salt leaching could be used in conjunction with PW blending to control soil salinity and sodicity.

Finally, along with the possibility of having sustainable irrigation with PW, the cost of achieving irrigation sustainability remains unknown. Indeed, there is a lack of data regarding the financial feasibility of PW reuse in irrigation (Plappally and Lienhard, 2013). Although a cost analysis has been carried out to assess the feasibility of upgrading PW up to potable level using desalination in California (USA) (Meng et al., 2016), crops do not need to be irrigated with such high water quality. Dolan et al. (2018) considered the reuse of raw PW in Colorado (USA) but without considering any mitigation technique to adapt the PWs that were too saline-sodic to be used untreated in irrigation. A regional-scale study has been conducted in Queensland, Australia estimating the cost of treating coalbed methane (CBM)-PW for irrigation purpose at AU\$1.24/m^3. This treatment cost is achieved with an investment of AU\$800 million for building a water treatment plant with a lifespan of 20 years (Monckton et al., 2017). However CBM-PW is generally of higher quality compared to conventional O&G PW (Rice and Nuccio, 2000) which would be more expensive to treat.

For these reasons, there is a need for quantifying the long-term environmental impacts of irrigation with PW in Qatar. Also, potential sustainable irrigation strategies using PW blending and desalination need to be identified and their costs estimated.

This paper aims to, first, identify possible agro-environmentally sustainable irrigation strategies with gasfield-PW in Qatar, using over-irrigation, PW blending and PW desalination to protect the soil and the aquifer from salinisation and sodification. The second objective of this study is to estimate the costs of these irrigation scenarios that are potentially agro-environmentally sustainable.

2 Material and methods

This paper combines a modelling approach to simulate the impacts of irrigation with PW on soil salinity and sodicity with a cost analysis to estimate the operating costs of agro-environmentally sustainable irrigation scenarios (Figure 1).

2.1 Agro-environmental sustainability

Sustainability is generally defined as meeting current human needs without compromising the ability of future generations to meet their own needs (Held, 2001). In this paper, agro-environmental sustainability is considered as conserving the current soil and groundwater capital for future generations. For this, it is necessary to prevent soil and aquifer salinisation and sodification as a result of irrigation with PW. In order to quantify these degradations, indicators were selected.

2.2 Sustainability indicators and sustainability assessment

To estimate the risk of destabilising the soil structure, the sodium adsorption ratio (SAR_e) of the soil saturation extract was selected as an indicator. This indicator is widely used to estimate the risk of soil sodification as a result of irrigation (Hillel, 2000) and can be compared to the Australian and New Zealand Environment Conservation Council threshold SAR_e values informing about the risk of soil structural instability (ANZECC, 2000). The ANZECC guidelines were used as a reference to study the risks and feasibility of using PW in irrigation under dry climates globally (Echchelh et al., 2019) but also specifically 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 northern Qatar is sandy with a clay content lower than 15%. Due to the critical importance of SAR_e for soil structural stability, no scenario can be considered sustainable if the simulated SAR_e exceeds the ANZECC guidelines threshold value of 20.

Similarly, the electrical conductivity (EC_e) of the soil saturation extract is commonly used as an indicator of soil salinity in irrigation studies (Ezlit et al., 2010). Moreover, both indicators were also adopted in environmental assessments addressing the impacts of PW on soil, plant and groundwater (Biggs et al., 2013; Newell and Connor, 2006). The relative crop yield was estimated through its expected response to the EC_e considering the FAO salt tolerance parameters given by Shaw et al (2011). For sugar beet, the threshold EC_e for a maximum yield is 7 dS/m. From this value, the crop productivity decreases by 5.9% per dS/m increase of the EC_e. Although, maximising crop yield is important from a farming perspective, O&G firms do not necessarily have the same target and can accommodate low yields as long as PW reuse in irrigation remains less costly compared to traditional disposal practices. Therefore, considering a minimum acceptable yield corresponding to 50% of the crop yield potential, the resulting threshold EC_e used in this study is 15.5 dS/m.

The quality of drainage water (DW) can affect groundwater. In fact, DW carries dissolved salts and depending on the aquifer depth and quality, it may increase groundwater salinity and sodicity (Shannon et al., 1997). The volume and quality of the DW leaving the soil were simulated at the maximum soil depth (1 m). The quality of DWs (EC_d and SAR_d) were compared to the average maximum EC (30.6 dS/m) and SAR (48) values of Qatar's northern aquifer to estimate the risks of groundwater salinisation and sodification.

2.3 Quantification of the sustainability indicators

The sustainability indicators were calculated using the soil-water model SALTIRSOIL_M (Visconti, 2013). The modelling approach was chosen primarily for minimising the time to obtain results compared to field experiments. Moreover, multiple 'what-if' scenarios can be tested with models without the need for a huge number of field experiments. Finally, extreme scenarios can be simulated without any negative environmental impact (Graves et al., 2002).

The SALTIRSOIL_M model is a deterministic, transient-state, unidimensional model with a monthly time step. It has been successfully used to calculate the long-term ionic composition and EC_e of the soil saturation extract of an irrigated field in semi-arid SE Spain (Visconti et al., 2014). The ability of the SALTIRSOIL_M model to simulate the equilibrium state (that is reached in the long-term) of soil solution ionic composition and EC_e makes it relevant for appraising the impacts of PW salinity, sodicity, pH and alkalinity on the sustainability of irrigation.

The soil depth selected for the simulation was 0–60 cm as this is the depth where sugar beet root density is maximal (Draycott, 2006). 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.

2.4 Irrigation scenarios and site characteristics

Irrigation was considered sustainable only if the root zone EC_e and SAR_e remained below their critical threshold levels of 15.5 dS/m and 20 respectively. This can be achieved by leaching salt out of the root zone through over-irrigation and/or by reducing the salt input to the soil through diluting PW with TSE or ROPW.

1. Although groundwater is the main source of irrigation water in Qatar, this resource cannot be used for blending PW. Indeed, the local authorities restrict groundwater abstraction for irrigation to preserve the aquifers and to use them as strategic reserves

in case of severe water shortage (Mohieldeen and Al-Marri, 2016). On the other hand, the use of non-conventional water resources, such as TSE, is developing particularly for substituting groundwater in irrigation (Ali et al., 2016).

2. TSE can be used to dilute PW and improve irrigation water quality.
3. PW can be desalinated through reverse osmosis (RO) and the RO-treated PW can be used to dilute PW and improve irrigation water quality. RO has been successfully used for adapting PW to irrigation (Brown et al., 2010) and remains the cheapest commercial technology for PW desalination (Jiménez et al., 2018).

In this paper, 39,999 simulations were performed to simulate irrigation with raw PW (1), PW blended with TSE (99 blends) and PW blended with ROPW (99 blends) with 201 irrigation amounts varying from 100–300% of the crop water needs for each water quality. The irrigation water composition varied from 99% PW-1% TSE or 99% PW-1% ROPW up to 1% PW-99% TSE or 1% PW-99% ROPW (Figure 1).

2.4.1 Crop choice

Tropical sugar beet was chosen as an exemplar crop due to its salt-tolerance (Tanji and Kielen, 2002), sodium- and chloride-tolerance (Wakeel et al., 2010), and its adaptation to sandy soils, high soil pH (SESVanderHave, 2016) and to dry climates (Chatin et al., 2004; Nilsson, 2005). Although sugar beet is not currently grown in Qatar (Ministry of Development Planning and Statistics, 2016), it could be of interest to supply a part of the needs of the country's first sugar refinery (Saul et al., 2018). This crop is a raw material for multiple products such as foodstuff (e.g. refined sugar) but also animal feed (e.g. pellets and molasses) and biofuel. It is therefore aligned with Qatar's policy aiming to improve food security and reduce carbon emissions (Abdel Bary, 2018).

2.4.2 Water quality

Three types of effluents were used: raw PW, PW-TSE, and PW-ROPW. Irrigation waters of decreasing salinity were simulated by blending PW with TSE or with ROPW.

PW is generated by several O&G fields in Qatar. North Field has been selected because of the large volume and the relatively good quality of PW it generates. Indeed, the salinity of its PW (7.1 dS/m) is much lower than the PW of Qatar's offshore oil fields which have an EC above 100 dS/m (Ahan, 2014). Data on PW quality were sourced from Janson et al (2015), Al-Kaabi (2016) and Ahan (2014) (Table 2).

TSE is mostly generated in Doha, the capital city and the largest urban area in Qatar gathering 80% of the country's population (Suez Group, 2019). The quality values of TSE from Doha municipal wastewater treatment plant were sourced from Ahmad (1989) except for nitrate content which was sourced from a similar type of effluent produced in Abu Dhabi, UAE (Dalahmeh and Baresel, 2014) (Table 2).

The quality of ROPW was estimated according to the performance of a pilot treatment train which successfully treated PW generating 70% ROPW and 30% brine from the inflow PW (Ersahin et al., 2018) (Table 2).

2.4.3 Climate

Qatar's climate is classified as hyper-arid with an aridity index of 0.02 (Cherlet et al., 2018), it has very limited rainfall making its agriculture totally dependent on irrigation (FAO, 2009a).

Qatar's monthly climatic averages of temperature, relative humidity, precipitation, wind speed, downward solar radiation, and number of rainy days for the period 1975–1992, were obtained from the World Meteorological Organisation Standard Normals (UN Statistics Division, 2010). The number of sunshine hours was estimated using the adapted equation of Ångström-Prescott (Viswanadham and Ramanadham, 1969) and the reference evapotranspiration (ETo) estimated using the Penman-Monteith equation integrated into the CROPWAT 8.0 model (FAO, 2018a) (Table 1).

2.4.4 Soil

Calcisol is the dominant soil type in Qatar, especially in the northern part of the country where North Field is located. This soil type is usually shallow with a light texture (IUSS Working Group WRB, 2015; FAO, 1973).

Soil parameters were sourced from the Harmonised World Soil Database (FAO, 2009b). The soil volumetric water contents at saturation and at field capacity were estimated from the soil texture and organic matter content (Saxton and Rawls, 2006). The soil organic matter content (SOM) was estimated from the total organic carbon content using the Van Bemmelen factor of 1.72 (Soil Survey Staff, 1996). The soil CO_2 partial pressure (pCO_2) was estimated from the soil pH (Thomas, 1996) (Table 3).

2.4.5 Crop growth and irrigation requirements

The planting date of sugar beet was set on the first of August, a typical planting date in Egypt, which is a major sugar beet producer and has a hyper-arid climate and sandy calcic soils as in Qatar (Tate and Hamza, 2017). The shaded area values of sugar beet were obtained from Webb et al (1997). Crop coefficients, growth stages length and root depth values were obtained from FAO (2018) (Table 1).

The CROPWAT 8.0 model, a decision support system for the planning and the management of irrigation (FAO, 2018a) was used to estimate the crop water needs and the irrigation requirements in the conditions of Qatar.

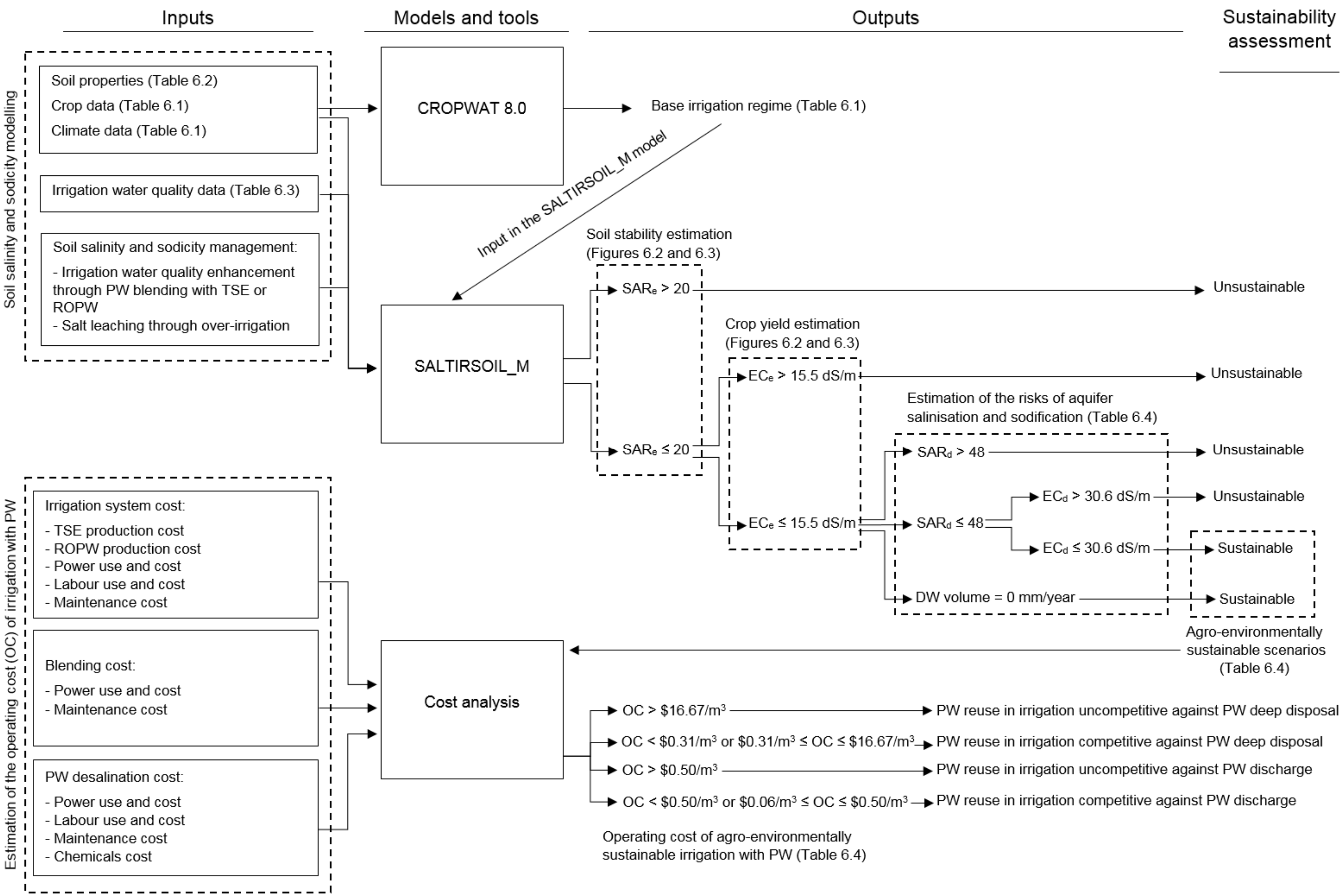


Figure 1. Research methodology flowchart and decision tree for the sustainability assessment.

Table 1. Climate and crop development parameters and reference irrigation regime used in the simulations

	Parameter	January	February	March	April	May	June	July	August	September	October	November	December	Total
Doha Airport meteorological station	P (mm)	10	20	10	10	0	0	0	0	0	0	0	10	60
	ETo (mm)	102	104	155	214	302	342	302	281	215	188	138	108	2450
	I (mm)	199	168	122	0	0	0	0	116	94	122	101	142	1064
Crop growth	K_{cb}	1.15	0.70	0.70	0	0	0	0	0.43	0.70	0.80	1.20	1.20	-
	Root depth (cm)	100	100	100	0	0	0	0	30	49	56	84	92	-

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

Table 2. Quality of the different waters used for irrigation simulations (all ions contents are expressed in mmol/L or in mmol$_c$/L for alkalinity and the EC_w in dS/m).

	$[Na^+]$	$[K^+]$	$[Ca^{2+}]$	$[Mg^{2+}]$	$[Cl^-]$	$[NO_3^-]$	$[SO_4^{2-}]$	Alk_w	EC_w	SAR_w	pH_w
PW	[a]52.12	[a]2.58	[a]7.13	[a]1.85	[a]82.39	[a]0.04	[b]0.56	[c]3.00	[a]7.04	[a]17.39	[a]4.43
ROPW	[d]0.42	[d]0.07	[d]0.00	[d]0.01	[d]1.07	[d]0.00	[d]0.34	[d]0.00	[d]0.17	[d]4.33	[d]6.12
TSE	[e]15.70	[e]0.95	[e]12.40	[e]6.22	[e]14.10	[f]0.14	[e]25.00	[e]3.92	[e]3.83	[e]3.64	[e]5.15

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

[a](Al-Kaabi, 2016), [b](Janson et al., 2015), [c](Ahan, 2014), [d](Ersahin et al., 2018), [e](Ahmad, 1989), [f](Dalahmeh and Baresel, 2014).

Table 3. Soil parameters used in the simulations

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
Calcic Yermosol	Topsoil 0–30	1.7	12	5	86	9	5	8.1	0.1	5.9	0.55	-3
	Subsoil 30–100	1.6	12	5	80	11	9	8.2	0.9	3.0	0.40	-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.

2.5 Cost analysis

A cost analysis was developed to estimate the annualised operating costs of the identified agro-environmentally sustainable irrigation scenarios. The operating cost (OC) is defined as the cost of watering one hectare of sugar beet equipped with drip irrigation and calculated as the sum of the operating costs associated with PW blending, PW desalination, and with the irrigation system. The operating costs related to PW treatment (de-oiling) and to farming operations such as crop fertilisation, farm machinery, seasonal labour, pests and diseases control, etc., were not considered. Also, the capital cost related to the necessary investments as well as bank loans were not considered. These parameters would be dependent on the studied project size (e.g. infrastructure dimension) and local financial conditions (e.g. interest rates, governmental subsidies, etc.) which are site-specific.

The OC was estimated in Eq. (1) as the sum of the irrigation cost (IC), blending cost (BC) and PW desalination cost (DC), all terms are expressed in US$/ha/year:

$$OC = IC + BC + DC \tag{1}$$

2.5.1 Cost of the irrigation

IC, in $US/ha/year, was estimated in Eq. (2) as:

$$IC = WC + PC + MC + LC \tag{2}$$

The water cost (WC), in US$/ha/year, was estimated in Eq. (3) as:

$$WC = \sum_{i=1}^{k} (V_i \times C_i) \tag{3}$$

where V_i is the volume of PW, and/or TSE, and/or ROPW in m^3 and C_i the production cost of PW, and/or TSE and/or ROPW in $\$/m^3$. The production cost of TSE for unrestricted irrigation was estimated at $\$0.45/m^3$ (Pistocchi et al., 2018), the production cost of ROPW was estimated at $\$0.89/m^3$ (Ersahin et al., 2018) and de-oiled PW (i.e. raw PW) was assumed to be delivered at no cost.

The power cost (PC), in US$/ha/year, was estimated in Eq. (4) as:

$$PC = \frac{volume\ of\ water\ applied}{pump\ flow\ capacity} \times pump\ motor\ power\ \times electricity\ cost \tag{4}$$

PC is related to pumping irrigation water, with a pump of 48 m^3/h flow capacity powered by a 7.5 kW-electric motor (Oosthuizen et al., 2007). The electricity cost without subsidies in Qatar was assumed to be $0.10/kWh (Krarti et al., 2017).

The maintenance cost (MC) of the irrigation system, in US$/ha/year, was estimated in Eq. (5) as:

$$MC = \frac{annual\ maintenance\ cost\ of\ the\ irrigation\ system}{plot\ area} \tag{5}$$

The annual maintenance cost of a 25 ha-plot equipped with drip irrigation, in US$/ha/year, was derived from Oosthuizen et al (2007).

The labour cost (LC) , in US$/ha/year, was estimated in Eq. (6) as:

$$LC = \frac{annual\ amount\ of\ hours\ of\ labour\ required}{plot\ area} \times hourly\ mimimum\ wage \tag{6}$$

The annual hours of labour required, in hours/25ha, was obtained from Oosthuizen et al (2007). The hourly minimum wage was estimated at $1.98/hour for the generic profession ‘labour’ (Embassy of India in Qatar, 2014) and the maximum working hours of 47 hours per week allowed by the Qatari labour law (Qatar e-government, 2019b).

2.5.2 Cost of blending produced water

DC, expressed in $US/ha/year, was estimated in Equation **Error! Reference source not found.**) as:

$$DC = WC_{ROPW} + \ PC + MC + LC + CC + other\ costs \tag{7}$$

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 Equation **Error! Reference source not found.**) as:

$$PC = Total\ power\ use\ of\ the\ desalination\ unit\ \times electricity\ cost \tag{8}$$

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).

3 Results

The impact of irrigation with PW on the long-term EC_e and SAR_e are presented in Figure 2 for the PW-TSE blends and in Figure 3 for the PW-ROPW blends. For clarity, only selected blends are presented.

3.1 Irrigation with raw produced water

Figure 2 shows that at a base irrigation regime (100% of the crop water needs), the use of raw PW led to a SAR_e of 49, way above the ANZECC threshold level for maintaining the soil structural stability. Likewise, the EC_e reached 45.8 dS/m which is much greater than 15.5 dS/m, the crop threshold value corresponding to 50% of the crop yield potential. Therefore, the soil structural stability and crop development cannot be preserved in these circumstances. The soil salinity and sodicity can be improved to a certain limit by increasing the irrigation amount. In fact, over-irrigation up to 300% of the crop water needs was effective to reduce the SAR_e to 21 and the EC_e down to 8.6 dS/m which would correspond to a yield of 90% of the crop yield potential. Despite that, irrigation with raw PW remained unsustainable as over-irrigation was unable to reduce the SAR_e below the threshold level for soil structural stability conservation.

Consequently, no irrigation strategy could be found with raw PW without causing soil structural instability due to excessive SAR_e. As using raw PW cannot be considered, it was not necessary to further study its impact on groundwater and its cost of use in irrigation.

3.2 Irrigation with produced water blended with treated sewage effluent (PW-TSE)

3.2.1 Impact on soil structural stability and on crop yield

There are multiple possibilities of irrigating sugar beet with PW-TSE while preserving the soil structural stability and a yield of at least 50% of the crop yield potential.

An extreme example is to use a low water quality combined with a high irrigation amount. Indeed, the minimum blending ratio and irrigation amount for preserving the soil structural stability and for having a yield of at least 50% of the crop yield potential was 96% PW-4% TSE with an irrigation amount of 272% of the crop water needs. In this scenario, the simulated SAR_e and EC_e reached 20 and 8.6 dS/m respectively (Figure 2).

The opposite extreme scenario is to use a higher water quality and a lower irrigation amount, such as 26% PW-74% TSE with an irrigation amount covering 100% of the crop water needs. In this scenario, the simulated SAR_e and EC_e reached 13 and 12.9 dS/m respectively. Thus, the soil structural stability would be preserved, and the crop could yield at 65% of the crop yield potential (Figure 2).

3.2.2 Impact on groundwater quality

Even if irrigation with PW-TSE could preserve the soil structural stability and a crop yield of at least 50% of the crop yield potential, it could represent a threat to groundwater quality. As an example, the irrigation scenario previously mentioned with 96% PW-4% TSE at 272% of the crop water needs, generated 1,733 mm of annual drainage with an EC_d of 43.1 dS/m, this is higher than the maximum aquifer EC value, and a SAR_d of 45, which is below the maximum aquifer SAR value. Therefore, this irrigation scenario is unsustainable as DW would significantly increase groundwater EC.

Improving DW quality until it no longer constitutes a threat to groundwater was possible by increasing the dilution of PW and the irrigation amount. In fact, the minimum blending ratio for preserving soil fertility while preserving groundwater quality was 66% PW-34% TSE at 294% of the crop water needs. In this scenario, DW volume was higher (1,988 mm/year), but its salinity and sodicity were both lower ($EC_d = 30.6$ dS/m, $SAR_d = 27$) compared to the previous scenario with 96% PW-4% TSE at 272% of the crop water needs (Table 4).

Alternatively, DW could be suppressed to avoid groundwater contamination. In fact, the excess irrigation water started to drain when the irrigation amount was greater than or equal to 109% of the crop water needs, the scenarios with an irrigation amount below 109% of the crop water needs which were sustainable from a soil point of view also did not pose any risk to the aquifer. On the other hand, when the irrigation amount was greater than or equal to 109% of the crop water requirements, DW could potentially increase the groundwater EC and/or SAR, even if the irrigation scenario was safe for the soil structural stability and for the crop yield. Thus, the groundwater could be preserved when the irrigation amount was minimised such as for the scenario using 26% PW-74% TSE with an irrigation amount covering 100% of the crop water needs (Table 4).

3.3 Irrigation with produced water blended with reverse osmosis-treated produced water

3.3.1 Impact on soil structural stability and on crop yield

When PW was blended with ROPW, the minimum PW dilution ratio for preserving the soil structural stability and a minimum yield of 50% of the crop yield potential was 89% PW-11% ROPW with an irrigation amount of 297% of the crop water needs. In this scenario, the SAR_e reached 20 and the EC_e was 8.3 dS/m enabling the crop to yield up to 90% of the crop yield potential (Figure 3).

On the other hand, a higher water quality and a lower irrigation amount could be used such as 15% PW-85% ROPW with an irrigation amount covering 100% of the crop water needs. In this scenario, the simulated SAR_e and EC_e reached 17 and 5.3 dS/m respectively. Thus, the soil structural stability would be preserved, and the crop could reach its full yield potential (Figure 3).

3.3.2 Impact on groundwater quality

The same way as for the PW-TSE blends, a low PW dilution ratio had to be coupled to a high irrigation volume to maintain suitable SAR_e and EC_e values leading to high DW volumes. Although irrigating with 89% PW-11% ROPW at 297% of the crop water needs was sustainable from a soil point view, it generated 1,999 mm of annual drainage with an EC_d of 39.4 dS/m, which is higher than the maximum aquifer EC, and a SAR_d of 45, which is below the maximum aquifer SAR. The minimum dilution ratio for preserving soil fertility and groundwater quality was 68% PW-32% ROPW at 290% of the crop water requirements. In this scenario, DW volume was higher (1,924 mm/year) but its salinity and sodicity were both lower (EC_d = 30.6 dS/m, SAR_d = 40) compared to the previous scenario (Table 4).

Here again, a 'zero drainage' irrigation strategy with 15% PW-85% ROPW at 100% of the crop water needs was safe for the aquifer (Table 4).

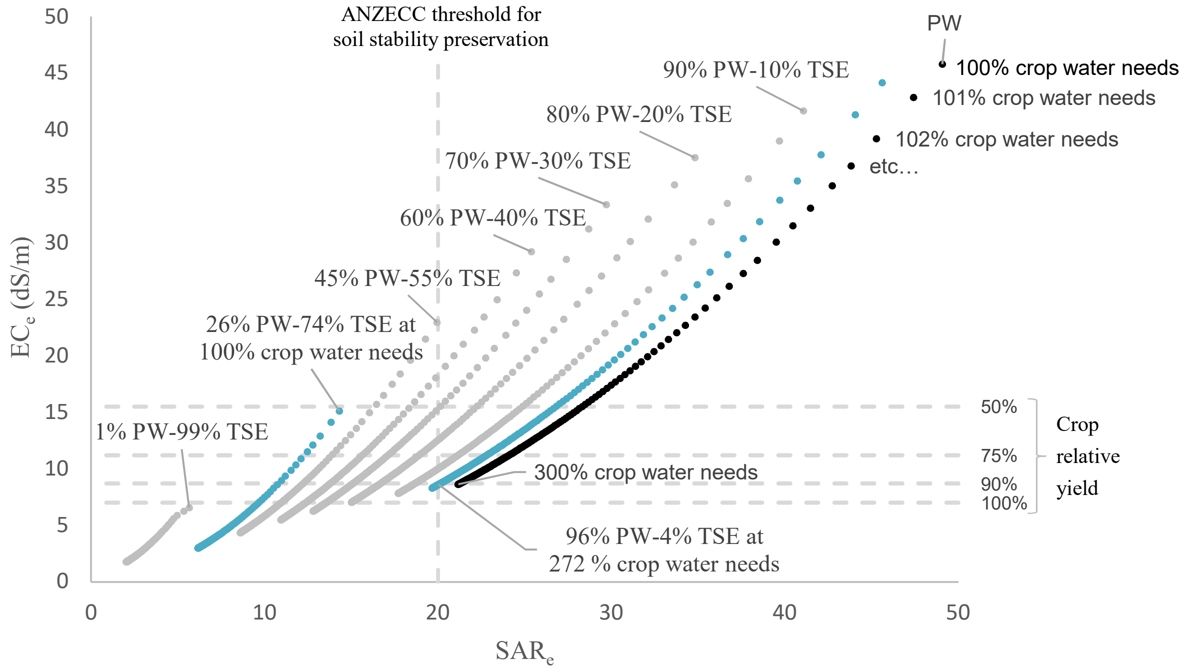


Figure 2. Long-term EC_e and SAR_e following irrigation of sugar beet with different blends of PW diluted with TSE (from 100% PW down to 1% PW + 99% TSE) and with different irrigation amounts (from 100% up to 300% of the crop water needs).

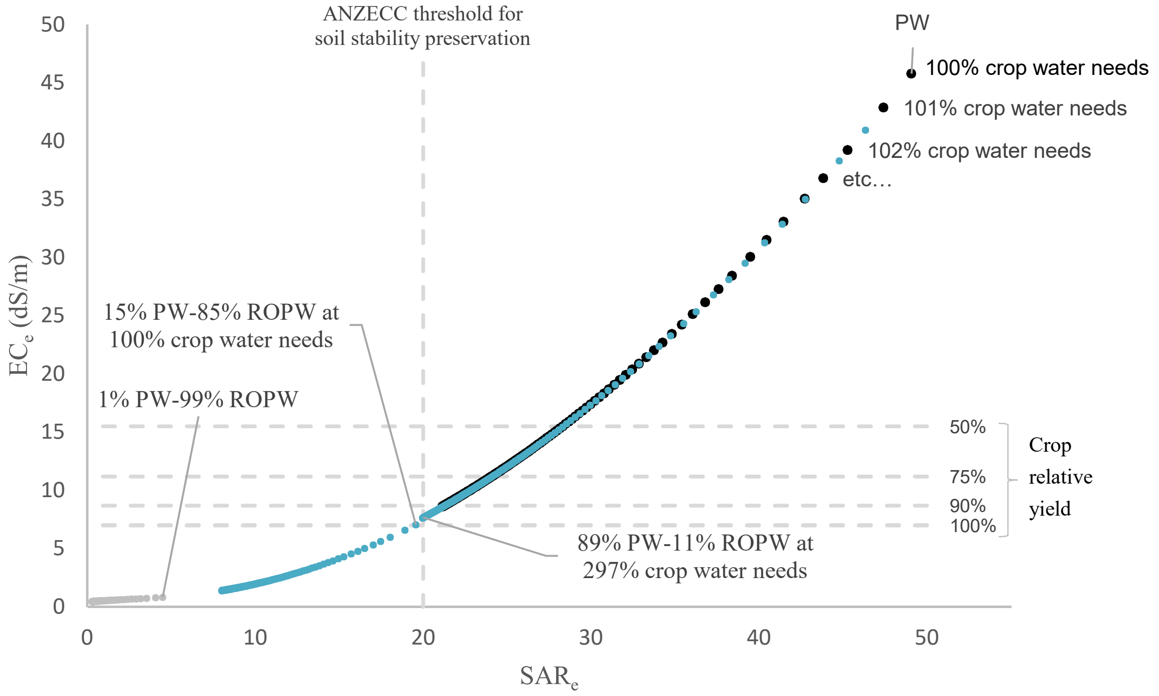


Figure 3. Long-term EC$_e$ and SAR$_e$ following irrigation of sugar beet with different blends of PW diluted with ROPW (from 100% PW down to 1% PW + 99% ROPW) and with different irrigation amounts (from 100% up to 300% of the crop water needs).

3.4 Operating cost of irrigation

The operating cost of irrigation was negatively correlated to the proportion of PW in the irrigation water which was itself positively correlated to the irrigation amount. Actually, increasing the proportion of PW in the irrigation water, led to higher long-term EC$_e$ and SAR$_e$ and thus, more water had to be applied to leach excessive salt out of the root zone which requires more energy for pumping water. It also depended on the type of water used for blending PW (i.e. TSE or ROPW) (Table 4).

The water consumption of irrigation depended on the volume of water applied but also on the volume of PW that had to be desalinated in the case of PW-ROPW blends. Indeed, desalinating PW led to a water loss (i.e. brine) representing 30% of the inflow PW volume. Thus, using ROPW to blend PW leads to a higher water consumption per hectare compared to using TSE to blend PW. Therefore, the higher the irrigation volume and the proportion of ROPW in the irrigation water, the higher the water consumption of irrigation.

The energy consumption was related to the pumping of water (from the gas field to the irrigated field and from the gas field to the constructed reservoir when PW was blended) and also to PW desalination. Thus, the water consumption and the energy consumption depended on the same parameters.

4 Discussion

4.1 Agro-environmentally sustainable irrigation scenarios

The potential agro-environmentally sustainable irrigation scenarios that have emerged from the simulations are summarised in Table 4. All these scenarios were preserving soil structural stability, maintaining the EC_e below 15.5 dS/m to enable a minimum yield of 50% of the crop yield potential, maintaining the pH_e between 4 to 9 to accommodate tropical sugar beet, and these scenarios were preserving the aquifer from alteration by DW. These objectives were achieved in two ways; either through a combination of relatively low PW dilution along with a high irrigation amount or through a high dilution of PW along with a low irrigation amount.

Once the soil structural stability and a minimum yield of 50% of the crop yield potential were reached, groundwater preservation was the main factor limiting the irrigation water quality and the irrigation amount that could be used. Actually, DW minimisation is one way to prevent groundwater alteration, while the alternative was to increase the dilution of PW and the irrigation amount to decrease the EC_d and the SAR_d below the maximum aquifer EC and SAR values.

pH_e increased from 8.1–8.2 (Table 3) to 8.5–8.7 as a result of irrigation despite the acidic pH of the applied waters (Table 2). Indeed, irrigation water dissolves calcite contained in the soil and forms bicarbonate which increases the pH and alkalinity of the soil solution, the amount of acid (H^+) brought by the irrigation water reduces the amount of bicarbonate and forms carbonic acid which dissociates and releases carbon dioxide decreasing the soil CO_2 partial pressure.

Because there was more bicarbonate being formed than bicarbonate being neutralised, the soil solution concentration in bicarbonate increased, thus the long-term soil solution alkalinity increased and the long-term pH_e increased by 0.4–0.6 pH units compared to pre-irrigation value (Table 4). Although relatively high, the soil pH reached were still within the suitability range of tropical sugar beet (SESVanderHave, 2016). PW extracted from conventional gas fields tend to be acidic (Alley et al., 2011; Echchelh et al., 2018) due to the dissolution in PW of hydrogen sulphide contained in gas reservoirs (Ogden, 2008). The acidic properties of conventional gasfield-PW limit the increase of soil pH and alkalinity in calcareous soils such as in Qatar. On the other hand, the risks of dramatically increasing the pH_e above crop pH-tolerance would be higher with alkaline PW such as CBM-PW (Hamawand et al., 2013). Indeed, a laboratory experiment showed that applying 36,000 m^3/ha of CBM-PW of pH 9.4 on Red- (pH 6.7) and Red-Brown Utilisols (pH 5.0) resulted in an increase of soil pH by $\geq$ 3.0 pH units (final soil pH = 8.5–9) at depths of 2.5–5 cm (McKenna et al., 2019). Consequently, the low risk of increasing soil pH beyond the suitable pH range for the crop in this study does not imply that this is the case for other irrigation projects using PW of different quality on different soil type.

Table 4. Selected agro-environmentally sustainable irrigation scenarios with PW blended with TSE (PW-TSE) and PW blended with ROPW (PW-ROPW), and their impacts on soil structural stability, crop yield, groundwater quality, water use (including losses through desalination brine), energy use and operating cost.

Scenarios	Irrigation water quality and amount					Impact on soil and crop					Impact of DW on Qatar's northern shallow aquifer			Water and power consumption		Irrigation operating cost	
	PW (%)	TSE (%)	ROPW (%)	Volume (mm)	Crop needs (%)	EC_e (dS/m)	SAR_e	pH_e	Alk_e ($mmol_c$/L)	Crop yield (%)	EC_d (dS/m)	SAR_d	Volume (mm)	Water (m^3/ha)	Power (kWh/ha)	$/ha	$/$m^3$
Lowest irrigation water quality acceptable	66	34	0	3127	294	6.0	12	8.5	110	100	30.1	27	1967	31270	4886	5824	0.19
	68	0	32	3085	290	5.9	18	8.5	116	100	30.6	40	1924	33811	37888	18570	0.60
Lowest water and energy use	26	74	0	1064	100	12.9	13	8.7	212	65	-	-	0	10640	1662	3937	0.37
	15	0	85	1064	100	5.3	17	8.6	136	100	-	-	0	12523	22686	11548	1.09
Least-cost scenarios	50	50	0	1149	108	14.2	16	8.7	270	58	-	-	0	11490	1795	3006	0.26
	21	0	79	1106	104	6.0	18	8.6	145	100	-	-	0	14808	31005	5038	0.46

PW: produced water, TSE: treated sewage effluent, 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, DW: drainage water, EC_d: electrical conductivity of the drainage water, SAR_d: sodium adsorption ratio of the drainage water.

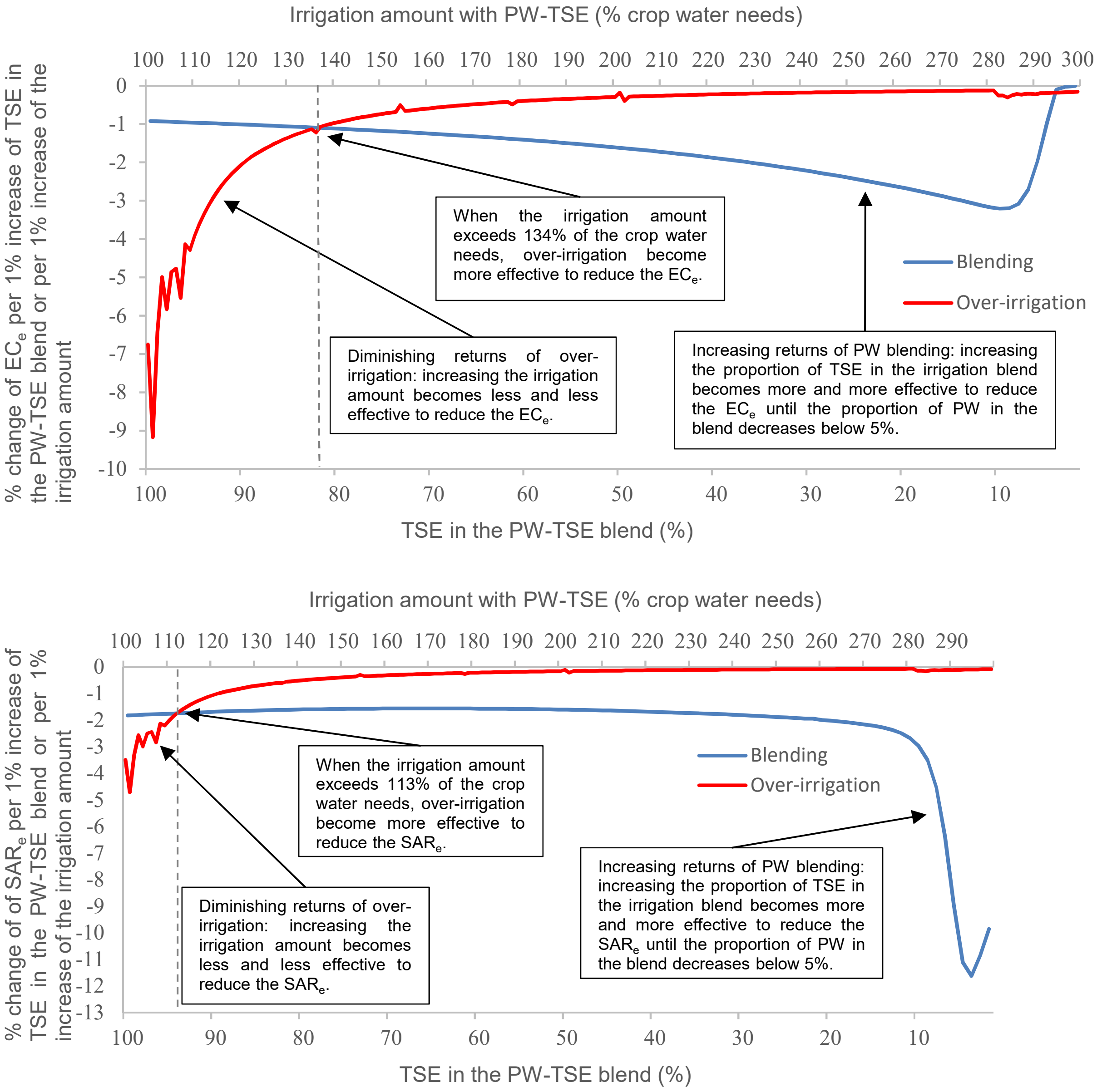
4.2 Understanding how agro-environmentally sustainable irrigation can be achieved

4.2.1 Salt leaching through over-irrigation and salt dilution through produced water blending

Figure 4 shows the marginal effects of over-irrigation and PW blending on the EC_e and SAR_e and how they differed in terms of dynamic and amplitude. Indeed, diminishing returns were observed regarding the marginal effect of over-irrigation on the reduction of the EC_e and SAR_e. The average EC_e decrease per percentage of increase of the irrigation amount (all PW-TSE blends considered) was higher than 4% for an irrigation amount up to 110% of the crop water needs. It then constantly decreased and was below 1% when the irrigation amount was higher than 142% of the crop water needs. The same was observed for the SAR_e, the average SAR_e decrease per percentage of increase of the irrigation amount was higher than 2% for an irrigation amount up to 110% of the crop water needs. It continuously decreased and was below 0.5% when the irrigation amount was greater than 146% of the crop water requirements.

In contrast, increasing returns were observed regarding the marginal effect of PW blending to reduce the EC_e and SAR_e. The average EC_e decrease per increase of the TSE percentage in the PW-TSE blend was lower than 1% when the proportion of TSE in the blend was below 4%. It then increased and was over 2% when the percentage of TSE in the blend was between 63–95%. The SAR_e reduction was quite steady, below 2% when the percentage of TSE in the blend was between 1–78%. It then drastically increased and was over 2% (up to 12%) when the proportion of TSE in the blend was between 79 to 99% (Figure 4).

These results show that the efficiency of over-irrigation in reducing the EC_e and SAR_e was very quickly limited. Blending PW with TSE became more efficient than over-irrigation to reduce the EC_e and SAR_e when the irrigation amount was higher than 134% and 113% of the crop water needs respectively (dotted lines in Figure 4). This suggests that, from the perspective of soil salinity management, it is more effective to leach excessive salt by over-irrigating first (until the irrigation amount reaches 134% of the crop water needs) before completing the soil salinity control strategy by diluting PW with TSE. However, if the soil sodicity is the main issue, due to its negative impact on soil structural stability, over-irrigation should be at least practised until covering 113% of the crop water needs before considering to blend PW with TSE.



When the irrigation amount exceeds 134% of the crop water needs, over-irrigation become more effective to reduce the EC_e.

Diminishing returns of over-irrigation: increasing the irrigation amount becomes less and less effective to reduce the EC_e.

Increasing returns of PW blending: increasing the proportion of TSE in the irrigation blend becomes more and more effective to reduce the EC_e until the proportion of PW in the blend decreases below 5%.

When the irrigation amount exceeds 113% of the crop water needs, over-irrigation become more effective to reduce the SAR_e.

Diminishing returns of over-irrigation: increasing the irrigation amount becomes less and less effective to reduce the SAR_e.

Increasing returns of PW blending: increasing the proportion of TSE in the irrigation blend becomes more and more effective to reduce the SAR_e until the proportion of PW in the blend decreases below 5%.

Figure 4. The marginal effect of produced water blending (upper horizontal axis) and over-irrigation (lower horizontal axis) on the average percentage reduction of EC_e and SAR_e

4.2.2 Produced water blending with treated sewage effluent and with reverse osmosis-treated produced water

The type of effluent used to dilute PW influenced irrigation agro-environmental sustainability. Blending PW with ROPW while irrigating at a base irrigation amount could have a similar impact on the EC_e and SAR_e to increasing the irrigation amount with raw PW (Figure 3). In contrast, blending PW with TSE at a base irrigation amount could result in similar EC_e values but lower SAR_e values compared to increasing the irrigation amount with raw PW (Figure 2). This is explained by the lower salinity of ROPW compared to TSE which created blends of lower salinity (EC_w) compared to the PW-TSE blends. Nonetheless, ROPW has a higher SAR_w compared to TSE as the latter has not been demineralised by the desalination process. Thus, at a comparable irrigation amount and PW dilution ratio, irrigation with PW-TSE was more sustainable than irrigation with PW-TSE blends.

In practice, a remineralisation of ROPW could adjust the SAR of the irrigation water. The addition of gypsum or any other source of calcium and magnesium into the irrigation water would not be adapted to a drip irrigation system as it would increase pipes scaling and drippers clogging. Alternatively, the application of gypsum to the soil could be efficient to reduce the SAR_e and preserve the soil structural stability. However, as gypsum dissolves in the soil solution, it would increase the EC_e and so, the crop osmotic stress and thus, it would limit crop yield if the EC_e exceeds the crop EC_e threshold values after the addition of gypsum to the soil. Besides, as gypsum releases free Ca^{2+} and Mg^{2+} ions in the soil solution, it displaces Na^+ ions which are leached by DW (Ashworth et al., 1999). Thus, groundwater sodicity could be affected if the irrigation amount is high enough to generate DW high in sodium.

4.3 Operating cost of agro-environmentally sustainable irrigation scenarios

4.3.1 The drivers determining the operating cost of agro-environmentally sustainable irrigation

The water and energy consumptions of the irrigation system, the blending system, and of the RO unit were the main factors determining the operating cost of irrigation (Table 4).

The type of water used to blend PW largely influenced the operating cost of irrigation. Using ROPW for blending PW was more costly than blending PW with TSE. Indeed, the production cost of ROPW (\$0.89/m^3) is about twice as much as the production cost of TSE (\$0.45/m^3). This difference of cost between both effluents is explained by the high costs of the inputs related to PW desalination (i.e. energy, chemicals, labour and maintenance costs of the RO unit). Moreover, in the least-cost scenario, the PW dilution ratio was higher and the irrigation amount was just slightly lower when ROPW was used rather than TSE for blending PW (i.e. 21% PW-79% ROPW at 1,106 mm compared to 50% PW-50% TSE at 1,149 mm). As a result, the volume of ROPW that had to be used (8,737 m^3/ha) was significantly higher than the volume of TSE that had to be applied (5,745 m^3/ha) for a comparable scenario objective (i.e. cost minimisation) (Table 4). The higher cost of blending PW with ROPW discourages the use of this type of effluent to improve PW quality for irrigation.

Although the volume of water and the power consumed highly contributed to the operating cost of irrigation, the least-cost scenarios were not those which were consuming least water and power. In fact, the least-cost strategies were an equilibrium between using over-irrigation and PW blending. This could be explained by the marginal effect of these two techniques on the reduction of the EC_e and of the SAR_e as the most efficient way to reduce these agro-environmental sustainability indicators is to combine both over-irrigation (between 100 to 134% of the crop water needs) and PW blending.

Avoiding generating DW through higher PW dilution rate was less costly than increasing the irrigation amount to improve DW quality. Indeed, the least-cost scenarios with TSE and

ROPW were covering 108% and 104% of the crop water needs respectively (Table 4). These irrigation amounts were just below 109%, the amount of water from which excess irrigation water starts to drain.

4.3.2 The cost of reusing produced water in irrigation compared to the cost of produced water disposal

Qatar has a favourable environment for developing the reuse of PW in irrigation including a hyper-arid climate, a pro-active wastewater reuse policy, a need for alternative irrigation water resources, and geographical proximity between the PW supply (i.e. North Field) and the farmlands (Shomar et al., 2014). Nonetheless, in order to be considered by O&G firms, the reuse of PW in irrigation must be competitive compared to current disposal practices. Although the cost of PW disposal practices are site-specific, it was estimated that the cost of deep-well injection was between \$0.31–\$16.67/m^3 globally (Fakhru'l-Razi et al., 2009) and between \$1.57–\$15.72/m^3 in the USA, depending on PW quality and well ownership (Dolan et al., 2018). If the deep disposal well is located at a long distance from the O&G field and if there is no pipeline to convey PW to the deep disposal well, PW needs to be hauled at a cost of \$0.20/m^3/km in the USA (Coday et al., 2015). The cost of surface discharge was estimated at \$0.06–\$0.50/m^3 globally (Fakhru'l-Razi et al., 2009) but this disposal practice mainly exists in coastal locations with a discharge point into the sea. The estimated operating cost of irrigation in Qatar was between \$0.19–\$0.37/m^3 for PW-TSE blends and between \$0.46–\$1.09/m^3 if PW-ROPW was chosen. The operating cost of PW reuse in subsurface drip irrigation in the USA was estimated at \$0.98–\$1.48/m^3 while the capital cost was estimated at \$14,826/ha (Plappally and Lienhard, 2013). The total cost of other commercial-scale irrigation projects with PW in the USA was estimated at \$0.7–\$5.8/m^3 (Siagian et al., 2018).

Although the total cost of the management of PW through irrigation in Qatar needs to be estimated, the estimated operating costs alone remain within the lower range of the cost of

PW deep disposal (for PW-TSE and PW-ROPW blends) and within the cost range of PW surface discharge worldwide (for PW-TSE blends only). This suggests that PW reuse in irrigation in Qatar is potentially competitive against traditional PW disposal practices.

4.4 Limitations

The simulations carried out and the cost analysis are exploratory, their limitations related to the model, the method and the assumptions used in this study are acknowledged.

The assessment of agro-environmental sustainability of irrigation with PW has focused on the principal agro-environmental risks of reusing PW in irrigation that are posed by PW salinity and sodicity. The environmental and safety hazards risks related to other constituents of concern present in PW need to be considered (Alley et al., 2011). Indeed, heavy metals (Al-Kaabi, 2016) and specifically cadmium, nickel, zinc and lead which are known to accumulate in sugar beet sometimes beyond food safety values (Papazoglou and Fernando, 2017; Topcuoğlu, 2017) need to be included in a environmental toxicology assessment. While the high pH and low SOM content of soils in northern Qatar limit heavy metals bioavailability, the high EC_e increases the risk of absorption by plants (Singh et al., 2009). Also, the environmental and toxicological hazards represented by production chemical compounds which were shown to affect plant development (Burgos and Lebas, 2015) and radioelements which were observed accumulate in sugar beet (Ratnikov et al., 2019) would need to be addressed.

The assessment of the risks posed by irrigation with PW is very specific to the PW quality, the soil properties, the climate aridity, the irrigation practices and the crop cultivated (Echchelh et al., 2019; Horner et al., 2011). As these parameters widely vary between locations, it is recommended to carry out sustainability assessments at the irrigation project scale instead of relying on generic guidelines.

The agro-environmental sustainability assessment based on threshold SAR_e and EC_e values chosen in this study needs further improvement. Recent research has highlighted the risk of using generic standards as they are too general regarding the soil response to irrigation water quality (Bennett et al., 2019; Dang et al., 2018). Although by considering the soil clay content to assess the soil vulnerability to dispersion, the ANZECC guidelines are more specific than the FAO guidelines (Ayers and Westcot, 1985), they still lack precision. Therefore, threshold irrigation water quality parameters (EC, SAR, alkalinity and pH) should be specifically determined for each soil where irrigation with PW would take place. Additionally, the use of the SAR as an indicator of soil structural stability is being questioned by soil scientists (Rengasamy and Marchuk, 2011). Unlike the SAR, the CROSS (cation ratio of soil structural stability) accounts for the differential dispersive powers of Na^+ and K^+ and the differences in the flocculating effects of Ca^{2+} and Mg^{2+} (Marchuk and Rengasamy, 2012; Zhu et al., 2019). This could be used as an indicator if suitable guidelines for soil structural stability preservation are developed.

Besides, soil amendments aiming at buffuring soil sodicity and alkalinity need to be included as these were not considered in the simulations. Soil amendments have functional groups such as hydroxyl and carboxyl groups which can assist in buffering alkalinity. Without a reduction of soil alkalinity, a part of the calcium provided by amendments would be ineffective to reduce the SAR_e as the free carbonate ions of the soil solution would combine with the free calcium ions and precipitate as calcite. To prevent this, the increasing soil alkalinity resulting from irrigation with PW would need to be neutralised using acidic inputs (e.g. elemental sulphur, sulphuric acid and phosphoric acid) prior to adding SAR-adjusting amendments such as gypsum.

Although the SALTIRSOIL_M model has been calibrated and validated against field results in a semi-arid environment with irrigation water of moderate salinity (Visconti et al., 2014), it has not yet been tested and validated in hyper-arid conditions with irrigation water as saline as North Field PW. Therefore, the obtained results highlight possible agro-environmentally sustainable irrigation practices with PW in hyper-arid Qatar rather than present design criteria.

Given the lack of model validation specifically in Qatar, and the simplicity of the model compared to the complexity of soil-specific responses in the presence of PW and soil amendments (McKenna et al., 2019) the modelling presented would benefit from laboratory and field experiments. A combined modelling and field-experiment approach would further increase the confidence in the sustainability assessment and provide empirical evidence regarding sustainable irrigation strategies with PW in Qatar.

Although DW salinity is unlikely to significantly change after 1 m of depth as it is no longer affected by evaporation nor plant uptake, the volume of DW that would reach the aquifer and its impact on groundwater quality remains unknown and would need to be specifically quantified. As Qatar's northern shallow aquifer lies between 40 to 80 m deep (Shomar, 2015), DW would continue to migrate deeper and eventually, reach the aquifer.

There are uncertainties regarding the estimated operating costs of PW reuse in irrigation. First, the cost of de-oiling PW was not considered due to lack of data in Qatar. Second, the cost of natural gas (the main fuel used for generating electricity in Qatar) fluctuates and would affect PW desalination cost (Darwish et al., 2015). Third, the operating cost of RO-desalination has been decreasing and is as low as \$0.21/m^3 for recent large-scale plants treating seawater of 40,679 ppm of salinity (Bashitialshaaer et al., 2011; Plappally and Lienhard, 2013). Assuming this lower production cost for ROPW, it would reduce the cost of the least-cost irrigation scenario with PW-ROPW to \$4,306/ha, that is ~15% cost reduction compared to the simulated scenario. This cost reduction would improve the cost competitiveness of PW-ROPW blends compared to the use of PW-TSE. However, PW desalination facilities are smaller and do not benefit from scale economies compared to large seawater desalination facilities (Bernat et al., 2010). In fact, recent experiments have demonstrated that the total desalination cost of PW with a salinity of 50,000 ppm could be below \$1.5/m^3 (Osipi et al., 2018). A cost analysis based on numerical simulations estimated the total cost of desalinating water of 15,000 ppm of salinity to produce irrigation water (400 ppm of salinity) in a 24 000 m^3/day plant capacity at \$1.39/m^3 (Sarai Atab et al., 2016). PW desalination cost could actually be cheaper in Qatar thanks to the relatively low salinity of North Field PW (4,502 ppm). Despite possible lower cost for producing ROPW, it is unlikely that it becomes more advantageous than TSE for blending PW as TSE does not need an energy-intensive desalination process to be produced.

5 Conclusions

Reusing PW to irrigate croplands in dry areas can contribute to food security and provide O&G firms with an alternative to conventional disposal techniques which are environmentally risky, increasingly regulated and costly. Unfortunately, PW is high in salt and sodium, thus its long-term use in irrigation can degrade soil fertility, crop productivity and contaminate groundwater. However, mitigation strategies such as over-irrigation, PW blending and PW desalination can be adopted to reduce these negative externalities. Based on a case-study growing sugar beet in Qatar, the simulations showed that multiple combinations could be used to achieve agro-environmentally sustainable irrigation with PW. Irrigation managers might prefer over-irrigation as this practice allows the use of low-quality irrigation water (i.e. a higher proportion of PW in the irrigation water blend). In this case, the soil and the aquifer could be protected from salinisation and sodification by applying an irrigation volume up to ~300% of the crop water needs with a blend composed of two-thirds PW and one-third TSE or ROPW. On the contrary, irrigation managers might be concerned about water efficiency in the field to minimise the cost of adding ROPW or TSE in the irrigation water, minimise pumping cost, and maximise farmer's revenue through irrigating the largest possible area. In this case, higher irrigation water quality is required. For example, irrigation at a little over the crop water needs was shown to be agro-environmentally sustainable if PW was mixed with an equivalent volume of TSE or four equivalent volumes of ROPW respectively.

The simulations and the cost analysis highlighted that the quest for agro-environmentally sustainable irrigation implies trade-offs between the irrigation volume, the water quality and the crop yield potential. Although irrigation with blended PW can be sustainable from a soil-plant point of view, it could potentially affect groundwater even if the volume of DW that would reach the aquifer is uncertain. Thus, DW leaving the root zone must be properly managed to avoid transferring the salinity and sodicity hazards from the soil to the groundwater. In case of a high risk of groundwater degradation, precautions such as DW capturing or eventually soilless agriculture could be imagined.

The limitations of the modelling approach and of the sustainability indicators used in this paper require further laboratory- and field-based research in order to demonstrate the environmental sustainability and the financial viability of irrigation with gasfield-PW in Qatar.

Conflict of interests

None.

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