Environmental Earth Sciences (2018) 77:90
https://doi.org/10.1007/s12665-018-7259-z

ORIGINAL ARTICLE

A technical model for reclaimed water reuse in agricultural irrigation: a case study in Kordkuy, Iran

Sepideh Ansari[1] · Javad Alavi[1] · Mohammad Ghafoori[2]

Received: 20 July 2017 / Accepted: 15 January 2018

Abstract

This study aims at developing a systematic and holistic logical decision-making model to assess technical feasibility of reclaimed water reuse in agriculture. The hypothesis of algorithm was based on the basic conditions recommended by Food and Agriculture Organization of the United Nations which are required to make irrigated farming a success. The model innovatively integrates technical aspects by using a hierarchical modular structure consisting of three modules to tackle an unstructured assessment process. Reusability analysis module is concerned with determining the restrictions imposed on effluent quality, selection of suitable types of crops as well as the best available irrigation method. In order to select crops, a framework of potential restrictions was developed to match effluent, soil and types of crops, simultaneously, with a high level of intricacy as well as adaptability to any cases. Supply–demand analysis module provides an estimation of reuse potential in terms of quantity and irrigated area based on the water requirements of selected crops and the volume of produced treated wastewater. Module of field management practices aims at controlling adverse impacts of prolonged irrigation by effluent on the environment. The compatibility with different guidelines and regulations, the simplicity achieved by a series of logical steps and the integration of modules are the main features of the algorithm. To test algorithm robustness, it was successfully applied in Kordkuy, Iran. As a result of model performance, the water reuse scheme can annually save up to 718,560 m^3 of freshwater by planting soybean and rapeseed as the most suitable crops in the region.

Keywords Agriculture irrigation · Treated wastewater reuse · Technical features · Potential restrictions · Crop water requirement · Field management

Introduction

Water scarcity poses a substantial threat to human existence and future economic progress. Water reuse represents a viable alternative supply of water (Molinos-Senante et al. 2011) and emerges as an integral approach toward sustainability, environmental sound technology and potentially cost-effective solution for wastewater disposal problem (Aoki et al. 2005; Molinos-Senante et al. 2011). Treated wastewater (TWW) reuse, when appropriately applied, enhances the exploitation of non-conventional resources and helps to close the loop between water supply and wastewater disposal.

Agriculture is the largest worldwide consumer of reclaimed water (Asano et al. 2007; Lazarova et al. 2013). Closed-loop orientation between sanitation and agriculture or ecological sanitation (Ecosan) approach enables the recovery of nutrients from human feces and urine to the benefit of agriculture and helps to preserve soil fertility, to ensure food security for future generations and to minimize water contamination (Masi 2009). Even though irrigation by TWW is the traditional and more practical purpose of water reuse (Garcia and Pargament 2015), unplanned reuse is associated with negative human health and environmental degradation (USEPA 2004). Accordingly, applying marginal quality in comparison with

✉ Javad Alavi
alavi.sharif@gmail.com

Sepideh Ansari
aisan_ansari@yahoo.com

Mohammad Ghafoori
ghafoori@um.ac.ir

1 Department of Environmental Sciences and Engineering, Kheradgarayan Motahhar Institute of Higher Education, Mashhad, Iran

2 Department of Geology, Faculty of Science, Ferdowsi University of Mashhad, Mashhad, Iran

Published online: 01 February 2018

high-quality water requires more complex management practices and stringent monitoring procedures (Ayers and Westcot 1994). In order to minimize or avoid the possible risks and reach the success of a water reuse project, a feasibility study (FS) should be taken into account in the decision-making process (AQUAREC 2006).

Successful implementation of water reuse projects in agriculture is a multi-faceted technical challenge since there is an urgent need to develop integrated decision support systems that are generic and practical. The main purpose of the models is to provide assistance in evaluating the basic conditions required for effective irrigation and the most likely environmental and health risks. Despite the fact that there is a more significant bias toward the strictly technical analysis of agricultural reuse (Molinos-Senante et al. 2011), there are relatively few reference methodologies presented in the literature to address specific and in-depth decision-supporting tools for technical feasibility study in this field (AQUAREC 2006). Pescod and Arar (1985) proposed a decision-making model based on the quality assessment of effluent, soil, crops and irrigation method. A GIS-based model was also established by Ahmadi and Merkley (2009). The model is comprised of land suitability and availability, water availability, water storage and planning and project comparison modules. Styczen et al. (2010) built up a model system (DAISY) to identify safe modes of irrigation for low-quality water. The model simulates crop growth, water and nitrogen dynamics, heavy metals and pathogen fate in the soil. Murray and Ray (2010) developed a model which consists of a reuse-centric performance assessment as well as optimization for reuse in agriculture to assess business performance, design and simulate reuse options.

The most challenging task to develop a technical-based decision-making model for reclaimed water reuse is to consider factors needed to successful irrigated agriculture by a holistic approach. Moreover, it is imperative to determine the intervening mode of factors, whether they are sequential or simultaneous. The abovementioned literature review indicates that there are relatively few methodologies to address the challenge of integration and interrelation of technical factors in one configuration. Therefore, a typology of technical assessment model is required to be built up for a better-informed decision-making process via harmonizing interdependent technical features.

Iran suffers from water scarcity and deterioration of water quality. Kordkuy located in the northeast of Iran has deficient water balance especially during dry summer months because of irregular temporal water distribution and increased agricultural activity. Water shortage has led to unplanned and unpermitted wastewater reuse by farmers in the field across wastewater treatment plant. Thus, the technical assessment of effluent reuse as an appealing solution is required prior implementation in the region.

The primary focus of this work is to develop a logical decision-making model (LDM) to assess technical feasibility of reclaimed water reuse in agricultural irrigation. The unified methodology aims at developing a universal model through integrating the most relevant factors involved at different stages of decision-making process. The hypothesis of presented algorithm is based on the basic conditions needed to make irrigated farming a success which are recommended by Food and Agriculture Organization (FAO). However, the planning model presented here is primarily meant for technical assessment and is not intended to meet all the aspects of water reuse schemes in agriculture. In order to assess the performance of the model and implementation details, the proposed methodology was subsequently used in Kordkuy, Iran.

Model description

The hypothesis of algorithm is based on the following basic conditions presented by FAO that should be assessed to make irrigated farming a success (Pescod 1992): (1) water quality (2) water quantity (3) water application scheduling (4) selection of appropriate irrigation method (5) prevention of salt accumulation in the root zone (6) appropriate drainage and (7) plant nutrient management.

The structure of the model is subdivided into three sections including reclaimed water reusability analysis (RWRA), reclaimed water supply–demand analysis (RWSDA) and field management practices (FMPs). As the starting point, a set of specified technical parameters required in each component are defined as the input data to run the algorithm. The input data is comprised of TWW, crop and soil characteristics, national and international water quality standards, existing irrigation method in the region, meteorological data, quantity of effluent and potential user identification. Modules are described in detail in the following subsections.

RWRA—qualitative assessment phase

The module of RWRA aims at evaluating the quality of environmental matrices (reclaimed water, soil and crop), selecting the most suitable types of crops and the best available irrigation method. Figure 1 gives the flowchart of the first module. The module is divided into three main consecutive functional steps described in the following:

Step 1—Environmental matrices assessment: The first step is to determine the basic properties of environmental phases involved in water reuse projects. TWW, soil and crop are the main biophysical aspects involved in the process. The physiochemical and biological characteristics of TWW are introduced as inputs to the model. In an iteration step,

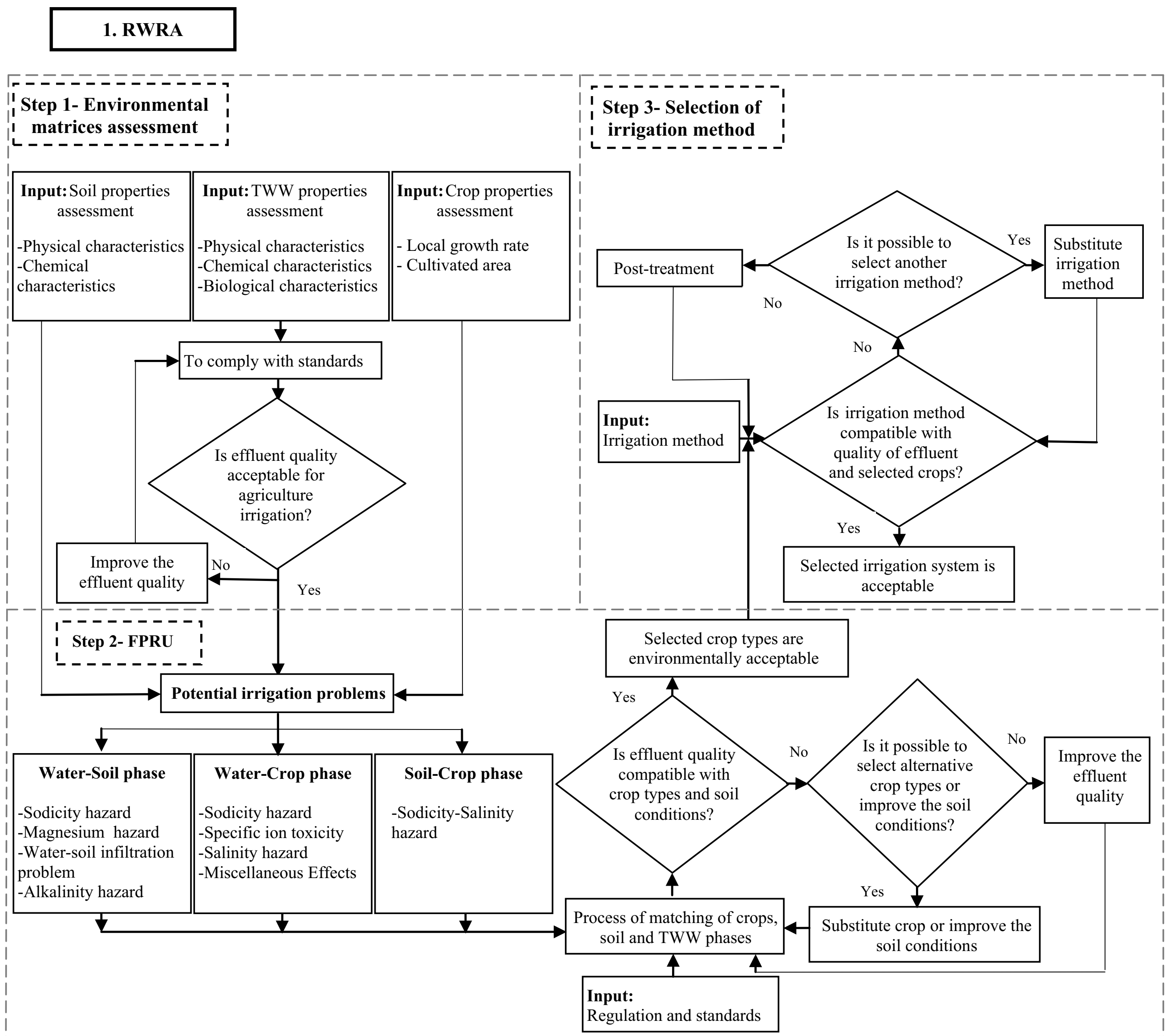

Fig. 1 Flowchart of the RWRA module

values are compared with the effluent quality criteria based on the standards and regulations. The iteration is terminated when effluent quality complies with the intended standards and guidelines. Otherwise, this process is iterated until the upgraded effluent meets water quality standards. The case for the universal applicability of the proposed LDM would be greatly strengthened by definition of open source data corresponding to locally relevant or international standards and guidelines databases.

The section devoted to the assessment of crop property aims at evaluating the characteristics of initial set of crop varieties according to the existing cropping patterns in the region or selected crop types by the user at the first round regardless of the cropping pattern. In addition to cropping pattern, the water reuse planning strategy should include a rough market assessment early in the planning process. The appropriate choice of crops is feasible only in the presence of a market for each selected crop type. The local growth rate of crop types and the estimated areas, which are intended to be seasonally cultivated, are the specific data requirements. To determine basic physicochemical properties of soil is also required to be carried out in this step.

Step 2—Framework of potential restrictions in use (FPRU): The complexity and challenge of the technical standpoint in modeling is to make a balance of the interactions among soil, effluent and crops. It is necessary to examine the constituents that particularly define the water suitability for agricultural and landscape irrigation (Pedrero et al. 2010) in addition to the routine pollutant indicators assessed. The approach, which is often used to evaluate irrigation water quality, is referred as “potential restrictions in use” presented by Ayers and Westcot (1985).

In this study, a classification framework was developed to support the assessment of potential restrictions in use derived from complex relations of involved phases. The FPRU consists of three phases to evaluate potential hazards originated from water–crop, water–soil and soil–crop interactions.

(1) Water–crop potential problems: Sodicity, specific ion toxicity, salinity and miscellaneous effects are the main potential irrigation problems associated with water–crop phase. In order to select the most suitable crop types, the degree of restrictions on use and tolerance ratings of the selected crops to water–crop potential hazards is determined and compared with the tolerance limits specified by corresponding references. The sodium adsorption ratio (SAR) as a relative index of sodicity is the ratio of sodium to calcium and magnesium ion concentrations. Adjusted SAR (SAR-adj) as a modification of the original SAR is also used. This modification reflects the effects of bicarbonate, dissolved carbon dioxide and water salinity by the Ca_x value instead of Ca (Asano et al. 2007). The concentration of Ca_x relies on the ratio of HCO_3^- to Ca^{2+} concentration versus conductivity of water which is available from the standard tables.

The equations for calculation of SAR and SAR_{adj} are shown below, and cations are in milliequivalent per liter (meq L^{-1}).

$$\mathrm{SAR} = \frac{[\mathrm{Na}^+]}{\sqrt{\frac{[\mathrm{Ca}^{2+}]+[\mathrm{Mg}^{2+}]}{2}}} \tag{1}$$

$$\text{Adjusted SAR } (\mathrm{SAR}_{\mathrm{adj}}) = \frac{[\mathrm{Na}^+]}{\sqrt{\frac{[\mathrm{Ca}_x^{2+}]+[\mathrm{Mg}^{2+}]}{2}}} \tag{2}$$

The usual toxic ions in irrigation water are chloride, sodium and boron, and the degree of restriction related to ion toxicity is determined in FPRU. In addition, the category of restriction related to salinity problem and miscellaneous effects including bicarbonate and nitrogen effect and pH are specified. The guideline to evaluate water quality through potential irrigation problems is presented in Table 1, which is often referred to in the literature reviews such as Pescod and Arar (1985), Asano et al. (2007), Pedrero et al. (2010) and EPA (2012). Moreover, a number of different references are summarized in Table 2. As an aid to proper selection of crops, the degree of irrigation restriction of each problem in FPRU is specified by thresholds presented in Tables 1 and 2.

(2) Water–soil potential problems: Sodicity on soil structure, magnesium, infiltration and alkalinity are assessed

Table 1 Guidelines for interpretations of water quality for irrigation (Ayers and Westcot 1985)

Potential irrigation problem		Units	Degree of restriction on use		
			None	Slight to moderate	Severe
Salinity *(affects crop water availability)*					
EC_w[a]		dS m^{-1}	< 0.7	0.7–3.0	> 3.0
TDS[b]		mg L^{-1}	< 450	450–2000	> 2000
Infiltration *(affects infiltration rate of water into the soil. Evaluate using EC_w and SAR together)*					
SAR[c]	= 0–3	and EC_w	> 0.7	0.7–0.2	< 0.2
	= 3–6		> 1.2	1.2–0.3	< 0.3
	= 6–12		> 1.9	1.9–0.5	< 0.5
	= 12–20		> 2.9	2.9–1.3	< 1.3
	= 20–40		> 5.0	5.0–2.9	< 2.9
Specific ion toxicity *(affects sensitive crops)*					
Sodium	Surface irrigation	SAR	< 3	3–9	> 9
	Sprinkler irrigation	meq L^{-1}	< 3	> 3	
Chloride	Surface irrigation	meq L^{-1}	< 4	4–10	> 10
	Sprinkler irrigation	meq L^{-1}	< 3	> 3	
Boron		mg L^{-1}	< 0.7	0.7–3	> 3
Miscellaneous effects *(affects susceptible crops)*					
Nitrogen (NO_3-N)		mg L^{-1}	< 5	5–30	> 30
Bicarbonate	*(overhead sprinkling only)*	meq L^{-1}	< 1.5	1.5–8.5	> 8.5
pH			Normal range 6.5–8.4		

[a]Electrical conductivity

[b]Total dissolved solids

[c]Sodium adsorption ratio

Table 2 Guidelines for agricultural reuse of wastewater and agronomic standards

Potential irrigation problem	Parameters	Degree of restriction on irrigation			Reference
		None	Slight to moderate	Severe	
Sodicity hazard of water on crop	SAR[a]	< 1	1–5	> 5	SAI (2013)
	SAR^{b}_{adj}	< 3	3–9	> 9	
Sodicity hazard of water on soil structure	SSP[c] (1), SSP (2) (%)	< 20, < 60	20–80, < 60	> 80, > 60	(1): USSL (1954) (2): Fipps (2003)
	ESP[d] (%)	< 5	6–9	> 9	Al-Shammiri et al. (2005)
	K.R[e]	< 1		> 1	Kelly (1957)
Water–soil infiltration problem	RSC[f] (meq L^{-1})	< 1	1–2.5	> 2.5	USSL (1954), SAI (2013)
		< 0	0–1	> 1	Williams and Ley (1994)
	SAR_{adj}	< 6	6–9	> 9	SAI (2013)
Alkalinity hazard	Alkalinity (mg L^{-1} $CaCO_3$)	< 100	> 100		Soil first Consulting (www.Soilfirst.com)
Magnesium hazard	MH[g] (%)	< 50		> 50	Al-Shammiri et al. (2005)
Sensitivity of crop to salinity and sodicity of soil	ESP (%), EC^{h}_{e} (dS m^{-1})	Saline, non-sodic		ESP < 15, EC_e > 4 dS m^{-1}	USSL (1954)
		Sodic, non-saline		ESP > 15, EC_e < 4 dS m^{-1}	
		Saline, sodic		ESP > 15, EC_e > 4 dS m^{-1}	
		Non-saline, non-sodic		ESP < 15, EC_e < 4 dS m^{-1}	
	EC_e (dS m^{-1})	< 2	2–4	> 4	DEC (2004)

[a]Sodium adsorption ratio

[b]Adjusted SAR

[c]Soluble sodium percentage

[d]Exchangeable sodium percentage

[e]Kelly's ratio

[f]Residual sodium carbonate

[g]Magnesium hazard

[h]Electrical conductivity of saturated paste extract of soil

as the key water–soil hazards. The principals concerning TWW reuse in agronomic factors are soil sodicity, salinity and reduced soil permeability (Asano et al. 2007). Soluble sodium percentage (SSP), exchangeable sodium percentage (ESP) and Kelly's ratio (K.R) are important indicators of potential sodium hazard from irrigation water. A commonly used method of determining the potential hazard from magnesium in irrigation water is magnesium hazard (MH). High levels of magnesium in relation to the level of calcium in irrigation water affect soil quality through converting it into alkaline and decreasing the crop yield (Gautam et al. 2015).

Infiltration rate (IR) and permeability of soil are affected by SAR in conjunction with EC_W of irrigation water. SAR_{adj} is suggested to be applied in place of SAR (Ayers and Westcot 1994). The residual sodium carbonate (RSC) index of irrigation water or soil water is also used to indicate the infiltration problem and alkalinity hazard. The indicators of water–soil potential problems are calculated based on Eq. (3) through Eq. (7).

$$ESP = \frac{100 \times (-0.0126 + 0.01475 \times SAR)}{1 + (-0.0126 + 0.01475 \times SAR)} \tag{3}$$

$$KR = \frac{[Na^+]}{[Ca^{2+}] + [K^+]} \tag{4}$$

$$SSP = \frac{[Na^+]}{[Ca^{2+}] + [Mg^{2+}] + [Na^+] + [K^+]} \times 100 \tag{5}$$

$$\mathrm{MH} = \frac{[\mathrm{Mg}^{2+}]}{[\mathrm{Ca}^{2+}] + [\mathrm{Mg}^{2+}]} \times 100 \tag{6}$$

$$\mathrm{RSC} = [\mathrm{CO}_3^{2-}] + [\mathrm{HCO}_3^{-}] - \left([\mathrm{Ca}^{2+}] + [\mathrm{Mg}^{2+}]\right) \tag{7}$$

In which all concentrations of cations and anions used in equations are expressed in milliequivalent per liter (meq L^{-1}).

(3) Soil–crop potential problems: Sodicity–salinity problem is considered in soil–crop phase. Crop tolerance ratings to the hazard are determined based on the thresholds of EC_e and ESP of soil given in Table 2.

After determining restriction levels of potential problems in phases, the compatibility level of effluent quality with crop types and local soil conditions is evaluated, and the level of effluent suitability, the need to improve the quality of effluent or soil amendment are specified to satisfy the requirements obtained from the framework findings.

Afterward, a series of rules of the form "if condition, then action" was constructed in order to infer the specifications of matched phases based on the FPRU findings. The first if condition of step (Fig. 1) reveals the compatibility of effluent quality with the selected crop types and soil conditions according to the criteria evaluated in FPRU. If the criteria are fulfilled, then the phase-matched process is completed and the characteristics of selected crop species at the first iteration are accepted and used as the input data of step 3 and the next module; otherwise, the second if statement starts. The applicability of soil amendment and crop substitution or improving quality of effluent are evaluated in the second if function. In both conditions, the matching process by FPRU is iterated until the criteria are satisfied.

Step 3—Selection of irrigation method: One of the main control measures that must be applied for health protection in the case of irrigation by effluent is the choice of appropriate irrigation method (Lazarova and Bahri 2004(. A decision on selection of irrigation system has an influence on wastewater treatment requirements, human exposure control and crop selection. In this context, choosing the suitable type of irrigation method is performed by an iterative method based on health and safety, costs and other specific requirements shown in Table 3.

Firstly, an irrigation method is assumed or selected based on local conditions. Under if condition order, the compatibility assessment of selected irrigation system with TWW quality and the selected crop types are assessed according to FAO, FPRU findings and the criteria summarized in Table 3. There are two available conditions: (1) if the criteria are fulfilled, the selected irrigation system is accepted and its efficiency will be calculated and then used as the input data for irrigation scheduling in the second module and (2) the algorithm should proceed to the next iteration step, which involves finding the optimal irrigation method. If the selected system could be practically substituted by an alternative, then the first loop of the step is iterated once more. Otherwise, post-treatment process is necessary to enhance the effluent quality to the desired level needed for specific irrigation method when a net benefit value is obtained by the cost–benefit analysis of reuse project regarding the additional costs incurred by extended technology.

RWSDA—quantitative assessment phase

RWSDA module concerns an estimate of TWW reuse potential in terms of quantity for agricultural irrigation and the area

Table 3 Factors affecting the choice of irrigation method and special measures required for recycled water application (WHO 1989)

Irrigation method	Factors affecting choice	Special measures for irrigation with recycled water
Flood irrigation	Lowest cost Exact leveling not required Low water use efficiency Low level of health protection	Thorough protection of field workers, crop handlers, and consumers
Furrow irrigation	Low cost leveling may be needed Low water use efficiency Medium level of health	Protection of field workers, possibly of crop handlers and consumers
Sprinkler irrigation	Medium to high cost Medium water use efficiency Leveling not required Low level of health protection (aerosols)	Minimum distance 50 –100 m from houses and roads Water quality restrictions: Anaerobic wastes should not be used due to odor nuisance
Subsurface and drip irrigation	High cost High water use efficiency Higher yields Highest level of health protection	No protection measures required Water quality restrictions: Filtration to prevent emitters from clogging

of irrigated farmlands. Moreover, the module aims at effective and safe management or reuse of excess effluent. Figure 2 demonstrates the flowchart of the second module and its relation with the first module. The procedure is described as follows:

Step 1—Irrigation scheduling: The aim of this step is to calculate crop water requirements (CWRs), from planting to harvest in a specific climate, gross irrigation water requirement (GIWR) and to determine optimum irrigation scheduling. The moisture deficit, or crop water requirement, is calculated by subtracting the effective precipitation from the estimated evapotranspiration of each crop (ET_{crop}). ET_{crop} can be compared with reference evapotranspiration in the region through an experimentally derived crop coefficient expressed with Eq. (8).

$$ET_{Crop} = ET_0 \times K_c \tag{8}$$

where ET_{Crop} is crop evapotranspiration (mm mo^{-1}); ET_0 is the reference evapotranspiration (mm mo^{-1}); and K_c is crop coefficient (dimensionless). Penman–Monteith or PM methodology given by the FAO 56 bulletin (Allen et al. 1998) is adopted in this study as the standard reference tool to estimate ET_0. Crop-specific coefficient values of the selected crop types are also obtained based on the procedure recommended by FAO bulletin. CWR is measured as follows:

$$CWR = ET_{Crop} - EP \tag{9}$$

in which CWR is crop water requirement (mm mo^{-1}) and EP is the effective precipitation (mm mo^{-1}). The collected meteorological data from the nearest station are used as the database to compute effective precipitation in the region. The actual amount of irrigation water to be applied is necessary to be adjusted for effective precipitation, leaching requirement, application losses and other factors. Hence, GIWR is defined as the net irrigation water requirement or CWR, besides conveyance losses between the source of water and the field, and any additional water for leaching over as well as above percolation (Ayers and Westcot 1994). Irrigation water requirement (IWR) is calculated in the following equation:

$$IWR = \frac{CWR}{e} \tag{10}$$

in which IWR is irrigation water requirement (mm mo^{-1}); and e is the scheme irrigation efficiency system.

The scheme irrigation efficiency percentage is estimated through Eq. (11).

$$e = \frac{e_c \times e_a}{100} \tag{11}$$

where e_c is the conveyance efficiency percentage (CEP); and e_a is the field application efficiency percentage (FAEP). The values of CEP and FAEP are calculated based on indicative

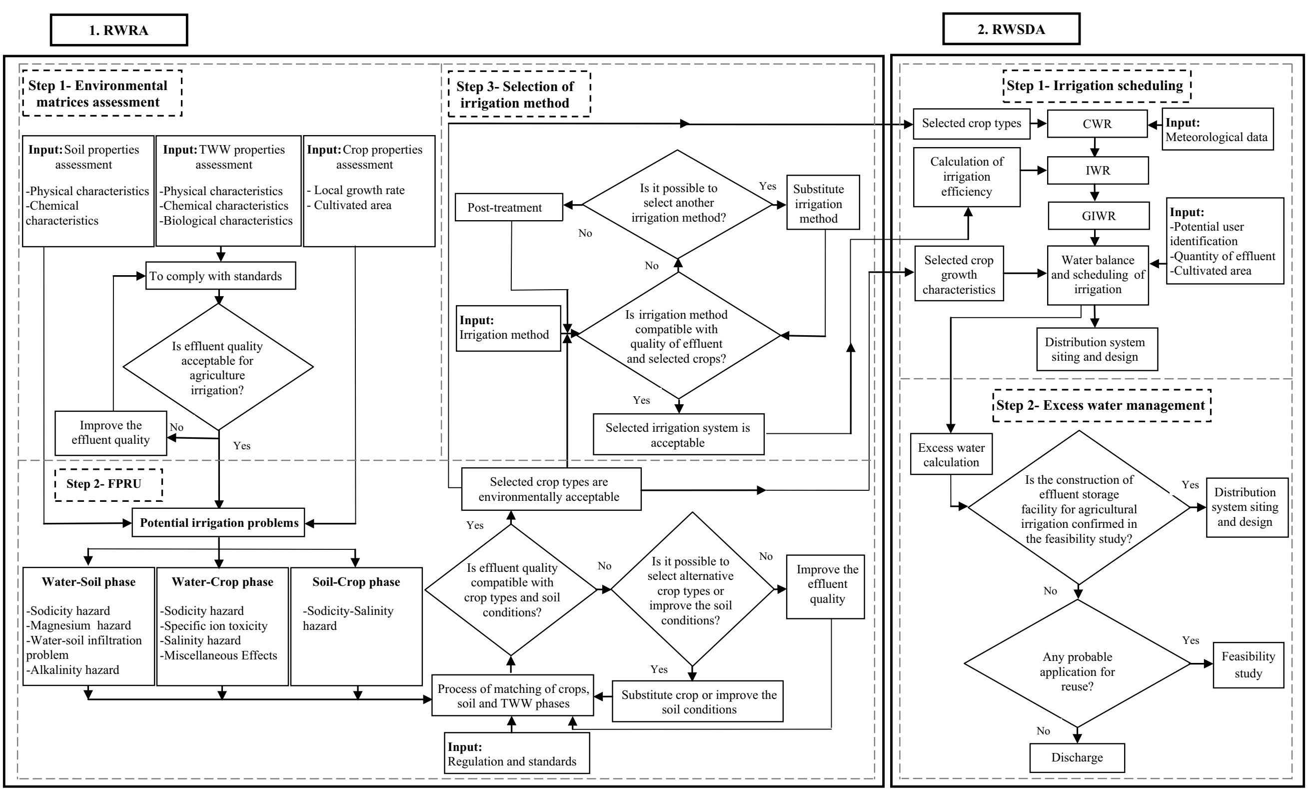

Fig. 2 Flowchart of the RWSDA module and interrelation with the first module

values proposed by Brouwer et al. (1989) which depend on the irrigation method obtained from the first module, length of the canals and soil type.

In addition, an extra amount of water is necessary for leaching to keep a favorable root-zone salt balance (Ayers and Westcot 1994). The leaching ratio could be obtained as follows:

$$LR = \frac{EC_w}{5EC_e - EC_w} \tag{12}$$

in which LR is leaching ratio, EC_W is salinity of applied irrigation water (dS m^{-1}) and EC_e is saturated soil extract salinity for a 90% crop yield potential (dS m^{-1}).

GIWR is then calculated with the following equation:

$$GIWR = \frac{IWR}{(1 - LR)} \tag{13}$$

where GIWR is gross irrigation water requirement (mm mo^{-1}) and LR is leaching ratio calculated by Eq. (12).

The total volume of TWW requirement based on the assumed irrigated area of selected crops is measured as:

$$V_T = \sum_{i=1}^{n} A_i \times \frac{GIWR_i}{1000} \tag{14}$$

where V_T is a total monthly volume of water (m^3 mo^{-1}), n is a total number of selected crop types, A_i is irrigated area of each crop in the region (m^2), and GIWR (mm mo^{-1}) is calculated by Eq. (13).

Afterward, an equitable and optimal scheduling of irrigation is developed based on crop-growing season and crop characteristics, potential users, and available effluent quantity and its variability. To achieve an optimal scheduling and balance between supply and demand, analysis should be redone by changing the irrigated areas or crop shifting. The process of water distribution system design can be conducted by the users at the end of the step.

Step 2—Excess effluent management: Management of excess effluent should be considered due to fluctuations in agricultural water demand and continuous flow mode of reclaimed water. What cannot be used immediately must be stored, re-allocated or disposed of according to the results of FS. Provided feasibility of effluent storage facility for agricultural irrigation returns negative, the excess effluent must be allocated to different uses. Water distribution system from storage facility is performed if FS returns positive. In case, there is no opportunity for appropriate application, and then excess TWW is necessary to be disposed of.

FMPs—management assessment phase

Field management practices is a system administration module which gives general information about irrigation management to prevent adverse impacts of prolonged effluent irrigation on crop, soil, and water resources. The flowchart of the third module and the hierarchical and integrated procedure of LDM paradigm, applied to research, are shown in Fig. 3. The procedure of FMPs module is based on outputs of the first and second modules and is divided into two steps described as follows:

Step 1—Irrigation management: The major components of this step include nutrient content control, and management of leachate and drainage. The nutrient content of effluent and soil, specific crop nutrient requirements and equivalent amount of (saved) fertilizer should be estimated in "Crediting nutrients" block. As result of water scheduling and nutrient credit steps, nutrients supplied by TWW are roughly determined to reduce environmental impacts of over-fertilization.

Leaching and drainage are two important water management practices to prevent soil salinization (Pescod 1992). In this subsection, the method for drainage control and the required level of leaching are determined. In order to avoid salinization, leaching with fresh water is recommended. Surface irrigation could resolve the problem of salinization (Papadopoulos et al. 2009). Another option for salinity control is blending TWW with stream water. Using the effluent alternately with the stream water or well water as an alternative strategy was also recommended (Pescod 1992). Besides, prolonged use of reclaimed wastewater in irrigation is not generally possible without adequate drainage (Pedrero et al. 2010). A good drainage is vital to allow a continuous movement of water and salt below the root zone (Pedrero et al. 2010). Furthermore, drainage is specifically highlighted in semiarid and arid areas to prevent secondary salinization (Pescod 1992).

Step 2—Long-term management: In order to minimize as much as possible the potential risks associated with water reuse, it is recommended to perform a very strict and complete monitoring program (AQUAREC 2006). At the end of FMPs module, a monitoring program is required to be set to assess the overall performance of the ultimate quality of TWW produced and the quality of receiving environment to ensure workers' safety and public health protection as well as healthy plant growth.

Case study

Project study area

Kordkuy is located in the northeast of Iran at the longitude of 54°1′ and latitude of 36°8′. The climate is characterized as Mediterranean humid with dry and warm summers. The county is subjected to water imbalance due to increasing trend of water demand and temporal variations

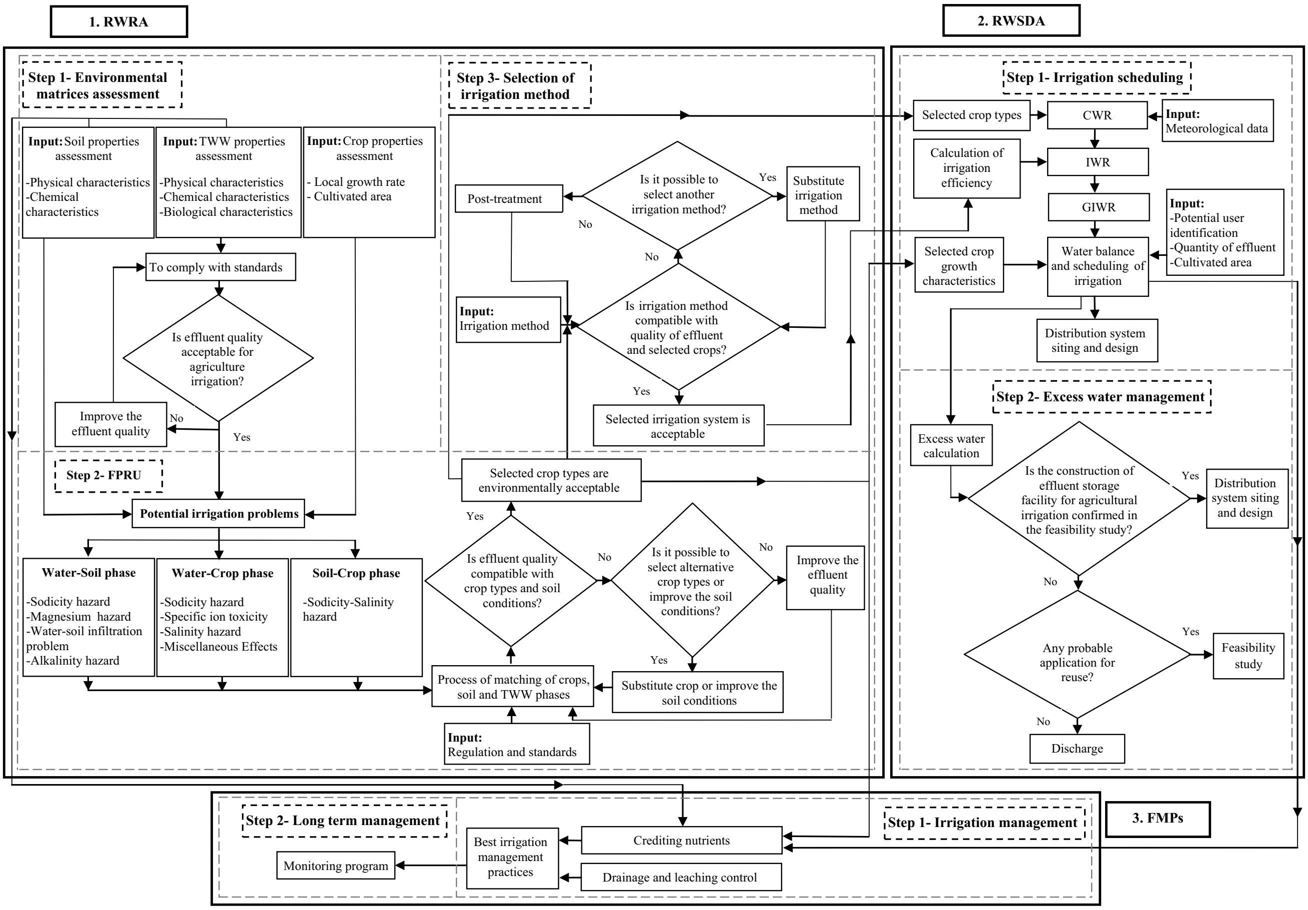

Fig. 3 LDM for technical feasibility assessment of reclaimed water reuse in agricultural irrigation

of precipitation, which is particularly observed during dry summer months.

The capacity of Kordkuy wastewater treatment plant (KWWTP) is 7200 m^3 day^{-1}. Wastewater flows through the headwork and is subsequently admitted to an extended-aeration activated sludge system for organic matter degradation. TWW is then disinfected in chlorine contact basin before being disposed of seasonal stream, Ghaz Mahale. Due to water shortage, farmers practice uncontrolled reclaimed water reuse in fields across KWWTP for a long time. Hence, water reuse feasibility studies are required to be conducted in the area.

Sampling techniques and analytical methods

The type and analytical techniques for the samples taken at the outlet of KWWTP are presented in Table 4. Samples were directly taken by a 2-L glass beaker and transferred to a 10-L cleaned plastic container. The contents of the container were completely mixed and kept at 4 °C and transferred immediately to the laboratory. Samples of biological analysis were collected by a tripled rinse sterilized clean glass beaker. Analytical procedures and protocols were conducted according to the standard methods for the Examination of Water and Wastewater (APHA 1998). Helminth eggs were measured following the modified Bailenger method (Ayers and Mara 1996). As part of the routine measurements performed, the characteristics of effluent were determined in a 5-year period from 2010 to 2015 which profoundly indicates the treatment level of KWWTP. Levels of TDS, turbidity, EC, heavy metals and ionic concentrations were also measured via grab sampling in 6 months.

Soil samples were collected from three plots located in the north, east and west of KWWTP. Three samples containing 1 kg of soil were taken at each plot from surface layers at the depth of maximum 30 cm. After being transported to the laboratory, samples were dried, ground and sieved to pass through a 2-mm screen. Basic physicochemical soil properties and analytical methods are shown in Table 5.

Table 4 Sample types and methods used to examine effluent characteristics

Parameters	Method	Sample type
BOD_5^a	5-day BOD test	Composite
COD[b]	Closed reflux, titrimetric method	
TSS[c]	Total suspended solid dried at 103–105 °C	
Fecal coliforms	Most probable number (MPN) method	
Nematodes	Modified Bailenger method and McMaster counting slide	
DO[d]	Electrometric method	Grab
pH	Electrometric method using Hanna instruments	
TDS[e]	Whatman 934AH glass fiber filter, dried at 105 °C	
Chlorine residual	*N*-Diethyl-*p*-phenylenediamine (DPD) method	
Turbidity	Nephelometric method using MicroTOL 3, HF Scientific, Inc.	
EC[f]	Electrical conductivity method using Hanna instruments	
TP[g]	Spectrophotometric method using (Jenway 6315, output 0–10 V) with a UV cell	
NO_3^-, NH_4^+	Ultraviolet spectrophotometric using (Jenway 6315, output 0–10 V) with a UV cell	
K^+, Na^+	Flame photometric method	
Ca^{2+}, Mg^{2+}	EDTA titrimetric	
SO_4^{2-}	Spectrophotometric method using (Jenway 6315, output 0–10 V) with a UV cell	
Cl^-	Ion chromatography with chemical suppression	
HCO_3^-	Titration with acid using phenolphthalein	
Alkalinity	Titration with acid using phenolphthalein	
Heavy metals	Atomic absorption spectrophotometer (AAS) using PerkinElmer 3030 Analyst	

[a]Biochemical oxygen demand

[b]Chemical oxygen demand

[c]Total suspended solids

[d]Dissolved oxygen

[e]Total dissolved solids

[f]Electrical conductivity

[g]Total phosphorous

Table 5 Methods used to soil physicochemical analysis

Parameters	Method	References
Soil texture	The sieve-pipette method	Richards (1954)
soil moisture content	Dried at 100–110 °C and weighted	IRI vice Presidency for Planning and Supervision-No. 467 (2009)
SOC[a]	Titration with using o-phenanthroline	
pH	Soil: water slurry using digital electronic pH meters (Hanna instruments)	
EC_e^b	Electrical conductivity method of saturated paste extract of soil	
$Ca^{2+,}$ Mg^{2+}	Flame atomic emission spectrometry (FAES)	
Na^+	Flame atomic emission spectrometry (FAES)	
CO_3^{2-}, HCO_3^-	Automatic titration	
Available Phosphorus	Olsen testing method (0.5 M $NaHCO_3$)	Olsen and Sommers (1982)
TKN[c]	2300 Kjeltec analyzer unit, Foss, Höganäs, Sweden	–

[a]Soil organic carbon

[b]Electrical conductivity of saturated paste extract of soil

[c]Total Kjeldahl nitrogen

Results and discussion

This section reports and discusses the results of the LDM performance in the case study based on the steps of the aforementioned modules.

Implementation of RWRA module

Step 1: A comparison of physicochemical and microbiological characteristics of TWW with corresponding reference values of effluent quality criteria for agricultural irrigation is presented in Table 6. The ranges of physical properties

Table 6 Average results of physicochemical and microbiological analyses (± standard deviation) of TWW in Kordkuy

Parameters (unit)	Value	USEPA (2004)	USEPA (2012)	WHO (1989)	Ayers and Westcot (1994)[f]	DOE, Iran (2001)[g]
Turbidity (NTU)	5.0 ± 2.0	2[a]	2[a]	–	–	50
TSS ($mg\ L^{-1}$)	11.7 ± 5.8	30[b]	30[b]; 5[a, c]	–	–	100
TDS ($mg\ L^{-1}$)	1062 ± 180	–	–	–	2000	–
EC ($dS\ m^{-1}$)	1.68 ± 320	–	–	–	3	–
pH	7.8 ± 0.2	6–9[a, b]	6- 9[a, b]	–	6–8.5	6–8.5
BOD_5 ($mg\ L^{-1}$)	14.3 ± 4.9	10[a], 30[b]	10[a];30[b]	–	–	100
COD ($mg\ L^{-1}$)	40.1 ± 17.7	–	–	–	–	200
DO ($mg\ L^{-1}$)	3.7 ± 0.7	–	–	–	–	2
NH_4^+ ($mg\ L^{-1}$)	5.6 ± 3.0	–	–	–	5 (NH_4-N)	–
NO_3^- ($mg\ L^{-1}$)	5.8 ± 2.1	–	–	–	10 (NO_3^--N)	–
Total N ($mg\ L^{-1}$)	20.1 ± 4	10[a, c]	10[a, c]	–	–	–
Total P ($mg\ L^{-1}$)	2.3 ± 0.3	–	–	–	–	–
Residual chlorine ($mg\ L^{-1}$)	0.3 ± 0.08	–	Min > 1[a, c]	–	–	0.2
Cl^- ($mg\ L^{-1}$)	250.3 ± 53.1	–	–	–	30 ($meq\ L^{-1}$)	600
Ca^{2+} ($mg\ L^{-1}$)	125.3 ± 21.4	–	–	–	20 ($meq\ L^{-1}$)	–
Mg^{2+} ($mg\ L^{-1}$)	68.0 ± 9.0	–	–	–	5 ($meq\ L^{-1}$)	100
K^+ ($mg\ L^{-1}$)	13.7 ± 2.3	–	–	–	2 ($meq\ L^{-1}$)	–
Na^+ ($mg\ L^{-1}$)	121.7 ± 35.6	–	–	–	40 ($meq\ L^{-1}$)	–
SO_4^{2-} ($mg\ L^{-1}$)	69.0 ± 15.8	–	–	–	20 ($meq\ L^{-1}$)	500
CO_3^{2-} ($mg\ L^{-1}$)	0.0	–	–	–	0.1 ($meq\ L^{-1}$)	–
HCO_3^- ($mg\ L^{-1}$)	479.0 ± 65.0	–	–	–	10 ($meq\ L^{-1}$)	–
Alkalinity ($mg\ L^{-1}$ $CaCO_3$)	392.5 ± 53.0	–	–	–	–	–
Bicarbonate alkalinity ($mg\ L^{-1}$ $CaCO_3$)	392.5 ± 53.0	–	–	–	–	–
Boron ($mg\ L^{-1}$)	N.D.	–	–	–	2	1
Arsenic ($mg\ L^{-1}$)	N.D.	0.1; 2[d]	–	–	–	0.1
Cadmium ($mg\ L^{-1}$)	N.D.	0.01; 0.05[d]	–	–	–	0.05
Lead ($mg\ L^{-1}$)	N.D.	5; 10[d]	–	–	–	1
$Chromium^{3+}$ ($mg\ L^{-1}$)	N.D.	0.1; 1[d]	–	–	–	2
Copper ($mg\ L^{-1}$)	N.D.	0.2; 5[d]	–	–	–	0.2
Mercury ($mg\ L^{-1}$)	N.D.	–	–	–	–	No detectable
Fecal coliforms (MPN 100 mL^{-1})	27 ± 8	–	No detectable[a]; 2×10^{2}[b]	≤ 1000[e]	–	4×10^2
Nematodes (Egg L^{-1})	N.D.	–	–	≤ 1	–	≤ 1

N.D. not detected

[a]Irrigation of food crops which are intended for human consumption, consumed raw

[b]Food crops commercially processed and non-food crops

[c]Parameter only set for the state of New Jersey

[d]Long-term and short-term irrigation

[e]Irrigation of crops likely to be eaten uncooked, cereal crops, industrial crops

[f]Water quality for agriculture. [g] Wastewater quality standard for agricultural use

(TDS, and EC) were found within acceptable limits of the standards. However, average turbidity level (5.0 NTU) and TSS concentration (11.7 mg L^{-1}) exceeded the constraints specified by the USEPA for irrigation of food crops intended for human consumption or consumed raw.

In terms of chemical attributes, the mean outlet pH was mildly alkaline without exceeding the standards. The COD and BOD_5 concentrations were below the maximum permissible limits defined by the Iranian Department of Environment (DOE). However, mean BOD_5 concentration was above the USEPA constraint for unrestricted irrigation. Concerning the organic pollutants, TWW could be safely used for agricultural irrigation except in irrigation of crops likely to be eaten uncooked.

The levels of TN and TP concentrations were in agreement with the recommended limits except USEPA limit of TN for unrestricted irrigation. It is worth mentioning that the threshold of total phosphorous concentration in irrigation recommended by IMOE (2010) is 20 mg L^{-1}.

Average amounts of ion concentrations were well below the recommended thresholds, except concentration level of Mg^{2+} compared to the threshold given by FAO. The mean chlorine residual concentration was slightly higher than DOE standard. Since heavy metals are not detected in samples, the effluent is conservatively expected to be used with low potential problems in short periods of time. The mentioned term refers to maximum 20 years of use for fine-textured and neutral or alkaline soils (EPA 2004). Even though fecal coliform values were much lower than the constraints for restricted irrigation, it did not comply with the standard for unrestricted irrigation established by USEPA (2012). Effluent was also found to be free from nematode egg.

Risk assessment is closely linked to the reclaimed water quality and the application given to this water (AQUAREC 2006). Domestic wastewater that has limited industrial wastewater input generally contains concentrations of organic and inorganic compounds that do not present health concerns when the recycled water is applied for irrigation (Lazarova and Bahri 2004). It should be noted that the risk of industrial wastewater discharged to the plant in the case study is very limited since there is low rate of industrialization in the region and in neighborhood of KWWTP. So, TWW contains no possible problematic chemical components. Moreover, in-depth knowledge and appropriate monitoring of water quality are also required to protect public health and reduce the negative impacts of TWW on irrigated crops (Lazarova and Bahri 2004). Monitoring program has been presented in FMPs module to minimize risks of long-term impact of reclaimed water irrigation.

Upon analysis of the results, the effluent quality met the standard requirements for restricted irrigation. Provided effluent is intended to be applied for unrestricted irrigation, quality improvement is necessary to meet more stringent standards.

Table 7 Main attributes of soil samples collected from the fields around KWWTP

Parameter	Observed value		
	East	West	North
Silt (%)	58	47	55
Clay (%)	30	43	29
Sand (%)	12	10	16
Moisture percent (%)	25.3	34.0	11.6
pH	8.0	8.1	8.1
EC (dS m^{-1})	1.6	0.6	1.6
TKN (%)	0.11	0.12	0.05
Phosphorus availability (%)	7.7	3.0	2.4
SOC (%)	1.1	1.1	0.5
CO_3^{2-} (mg kg^{-1})	0.0	0.0	0.0
HCO_3^- (mg kg^{-1})	378.0	329.0	293.0

Table 8 Area and local growth rate of crops cultivated across KWWTP

Crop	Botanical name	Base period[a] (day)	Area (ha)
Summer–autumn growing season			
Soybean	*Glycine max*	143	31
Spring–summer growing season			
Rice	*Oryza*	130–145	10
Spring–autumn growing season			
Plum	*Prunus domestica*	216	0.5
Peach	*Prunus persica*	216	0.5
Winter–spring growing season			
Barley	*Hordeum vulgare*	100–120	21
Rapeseed	*Brassica napus*	150–180	20

[a]The time between first watering of crop at the time of sowing and the last watering before harvesting

Table 7 shows the main physicochemical soil properties across KWWTP. Soil texture is categorized as silt–clay according to the United States' Department of Agriculture (USDA) textural soil classification and is characterized by a fine texture with low organic carbon content (0.46–1.1%) based on ISO (2002). Furthermore, the pH of spots was slightly alkaline. The values of phosphorus availability and total nitrogen are applicable in FMPs module to estimate required amounts of fertilizer per unit area. It should be noted that the clay in the case study contains non-expandable clay minerals (Kaolinite) wherein the potential to store water and nutrients seems to be less effective. Table 8 provides a summary of the cultivated area of crops and their local growth rate across KWWTP. Total area of farmlands across

KWWTP irrigated by mixed effluent and stream water is about 42 ha.

Step 2: A developed FPRU of the case study is shown in Fig. 4. The framework includes the assessment of six types of crops selected in the previous step. FPRU details are reported and discussed as follows:

Water–crop potential problems: The average SAR_{adj} of 2.85 in effluent samples indicates that there is no degree of irrigation restriction; however, SAR values of 2.27 show slight-to-moderate degree of constraint. No impact of sodicity hazard on crop types was concluded except very sensitive ones including peach and plum trees and soybean as sensitive crop.

Specific ion toxicity is of severe concern for chloride, sodium and boron, and many plants are expected to be adversely impacted (Asano et al. 2007). Since no amount of boron was detected in TWW samples, there is no degree of restriction on irrigation. However, irrigation with effluent may pose a risk on peach and plum, as very sensitive crops, rice and rapeseed as sensitive ones. The average chloride concentration of 250.3 mg L^{-1} (7 meq L^{-1}) was in the category of slight-to-moderate restriction. Sensitive plants, including peach and plum, may be impacted by chloride concentration. The sodium toxicity level is below the recommended constraints. However, peach and plum are very sensitive and soybean is sensitive.

Concerning salinity hazard, the levels of EC_w and TDS were 1.68 ds m^{-1} and 1062 mg L^{-1}, respectively, which indicate slight-to-moderate degrees of restriction. Thus, problem of salinity is serious for rice and especially with peach and plum trees.

In terms of miscellaneous effects, the restriction of bicarbonate concentration would be slight to moderate if sprinkler irrigation is selected. The restriction degree for surface irrigation system as the existing one in the case study is not determined in guidelines. The effect of pH appears to be insignificant on selected crops. The average nitrate content in reclaimed water indicates slight-to-moderate restriction. Therefore, over-fertilization and excessive vegetative growth may not occur. However, nutrients should be periodically monitored to avoid its accumulation to critical levels.

Water–soil potential problems: The average ESP value of reclaimed water is considered as minimal hazard of sodification to use. Besides, the average SSP value of samples indicates slight-to-moderate restrictions; therefore, fined-structure soil in the area (Table 7) may be susceptible to

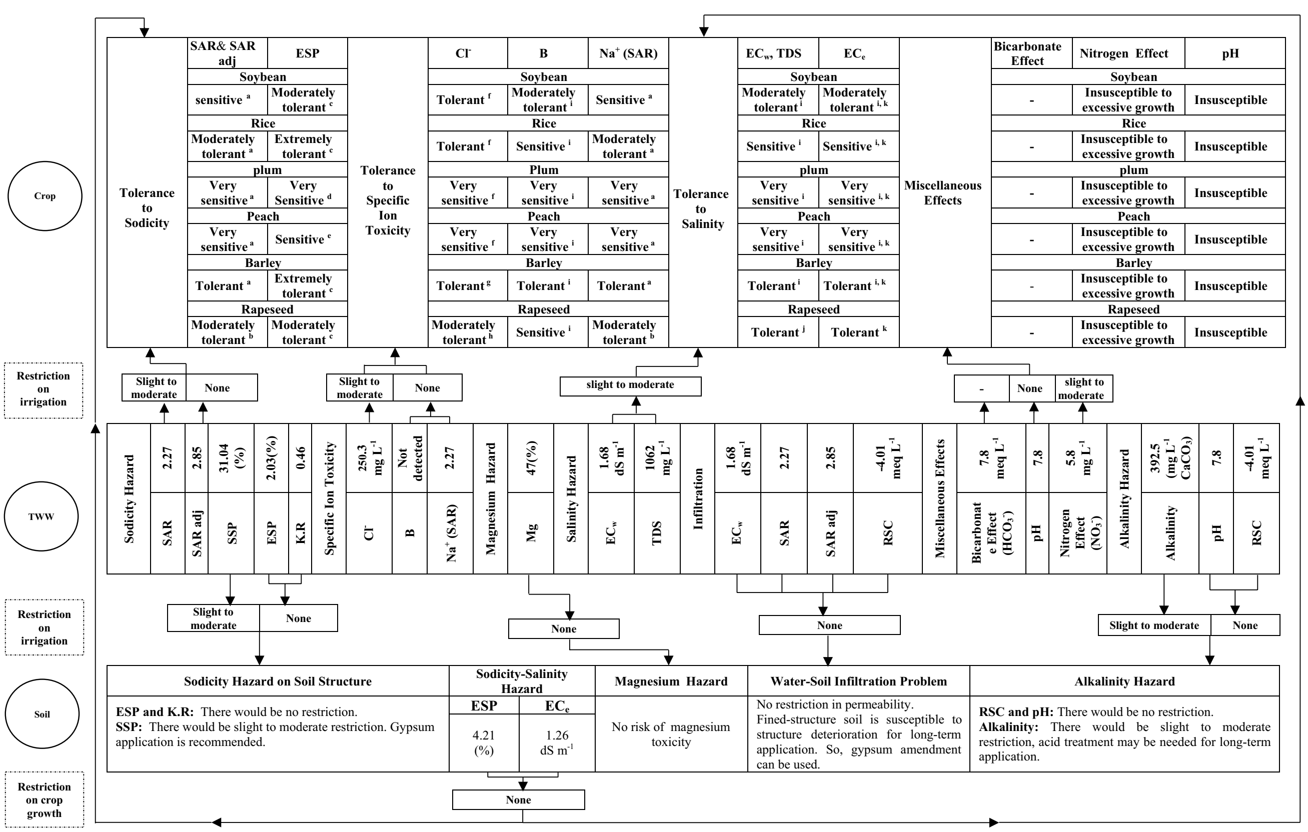

Fig. 4 Proposed FPRU of case study. [a]Anzecc (2000), [b]Jalili et al. (2013), [c]Gupta and Abrol (1990) and Kumar (2008), [d]www.waterquality.montana.edu, [e]Landon (1991), [f]www.kali-gmbh.com, [g]Ayers and Westcot (1985), [h]Shahbazi et al. (2011), [i]McFarland et al. (2014), [j]Canadian Water Quality Guidelines (1995), [k]Tanji and Kielen (2003)

structure deterioration for long-term application of effluent as irrigation source. The levels of K.R ranged from 0.35 to 0.62 with average value of 0.46 (Fig. 4) which were suitable for reuse. The value of MH does not appear to cause problem in soil. The mean values of EC_w, SAR and SAR_{adj} indicate that there is no risk of water infiltration problem. As mentioned before, the soil of fields across KWWTP, particularly in the west, is classified as fined structure (Table 7); therefore, the rate of seal formation would be faster under prolonged irrigation with effluent. In the present study, RSC values of all samples were negative, which falls in no restriction category. The average RSC and pH results determine that effluent reuse would not pose any risk of soil alkalinity hazard. However, concentration of alkalinity with regard to the average value of 392.5 mg L^{-1} $CaCO_3$ was observed to be above the permissible limit indicating possible alkalinity hazards in the project area.

Soil–crop potential problems: The soil in the fields is classified as non-saline and non-sodic. The mean ESP value indicates no restriction on crop growth. Meanwhile, peach and plum trees are considered to be sensitive crops. Besides, rice is a sensitive crop in comparison with other crops based on the average value of EC_e.

According to the findings of FPRU, rapeseed, soybean and barley achieved the highest relative tolerance ratings. Moreover, acid treatment by application of organic acids such as humic acids for adjusting the alkalinity effect of TWW and gypsum amendment are necessary to improve soil structure and aid in remediating sodic soil.

Step 3: The compatibility assessment of irrigation system with effluent quality and selected crop types was carried out in the first if condition of step 3 (Fig. 1). Gravity-surface irrigation has been selected as the available irrigation method which is already being applied on the farms of the study area. The method can be used for all types of crops and is applied when conditions are favorable: mild and regular slopes and soil types with medium to low rate of infiltration (Brouwer et al. 1988). The method application meets no degree of constraint in the case study based on the restriction category related to sodium and chloride of water (Table 1) and factors summarized in Table 3. As a result, preferred irrigation method is compatible with effluent quality, selected crop types and soil conditions. However, the method has high exposure or contact risk for workers and its efficiency of performance is low due to deep percolation, seepage, poor distribution effectiveness and tail water.

Implementation of RWSDA module

Step 1: Table 9 shows the water balance and the potential irrigated areas of each selected crop type for both winter–spring and summer–autumn planting. To estimate CWRs, daily recorded data from 1993 to 2009 at the nearest meteorological station were used. IWR values were computed from CWR via the scheme irrigation efficiency system (Eq. 11) on the basis of selected irrigation method resulted from the first module. According to FAO guideline (Brouwer et al. 1989), CEP value of canals with the length of more than 2000 m in clay–silt soils and FAEP value of the surface irrigation system were considered as 80 and 60%, respectively. The computed irrigation efficiency was achieved to be equal to 48%. Subsequently, GIWR values were calculated by considering the leaching requirement for 90% crop yield potential. In the last step, irrigation gross depth was multiplied by potential area to obtain an estimation of monthly distribution of water requirement.

To achieve optimum irrigated area, two scenarios were considered: (a) reuse of effluent in the fields across KWWTP and (b) reuse in the fields across and beyond KWWTP. In scenario A, the water demand of 21 ha barley and 20 ha rapeseed in winter–spring planting and 41 ha soybean in summer–autumn planting could be irrigated. Hence, it is possible to reserve a total amount of 309,120 m^3 freshwater annually. In scenario B, it is possible to supply water demand of 56 ha summer–autumn soybean. In addition, the area of rapeseed cultivation could be maximized by 262 ha in winter–spring planting instead of barley cultivation with the purpose of increasing the profitability of the plan in the region. Therefore, the scheme can annually save up to 718,560 m^3 of freshwater. Due to the potential demands in the region and financial constraints, the first scenario has priority to be performed.

Step 2: The volume of excess reclaimed water can be transferred to the reservoir or used in other potential applications in case of FS done by decision-makers. In this study, the alternative of effluent storage construction or other applications of water reuse was not considered due to the local conditions, level of technology and low potential demands. As a result, excess effluent should be discharged to Ghaz Mahale stream accordance with national regulatory standards.

Implementation of FMPs module

Step 1: Table 10 shows the amount of nutrient supplied by reclaimed water. The values were estimated on the basis of nutrient loading of TWW (Tables 6, 9) and the nutrient contents of soil (Table 7). The results indicate that nutrient supply is unsteady and insufficient to meet crops needs. Nevertheless, moderate amounts of N fertilizer are recommended to be applied, particularly when soybean is irrigated by TWW. In the case of P_2O_5 requirement, crop demands would not be satisfied by reclaimed water. However, the implementation of reuse scheme in the case study can play an important role in closing the nutrient loop by reusing wastewater and reduce fertilizer costs.

Table 9 Water balance and potential irrigated areas of selected crop types

Month	CWR[a] ($m^3\ mo^{-1}\ ha^{-1}$)			IWR[b] ($m^3\ mo^{-1}\ ha^{-1}$)			A × GIWR[c]—Scenario A ($ML\ mo^{-1}$)			A × GIWR—Scenario B ($ML\ mo^{-1}$)		TWW produced ($ML\ mo^{-1}$)	Excess water ($ML\ mo^{-1}$)	
	Soybean	Barley	Rapeseed	Soybean	Barley	Rapeseed	Soybean	Barley	Rapeseed	Soybean	Rapeseed		Scenario A	Scenario B
							41 ha	21 ha	20 ha	56 ha	262 ha			
Jan.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	126.18	126.18	126.18
Feb.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	172.80	172.80	172.80
Mar.	0.00	50.28	50.28	0.00	104.75	104.75	0.00	2.27	2.38	0.00	31.16	208.72	204.07	177.56
Apr.	0.00	388.80	340.84	0.00	810.00	710.08	0.00	17.59	16.12	0.00	211.27	212.53	178.82	1.26
May	0.00	259.20	220.32	0.00	540.00	459.00	0.00	11.73	10.42	0.00	136.56	223.20	201.05	86.64
Jun.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	208.92	208.92	208.92
Jul.	430.15	0.00	0.00	896.14	0.00	0.00	39.16	0.00	0.00	53.49	0.00	166.06	126.90	112.57
Aug.	970.08	0.00	0.00	2021.00	0.00	0.00	88.32	0.00	0.00	120.63	0.00	144.63	56.31	24.00
Sep.	970.11	0.00	0.00	2021.06	0.00	0.00	88.32	0.00	0.00	120.63	0.00	122.46	34.14	1.83
Oct.	350.07	0.00	0.00	729.31	0.00	0.00	31.87	0.00	0.00	43.53	0.00	131.67	99.80	88.14
Nov.	10.36	0.00	0.00	21.58	0.00	0.00	0.94	0.00	0.00	1.29	0.00	153.45	152.51	152.16
Dec.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	124.55	124.55	124.55

[a]Crop water requirement

[b]Irrigation water requirement

[c]Gross irrigation water requirement

Table 10 Amounts of nutrient as fertilizer supplied by effluent

Nutrient	Summer–autumn		Winter–spring		
	Soybean		Rapeseed		Barley
	Scenario A	Scenario B	Scenario A	Scenario B	Scenario A
Average amount of nitrogen provided from effluent (tons N crop^{-1})	5.0	6.8	0.6	7.6	0.6
Average amount of phosphate provided from effluent (tons P crop^{-1})	0.57	0.78	0.07	0.90	0.07
Requirement of nitrogen (tons crop^{-1})	4.1–6.2	5.6–8.4	5.0–7.0	65.5–91.7	2.1–3.2
Requirement of phosphate (tons crop^{-1})	6.2–9.4	8.4–12.9	2.0–3.0	26.2–39.3	1.1–4.2
Percentage of nitrogen requirement provided by TWW	81–121		8–12		19–28
Percentage of phosphate requirement provided by TWW	6.0–9.2		2.3–3.5		1.7–6.3

In the case study, the LR as portion of effluent to mobilize the excess of salts was calculated and added to IWR values (Table 9). Moreover, the use of effluent alternately with the stream water or well water is recommended in addition to the selection of surface irrigation system which helps to control salinity in the root zone.

Step 2: A monitoring program in the case study was set up and presented as follows:

(a) Controlling heavy metal concentrations in reclaimed water and accumulation rate in soil and crops.
(b) Groundwater quality control.
(c) Potential microbioloads of TWW, particularly content of Escherichia coli, FC, Giardia lamblia and helminth egg before reuse.
(d) Concentration of ubiquitous and persistent emerging contaminants and organic chemicals including persistent organic pollutants (POPs) and volatile organic compounds (VOCs) in the effluent.
(e) Controlling chlorine concentration in TWW to check restriction level in FRPU.
(f) Soil attributes specifically IR, hydraulic conductivity and the level of salinity–sodicity hazards predicted in the FPRU.
(g) Growth of the selected crops in the base period.
(h) Determining the long-term effectiveness of treatment proposed in the FPRU to control soil hazards.
(i) Health check of farm workers due to the risk of selected irrigation method.
(j) Controlling nutrients and over-irrigation.
(k) Assessment of the adequacy of leaching and drainage.

Conclusion

In order to avoid the risks of water reuse schemes in agriculture, decision-making models provide assistance in simulating the basic conditions needed for irrigation and evaluating the most likely environment and health risks before performance of the projects. In this paper, a logical decision-making model (LDM) for feasibility assessment of reclaimed water reuse in irrigation was developed for the attainment of the technical objectives of water reuse plans. The presented model has a hierarchical modular structure made up by three ordered submodules incorporating reclaimed water reusability analysis, reclaimed water supply–demand analysis and field management practices.

The proposed methodology is able to evaluate the quality of environmental matrices (soil, water and plant), select the most suitable crop types and choose the most appropriate irrigation method by the first-module implementation. The procedure of crop selection is carried out by performance of a framework of potential restriction in use, innovatively developed to match effluent, soil and crops simultaneously. The second module allows users to estimate effluent reuse potential in terms of quantity for agricultural irrigation and the area of irrigated farmlands as well as the effective and safe management or reuse of excess treated wastewater. The third module gives general information about irrigation management to prevent adverse impacts of prolonged effluent irrigation on the environment. Furthermore, this study presented coupled application of logical model in Kordkuy, Iran. The model enables integrating and interconnection of the most relevant technical factors involved at different stages of agricultural irrigation by effluent in one structure as well as specifying the intervening mode of processing. The compatibility with different policy guidelines and regulations, the simplicity achieved by a series of logical steps and the integration of all modules are the main features of the algorithm which make the model globally applicable, readily updatable and uniformly enforced.

Acknowledgements This project was funded by Golestan Regional Water Company as part of the program "Treated Wastewater Reuse Plans in Golestan Province, Iran". The authors gratefully acknowledge Pazhouhab Shargh Consulting Engineers Company for their enthusiastic support during the data collection period, sampling and water–soil quality analysis. Also the comments and assistance given by Emad

Mahjoobi, Mohammad Ali Ghanadzadeh and Navid Taheri Heravi are much appreciated.

References

Ahmadi L, Merkley GP (2009) Planning and management modeling for treated wastewater usage. Irrigat Drain Syst 23(2–3):97–107
Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. Irrigation and drainage paper no. 56. FAO, Rome
Al-Shammiri M, Al-Saffar A, Bohamad S, Ahmed M (2005) Waste water quality and reuse in irrigation in Kuwait using microfiltration technology in treatment. Desalination 185(1):213–225
Anzecc A (2000) Australian and New Zealand guidelines for fresh and marine water quality. Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand, Canberra, pp 1–103
Aoki C, Memon M, Mabuchi H (2005) Water and wastewater reuse: an environmentally sound approach for sustainable urban water management. United Nations Environmental Program, Nairobi
APHA (American Public Health Association) (1998) Standard methods for the examination of water and wastewater, 20th edn. American Public Health Association, Washington
AQUAREC (2006) Handbook on feasibility studies for water reuse systems. AQUAREC, Tacoma, pp 9–30
Asano T, Burton FL, Leverenz HL, Tsuchihashi R, Tchobanoglous G (2007) Water reuse issues, technologies, and application. Metcalf & Eddy/AECOM Press & McGraw Hill Professional, Massachusetts
Ayers R, Mara D (1996) Analysis of wastewater for use in agriculture; a laboratory manual of parasitological and bacteriological techniques. World Health Organization (WHO), Geneva
Ayers R, Westcot D (1985) Water quality for agriculture. Irrigation and drainage paper no. 29 (1). Food and Agricultural Organization (FAO), Rome
Ayers R, Westcot D (1994) Water quality for agriculture. Irrigation and drainage paper no 29 (1). Food and Agricultural Organization (FAO), Rome
Brouwer C, Prins K, Kay M, Heibloem M (1988) Irrigation water management: irrigation methods. Training manual no 5. Food and Agriculture Organization of the United Nations (FAO), Rome
Brouwer C, Prins K, Heibloem M (1989) Irrigation water management: irrigation scheduling: annex I: irrigation efficiencies. Food and Agriculture Organization of the United Nations (FAO), Rome
Dec N (2004) Environmental guidelines—use of effluent by irrigation. NSW Department of Environment and Conservation, Sydney
DOE (2001) Rules and regulations for environmental protection in Iran, 2nd edn. Department of the Environment, Tehran **(in persian)**
Fipps G (2003) Irrigation water quality standards and salinity management strategies. A&M Texas University Agri Life Extension B-1667, 4-03. http://soiltesting.tamu.edu/publications/B-1667.pdf. Accessed 16.06.12
Garcia X, Pargament D (2015) Reusing wastewater to cope with water scarcity: economic, social and environmental considerations for decision-making. Resour Conserv Recycl 101:154–166
Gautam SK, Maharana C, Sharma D, Singh AK, Tripathi JK, Singh SK (2015) Evaluation of groundwater quality in the Chotanagpur plateau region of the Subarnarekha river basin, Jharkhand State, India. Sustain Water Qual Ecol 6:57–74
Gupta RK, Abrol I (1990) Salt-affected soils: their reclamation and management for crop production. In: Lal R, Stewart BA (eds) Advances in soil science. Springer, New York, pp 223–288
http://www.kali-gmbh.com/uken/fertiliser/advisory_service/chloride_tolerance.html. Accessed 16.06.12
http://www.waterquality.montana.edu/energy/cbm/background/cheyenne.html. Accessed 16.06.12
IMOE I (2010) Environmental criteria of treated waste water and return flow reuse, Office of Deputy for Strategic supervision, No. 535 **(in Persian)**
IRI Vice Presidency for Planning and Supervision-467 (2009) Guidelines for laboratory analysis of soil and water samples. No. 467, pp 30–187 **(in Persian)**
ISO, EN (2002) 14688-1: 2002: Geotechnical investigation and testing—identification and classification of soil—part 1: identification and description. British Standards Institution, London
Jalili F, Mahalleh JK, Valizadegan E (2013) Effect of SAR and salinity on some physiological characteristics and yield of two cultivars of canola. Int J Agric 3(2):450–457
Kelly W (1957) Adsorbed sodium cation exchange capacity and percentage sodium sorption in alkali soils. Science 84:473–477
Kumar D (2008) Definitional glossary of agricultural terms, vol 1. IK International Pvt Ltd, New Delhi, p 285
Landon J (1991) Booker tropical soil manual: a handbook for soil survey and agricultural land evaluation in the tropics and subtropics. Longman Scientific and Technical, Essex, England, pp 130
Lazarova V, Bahri A (2004) Water reuse for irrigation: agriculture, landscapes, and turf grass. CRC Press, Boca Raton, pp 36–94
Lazarova V, Asano T, Bahri A, Anderson J (2013) Milestones in water reuse: the best success stories. IWA Publishing, London, p 6
Masi F (2009) Water reuse and resources recovery: the role of constructed wetlands in the Ecosan approach. Desalination 246(1–3):27–34
McFarland ML, Provin TL, Redmon LA, Boellstorff DE, McDonald AK, Stein LA, Wherley BG (2014) An index of salinity and boron tolerance of common native and introduced plant species in Texas. Texas A&M Agrilife Extension Service College Station, Texas
Molinos-Senante M, Hernández-Sancho F, Sala-Garrido R (2011) Cost–benefit analysis of water-reuse projects for environmental purposes: a case study for Spanish wastewater treatment plants. J Environ Manag 92(12):3091–3097
Murray A, Ray I (2010) Wastewater for agriculture: a reuse-oriented planning model and its application in peri-urban China. Water Res 44(5):1667–1679
Olsen SR, Sommers LE (1982) Phosphorus. In: Page AL, Miller RH, Keeney DR (eds) Methods of soil analysis. American Society of Agronomy, Madison, pp 403–430
Papadopoulos F, Parissopoulos G, Papadopoulos A, Zdragas A, Ntanos D, Prochaska C, Metaxa I (2009) Assessment of reclaimed municipal wastewater application on rice cultivation. Environ Manag 43(1):135–143
Pedrero F, Kalavrouziotis I, Alarcón JJ, Koukoulakis P, Asano T (2010) Use of treated municipal wastewater in irrigated agriculture—review of some practices in Spain and Greece. Agric Water Manag 97(9):1233–1241
Pescod M (1992) Wastewater treatment and use in agriculture-FAO irrigation and drainage paper 47. Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/docrep/T0551E/t0551e07.htm. Accessed 16.06.12
Pescod MB, Arar A (1985) Treatment and use of sewage effluent for irrigation: proceedings of the FAO regional seminar on the treatment and use of sewage effluent for irrigation held in Nicosia, Cyprus, 7–9 October, pp 30–31
Richards L (1954) Diagnosis and improvement of saline and alkali soils. USDA agriculture handbook, vol 60. United States Salinity Laboratory, Washington
Shahbazi M, Kiani A, Raeisi S (2011) Determination of salinity tolerance threshold in two rapeseed (*Brassica napus* L.) cultivars. Iran J Crop Sci 13(1):18–31

Soil First Consulting (unknown date) Irrigation water guidelines. earthworksturf.com. http://www.earthworksturf.com/pdf/soiltest/Irrigation_%20Water_Guidelines.pdf. Accessed 16.12.12

Spectrum Analytical Incorporated, USA (2013) Guide to interpreting irrigation water analysis. http://www.spectrumanalytic.com/support/library/pdf/guide_to_interpreting_irrigation_water_analysis.pdf. Accessed 16.12.12

Styczen M, Poulsen R, Falk A, Jørgensen G (2010) Management model for decision support when applying low quality water in irrigation. Agric Water Manag 98(3):472–481

Tanji K, Kielen N (2003) Agricultural drainage water management in arid and semi-arid areas, FAO irrigation and drainage paper 61, annex 1: crop salt tolerance data. United Nations Food and Agriculture Organization, Rome

Task Force on Water Quality Guidelines of the Canadian Council of Ministers of the Environment (1995) Canadian water quality guidelines. Canadian Council of Ministers of the Environment, Ottawa

United States Environmental Protection Agency (USEPA) (2004) Guidelines for water reuse. United States Agency for International Development, Washington

United States Environmental Protection Agency (USEPA) (2012) Guidelines for water reuse. United States Agency for International Development, Washington

USSL (United States Salinity Laboratory Staff) (1954) Diagnosis and improvement of saline and alkali soils. USDA handbook, vol 60. USSL, Washington

WHO (1989) Health guidelines for the use of wastewater in agriculture and aquaculture. Report of a scientific group, technical report series no. 778. World Health Organization, Geneva

Williams K, Ley T (1994) Tree fruit irrigation: a comprehensive manual of deciduous tree fruit irrigation needs. Good Fruit Grower Publishing (Washington State Fruit Commission), Yakima