Setting water quality criteria for agricultural water reuse purposes

K. Müller and P. Cornel

ABSTRACT

The use of reclaimed water for agricultural irrigation is practiced worldwide and will increase in the future. The definition of water quality limits is a useful instrument for the assessment of water quality regarding its suitability for irrigation purposes and the performance of wastewater treatment steps. This study elaborates water quality objectives for a water reuse project in a setting where national guidelines do not exist. Internationally established guidelines are therefore applied to the local context. Additional limits for turbidity, total suspended solids, biochemical and chemical oxygen demand, total phosphorus and potassium are suggested to meet the requirements of water reuse projects. Emphasis is put on water quality requirements prior to UV disinfection and nutrient requirements of cultivated crops. The presented values can be of assistance when monitoring reclaimed water quality. To facilitate the realization of water reuse projects, comprehensive and more detailed information, in particular on water quality requirements prior to disinfection steps, should be provided as well as regarding the protection of the irrigation infrastructure.

Key words | irrigation, reuse guidelines, standards, water quality, water reclamation, water reuse

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INTRODUCTION

The reuse of water for agricultural irrigation is common practice in many countries around the world (Raschid-Sally & Jayakody 2009). It is estimated that 1.5–6.6% of irrigated agricultural areas are irrigated with treated or untreated wastewater and that this percentage will increase in the future (Sato *et al.* 2013).

Monitoring the quality of irrigation water is necessary to protect human health, soil, plants and water bodies and to prevent the deterioration of irrigation infrastructure (Ayers & Westcot 1985). Furthermore, regular sampling and water analyses are required to collect routine operating data of wastewater treatment and water reclamation plants and to evaluate wastewater treatment processes (Tchobanoglous *et al.* 2004).

In many countries, water quality objectives are defined in national standards (Havelaar *et al.* 2001; Gurel *et al.* 2007; Paranychianakis *et al.* 2015). Where they do not (yet) exist, international guidelines of the WHO (1989, 2006) and the FAO (Ayers & Westcot 1985; Pescod 1992) or other well-established regulations (e.g. USEPA 2012; State of California 2015) are used to develop national standards (Blumenthal *et al.* 2000; Gurel *et al.* 2007). Most water reuse guidelines and related publications focus on public health issues whereas environmental protection (eutrophication, salinization, adverse effects of trace elements and trace organic compounds) plays a minor role in literature (Paranychianakis *et al.* 2015).

Among developing countries, roughly half do not have regulations regarding irrigation with treated wastewater (Raschid-Sally & Jayakody 2009). When realizing water reuse projects in countries without official rules, either water quality objectives need to be formulated by the

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implementing stakeholders (for instance a municipality or non-government organization) or existing guidelines can be used to assist in monitoring the water quality.

The FAO (Ayers & Westcot 1985) and WHO (1989) guidelines have been widely incorporated into national regulations and are considered suitable for developing countries (Crook 1991; Havelaar *et al.* 2001; Paranychianakis *et al.* 2015). The FAO guidelines give recommendations on physical and chemical water quality objectives to prevent harmful effects on soil, plants and irrigation equipment (Ayers & Westcot 1985). However, they do not specifically address the use of treated wastewater for agricultural irrigation. The presented water quality parameters differ from the range of parameters commonly used in wastewater treatment. A subsequent publication (Pescod 1992) is targeted towards the reclamation of treated wastewater for agricultural irrigation, but contains the same recommended limits as Ayers & Westcot (1985). For instance, whereas it is acknowledged that organics contained in the water may lead to the clogging of drip irrigation systems, no recommendation on acceptable maximum values is given for aggregate organic constituents (e.g. biochemical or chemical oxygen demand).

The WHO (2006) guidelines provide a comprehensive framework for monitoring microbial water quality in agricultural water reuse. However, they have not been used intensively in the development of national standards since their release (Paranychianakis *et al.* 2015). Two examples for the adoption of the WHO (2006) guidelines or the use of disability-adjusted life years (DALYs, cf. WHO 2006) for setting health based targets (HBTs) are available. These are the Ghanaian guidelines for agricultural irrigation (Amponsah *et al.* 2015) and the Australian Guidelines for Water Recycling (NRMMC *et al.* 2008).

Lack of legislation is a major obstacle for the implementation of water reuse projects (Angelakis *et al.* 1999; Miller 2006; Hochstrat *et al.* 2008). Consequently, development (or adoption) of comprehensive guidelines facilitate the realization of water reuse projects. This study chooses appropriate water quality objectives for a water reuse project in a setting where national regulations do not yet exist. Available international guidelines are applied to the local context. This paper addresses: (i) the parameters that should be modified or added considering the water quality requirements for agricultural irrigation; (ii) the suitability of the irrigation water for this specific case; (iii) the measures that have to be taken to comply with the desired water quality requirements; and (iv) the possible water reuse applications for the obtained water quality.

MATERIAL AND METHODS

The study consists of two parts. One part focuses on choosing and defining the parameters for monitoring the water quality for a sanitation and water reuse project. The parameters and water quality objectives were adopted from existing guidelines and reviewed literature. The other part of this study comprises sample collection, water quality analyses and the comparison of measured values with the chosen water quality objectives. Recommendations for the operation of the water reuse scheme are deduced. This work is part of a research project which is briefly described in the following section.

Sanitation and water reuse project

This study was conducted at a water reclamation facility in the city of Outapi in North Namibia. Together with local stakeholders, Outapi has been chosen as the location for a project on sanitation and water reuse (Deffner & Mazambani 2010; Deffner & Kluge 2013). This initiative is part of the interdisciplinary project 'CuveWaters'. Its overall objective is the development and implementation of an integrated water resources management for the Cuvelai-Etosha Basin in the north of Namibia (Kluge *et al.* 2008).

Project partners for the implementation in Outapi are the Institute for Social-Ecological Research (Frankfurt, Germany), Technische Universität (TU) Darmstadt (Darmstadt, Germany), Bilfinger Water Technologies (Hanau, Germany), the Outapi Town Council (Outapi, Namibia) and the Ministry of Agriculture, Water and Forestry (Windhoek, Namibia). The project is funded by the German Federal Ministry of Education and Research.

The implemented infrastructure includes shared and individual sanitation facilities, a vacuum sewer system (RoeVac, Bilfinger Water Technologies) for sewage conveyance, a wastewater treatment plant with sedimentation and anaerobic pre-treatment (upflow anaerobic sludge blanket

(UASB) reactors, Bilfinger Water Technologies), aerobic treatment and secondary clarifiers (rotating biological contactors (RBCs) and lamella clarifiers, System S&P, Dr. Scholz & Partner), a drum-type microscreen (15 μm mesh width, PASSAVANT® Micro Giant (MTSM) 1,000 × 1,000, PAN4-4711, Bilfinger Water Technologies), UV disinfection (low pressure UV lamps, LBX 50, WEDECO), a storage pond and surface drip lines (Figure 1). The reclaimed water is used for the production of raw-eaten vegetables for human consumption. The average flow is 30.34 (±11.7) m^3/d instead of 90 m^3/d (as planned). Hydraulic retention time in the storage pond is >100 d. About 800600 residents have access to the implemented sanitation facilities.

Definition of water quality parameters

Existing guidelines for irrigation water quality and water reclamation were reviewed. The project partners (TU Darmstadt and Outapi Town Council) discussed and decided on the guidelines to be suitable for application in this specific case. Additional parameters and modifications were suggested by TU Darmstadt based on information found in literature.

Sampling and analyses

The data presented here were collected between July 2013 and July 2015 by TU Darmstadt. The values represent data from the untreated wastewater, the effluent of the wastewater treatment plant and the storage pond (Table 1).

The pH, electrical conductivity (EC), temperature and turbidity were measured in grab samples during weekdays (pH and EC meter: Multi 1970i, pH electrode: Sentix 41-3, EC electrode: TetraCon 325, WTW; turbidity meter: 2100 Q IS Portable Turbidimeter, Hach Lange).

Total solids (TS) were measured weekly in grab samples (dry weight at 105 °C). To obtain total dissolved solids (TDS), the sample was filtered through glass microfiber filters (Whatman 934-AH) and dried at 105 °C.

Concentrations of total chemical oxygen demand (TCOD), total nitrogen (TN) and total phosphorus (TP) were measured in volume proportional mixed samples for 10 or 12 hours. Sampling was performed once per week, whereby weekdays were shifted to also include weekends. Hach Lange cuvette tests were used for analyses (LCK). TCOD, TN and TP were determined in homogenized samples (homogenizer: IKA Ultra-Turrax).

Escherichia coli was quantified using IDEXX Colilert-18 and Quanti-Tray/2000 (weekly, grab samples).

Sampling for helminth eggs (HEs) was carried out in the microscreen inlet and outlet (before UV disinfection), and in the irrigation water extracted from the storage pond. For the determination, wastewater samples were sieved. The material retained by the sieve (Retsch, 20 μm, 200 mm × 50 mm) was recovered in a centrifuge bottle and concentrated by centrifugation at 660 g and the addition of a sodium chloride/sucrose solution (relative density = 1.28). HEs were optically counted using a microscope (Axio Lab A1, Carl Zeiss) and a counting chamber (Sedgewick Rafter).

Biochemical oxygen demand (BOD), Cl, B, Na, K, Mg and Ca were determined in 10- or 12-hour mixed samples

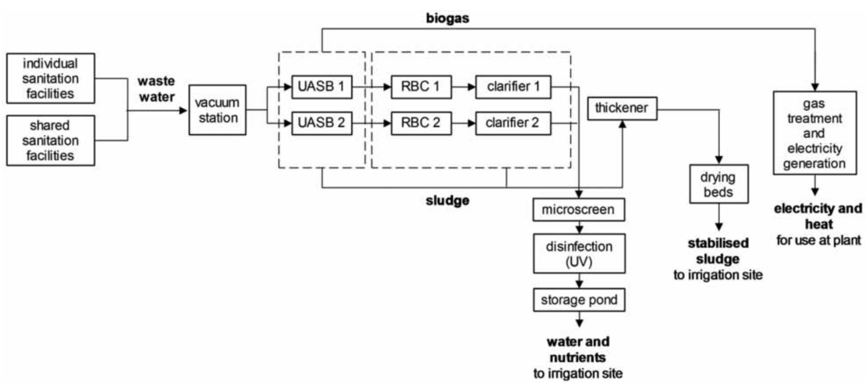

Figure 1 | Schematic drawing of the sanitation and water reuse project.

Table 1 | Effluent water quality of the water reuse plant (July 2013–July 2015), water quality objectives of the FAO and WHO guidelines (Ayers & Westcot 1985; WHO 2006) and suggested additional limits. FAO (1985) distinguishes three 'degrees of restriction on use' (1 = none, 2 = slight to moderate, 3 = severe)

		Monitoring data									Water quality objective			
		Untreated wastewater			Effluent			Storage pond			Degrees of restriction on use			
Parameter	Unit	Mean	sd	*n*	Mean	sd	*n*	Mean	sd	*n*	1	2	3	Source
Physical characteristics														
EC	μS/cm	612	180	372	527	132	344	596	100	75	<700	700–3,000	>3,000	FAO 1985
TDS	mg/L	–	–	–	375	46.7	4	455	133	5	<450	450–2,000	>2,000	FAO 1985
Turbidity	FNU	507	218	322	7.5	5.6	326	16.7	9.7	62	<21[a] < 10[b]	23–43[a]	>43[a]	this study
TS	mg/L	1,040	428	24	381	74.8	18	476	96.0	8	–	–	–	–
TSS	mg/L	–	–	–	9[c]	–	–	30[c]	–	–	<50[a] < 25[b]	50–100[a]	>100[a]	FAO 1985 this study
Chemical characteristics														
pH	–	7.8	0.3	347	6.8	0.5	344	8.0	1.3	73	'normal range': 6.5–8.4			FAO 1985
TCOD	mg/L	738	364	132	57.7	26.1	125	64.9	25.4	48	according to BOD/TCOD ratio			this study
TN	mg/L	57.5	25.8	131	33.5	17.2	127	32.6	13.1	48	<5	5–30	>30	FAO 1985
TP	mg/L	10.3	3.3	121	8.3	2.4	121	9.9	4.0	48	<3.5	3.5–13	>13	this study
K^+	mg/L	17.3	2.9	14	18.8	3.4	19	24.2	1.9	5	<6.5	6.5–28	>28	this study
Na^+	mg/L	58.7	21.7	14	53.2	15.5	19	64.6	4.5	5	<3[d]	3–9[d]	>9[d]	FAO 1985
Ca^{2+}	mg/L	10.4	3.9	12	17.8	4.5	17	7.8	3.2	5	–	–	–	–
Mg^{2+}	mg/L	3.6	0.8	12	4.4	1.5	17	5.6	2.5	6	–	–	–	–
SAR	–	8.0	–	–	5.9	–	–	8.6	–	–	>1,900[e]	1,900–500[e]	<500[e]	FAO 1985
B^-	mg/L	0.02	0.00	9	0.02	0.01	12	0.02	0.01	6	<0.7	0.7–3.0	>3.0	FAO 1985
Cl^-	mg/L	30.3	6.5	3	37.0	4.4	3	44.0	4.0	3	<4[d]	4–10[d]	>10[d]	FAO 1985
Biological characteristics														
BOD_5	mg/L	196	152	10	5.5	2.0	13	16.0	8.5	6		15		this study
HE	1/L	–	–	–	308	359	5	0.0	0.0	3	case specific			WHO (2006)
E. coli	MPN/	2.3×10^7	2.2×10^7	65	2.2×10^3	8.5×10^3	57	4.4×10^1	1.1×10^2	46	case specific			WHO (2006)

(*continued*)

Table 1 | continued

		Monitoring data									Water quality objective			
		Untreated wastewater			Effluent			Storage pond			Degrees of restriction on use			
Parameter	**Unit**	**Mean**	**sd**	***n***	**Mean**	**sd**	***n***	**Mean**	**sd**	***n***	**1**	**2**	**3**	**Source**
E. coli[f]	100 mL	1.7×10^{7} [f]	–	–	1.3×10^{1} [f]	–	–	9.6×10^{0} [f]	–	–	–	–	–	–
TC	MPN/	6.3×10^{7}	6.2×10^{7}	66	6.9×10^{3}	2.4×10^{4}	59	4.6×10^{3}	1.0×10^{4}	47	–	–	–	–
TC[f]	100 mL	5.3×10^{7} [f]	–	–	2.0×10^{2} [f]	–	–	2.0×10^{2} [f]	–	–	–	–	–	–

n = number of measurements, sd = standard deviation, EC = electrical conductivity, TDS = total dissolved solids, TS = total solids, TSS = total suspended solids, TCOD = total COD, TN = total nitrogen, TP = total phosphorus, SAR = sodium adsorption ratio, BOD_5 = 5-day biochemical oxygen demand, HE = helminth eggs, TC = total coliforms, MPN = most probable number.
[a]Prior to drip irrigation.
[b]Prior to UV disinfection.
[c]Calculated value (TSS = TS–TDS).
[d]Surface irrigation.
[e]EC limits are given for SAR = 6–12, for a higher or lower SAR, EC limits are different.
[f]Median.

by an external laboratory in Windhoek (Namibia Water Corporation, NamWater).

RESULTS AND DISCUSSION

Definition of water quality parameters

Guidelines for irrigation water quality or water reuse do not exist in Namibia. During planning the question arose which water quality objectives should apply to the implemented water reuse project. The use of guidelines from neighboring countries would be an option because it can be assumed that they fit to the (similar) local conditions. In the region, only South Africa has guidelines for irrigation water quality. However, they date back to 1978 and require drinking water quality for the irrigation of 'vegetables and crops consumed raw by men' (DNHPD 1978). These guidelines are assessed as 'largely inappropriate for low- to middle-income South African settlements' because they pursue a zero-risk approach without consideration of the available financial capacities and conceptual adaption to the local conditions (Ilemobade *et al.* 2009).

Usually, no detailed background information is given in national guidelines on how the suggested parameters and recommended limits were chosen. Paranychianakis *et al.* (2015) conclude that 'water reuse criteria have been set (semi-) empirically, instead than based on the interpretation of the available scientific knowledge'. Since detailed information is not available, an assessment of whether guidelines for other regions fit to the local conditions in Namibia is not possible. Consequently, at the moment there is no rationale for using national guidelines from another country for implementation in Namibia. Thus, in this case, the quality of irrigation water was assessed using the internationally accepted FAO (1985) and WHO (2006) guidelines.

As it turned out, additional parameters and modification of existing ones were needed to carry out the water quality monitoring required for this water reuse project. The individual aspects are described in more detail here. An overview on recommended limits from the FAO and WHO guidelines and additional values suggested in this study is given in Table 1. The following section outlines the definition of additional water quality limits needed for water quality monitoring.

Particles might cause clogging of irrigation equipment (e.g. drip lines), influence the efficiency of disinfection and lead to aesthetic impairment of the water (Ayers & Westcot 1985). The amount of particles in water can be expressed by turbidity or by the total suspended solids (TSS) content (Tchobanoglous *et al.* 2004). Ayers & Westcot (1985) give limits of <50 mg/L (= no restriction on use) and >100 mg/L (= severe restrictions on use) for TSS when irrigating with drip lines. In the Outapi case, the determination of TSS was not possible due to the rapid clogging of glass fiber filters (no weighable filter cakes could be obtained). TSS determination was only possible via the determination of TS and TDS in the same sample. Since this is very time-consuming, turbidity measurements were used as a surrogate.

Turbidity measurements are much easier to perform, and results are immediately available. Although it has to be kept in mind that the relationship between TSS and turbidity is plant-specific, it is approximately TSS (mg/L) = turbidity (NTU) × 2.35 for settled secondary effluents (Tchobanoglous *et al.* 2004). Thus, corresponding turbidity limits are <21 (= no restriction on use) and >43 NTU (= severe restrictions on use) to protect drip lines.

Disinfection of reclaimed water may be required for irrigation. Bulk parameters such as turbidity and TSS are often used to assess water quality prior to disinfection. Mamane (2008) concludes from reviewed literature that turbidity levels up to roughly 10 NTU can be neglected for the inactivation of seeded viruses, bacteria and parasites via UV disinfection. For this case, a turbidity limit <10 NTU is set as required water quality objective prior to UV disinfection.

For TSS, some studies show a relationship between TSS content and microorganisms after UV disinfection (Severin 1980; White *et al.* 1986; Darby *et al.* 1993; Whitby & Palmateer 1993; Carnimeo *et al.* 1994), and some show only minor or even no effects (Petrasek *et al.* 1980; Qualls 1983; Cantwell & Hofmann 2011). Suggested TSS concentrations prior to UV disinfection are <30 mg/L (Severin 1980; Carnimeo *et al.* 1994) or <20 mg/L (White *et al.* 1986; Darby *et al.* 1993). Although TSS measurements could not be used for water quality monitoring in this case (the determination of TSS was not possible due to rapid clogging of the glass fiber filters), a water quality objective of 25 mg/L is suggested whenever regular determination of TSS is possible.

On the whole, common solids-related parameters such as TSS and turbidity do not reliably predict UV disinfection performance (Madge & Jensen 2006). Instead, the size of the particles is crucial. Particles <10 μm do not influence UV disinfection (Parker & Darby 1995; Emerick *et al.* 1999). If and to what extent UV radiation can penetrate larger particles depends on the respective characteristics of the particles, e.g. their porosity. The critical size is therefore plant-specific (Parker & Darby 1995; Emerick *et al.* 1999). Particles >10 μm should be removed from the water when provision is made for UV disinfection. Ideally, the plant-specific maximum admissible particle size is determined and monitoring of particle size (via serial filtration, electronic particle size counting or microscopic observation (Tchobanoglous *et al.* 2004) is performed regularly or else the corresponding turbidity or TSS content should be used for water quality monitoring.

Degradable organic matter may cause anaerobic conditions during storage and trigger the clogging of irrigation equipment, either directly or indirectly, by stimulating the growth of microorganisms (Ayers & Westcot 1985). Therefore, organic matter contained in irrigation water should be stabilized to a large extent to inhibit further biodegradation. On the other hand, the input of organic matter has a positive effect on soil properties (Ayers & Westcot 1985). However, to protect the implemented infrastructure, control of degradable organic matter content is required.

In the FAO guidelines, no recommendation is given for the BOD of irrigation water. Several other guidelines include limits for 5-day BOD. The United States Environmental Protection Agency, for example, recommends a maximum BOD_5 of 10 mg/L for food crops and 30 mg/L for non-food and processed food crops (USEPA 2012). AQUAREC (2006) recommend a BOD_5 of 10–20 mg/L for irrigation purposes. In European guidelines, recommended limits for BOD range from 10 to 20 mg/L for irrigation of vegetables eaten uncooked (Paranychianakis *et al.* 2015). A BOD_5 of 15 mg/L could be set as water quality objective for irrigation water quality.

The TCOD is a widely used alternative parameter for BOD when assessing the efficiency of wastewater treatment steps because results are obtained faster and values are more reproducible (Tchobanoglous *et al.* 2004). This parameter is not included in the FAO guidelines. If the

BOD_5/TCOD ratio is stable, TCOD water quality objectives can be derived and used to assess the degree of stabilization of the water.

In some crops, excessive nitrogen might cause overstimulation of growth, delayed maturity or poor quality (Ayers & Westcot 1985). Excess P and K may accumulate in the soil or leach out (Pescod 1992). Thus, monitoring N, P and K loads is necessary for optimal nutrient management when reclaiming water for irrigation.

The FAO nitrogen limit of 5–30 mg/L corresponds to the range of N requirements for typical crops (Table 2, Doorenbos 1979). For adequate fertigation of, for example, tomatoes, total N should not exceed 25 mg/L. This limit is based on an N requirement of 125 kg N/ha per growing period and an irrigation demand of 5,000 m³/ha per growing period (125 kg N/ha ÷ 5,000 m³/ha = 25 mg/L) for two preconditions: irrigation only with reclaimed water and no leaching via excess irrigation or rainfall (Table 2).

When reclaiming water for agricultural irrigation, TN concentrations will usually exceed the FAO limits, if no N removal step is implemented. Even for relatively low per capita N loads (e.g. 8 g/(capita × d) (DWA 2008)) and high water consumption (e.g. 200 L/(capita × d)), total N concentration in the irrigation water will be higher than N needs of most crops (8 g/(capita × d) ÷ 200 L/(capita × d) = 40 mg/L, N removal via sedimentation or incorporation into biomass is neglected). To avoid negative impacts from excessive N loads, N intensive crops should be chosen for irrigation with reclaimed water. High N concentrations could also be handled by introducing a denitrification step. If all nutrients should be used for irrigation, the reclaimed water might need blending with other water sources.

Excess P and K may accumulate in the soil or leach out (Pescod 1992). When conventional water sources (surface water, groundwater (FAO 2015)) are used for irrigation, P and K concentrations in irrigation water are not expected to exceed crop requirements (UNEP 2007, 2008). However, when applying treated wastewater, excessive P and K loads are expected. For a typical P load ranging from 1 to 3 g/(capita × d) (DWA 2008) and a water use between 50 and 200 L/(capita × d), P concentrations are within a range of 5–60 mg/L and exceed most of the limits listed in Table 2 (P incorporation in biomass is neglected, no P removal during wastewater treatment). Potassium concentrations in treated wastewater might range from 15 to 120 mg/L and will also exceed requirements for many crops (3–6 g K/(capita × d) and a water use between 50 and 200 L/(capita × d) (DWA 2008)).

Table 2 | Irrigation and nutrient requirement for various crops (Doorenbos 1979) and water quality objectives for total N, P and K in irrigation water (when irrigated only with reclaimed water, no leaching, e.g. via excess irrigation or rainfall)

	Requirement per growing period				Required concentration		
Crop	Water m³/ha	Total N kg/ha	Total P kg/ha	Total K kg/ha	Total N mg/L	Total P mg/L	Total K mg/L
Groundnut	6,000	15.0	27.5	32.5	2.5	4.6	5.4
Bean	4,000	30.0	50.0	85.0	7.5	12.5	21.3
Sunflower	8,000	75.0	32.5	92.5	9.4	4.1	11.6
Safflower	9,000	85.0	22.5	32.5	9.4	2.5	3.6
Banana	17,000	300	52.5	260	17.6	3.1	15.3
Pepper	7,500	135	37.5	75.0	18.0	5.0	10.0
Water melon	5,000	90.0	42.5	57.5	18.0	8.5	11.5
Wheat	5,500	125	40.0	37.5	22.7	7.3	6.8
Maize	6,500	150	65.0	80.0	23.1	10.0	12.3
Sugarbeet	6,500	150	60.0	130	23.1	9.2	20.0
Tomato	5,000	125	87.5	201	25.0	17.5	40.1
Cabbage	4,400	125	57.5	115	28.4	13.1	26.1
Olive	7,000	225	62.5	185	32.1	8.9	26.4

In this study, mainly maize, peppers and tomatoes were cultivated. The adapted water quality objectives are 18–25 mg/L for TN, 5–18 mg/L for TP and 10–40 mg/L for K. For further classification, the limits for TP and K can be set at <3.5 and <6.5 mg/L (no restriction on use), 3.5–13 and 6.5–28 mg/L (slight to moderate restriction on use) and >13 and >28 mg/L (severe restriction on use, Table 1).

Water quality monitoring

EC and TDS

The salinity of irrigation water needs to be monitored in order to prevent soil salinization and reduced crop yields (Ayers & Westcot 1985). Since the determination of TDS is time-consuming, a surrogate parameter such as the EC is often used to characterize irrigation water quality (Eaton & Franson 2005).

In this study, the EC of the water increased from 52 μS/cm in tap water to 527 μS/cm in the effluent (due to domestic water use) up to 596 μS/cm in the storage pond (due to evaporation, Table 1). Similarly, TDS concentrations increased from 40.2 mg/L in tap water to 375 mg/L in the effluent and 455 mg/L in the storage pond. The mean EC value is lower than the FAO limit of 700 μS/cm. The mean TDS concentration slightly exceeds the FAO limit of 450 mg/L (Ayers & Westcot 1985). While there is no immediate limitation in crop choice, dissolved salts still need to be monitored and leached to prevent accumulation in the soil. In this case, salt management was carried out via regular drainage and leaching of the fields.

The example shows that even though the amount of TDS in tap water was very low, the domestic water use increased concentrations and loads (depending on the specific water consumption) to levels only slightly under the FAO limits for EC and TDS. Therefore, in cases with higher TDS levels in tap water, EC and TDS monitoring is even more important. Salts in irrigation water and soil have to be controlled to allow sustainable irrigation.

Turbidity and TSS

The mean value for turbidity was 7.5 FNU in the effluent and 16.7 FNU in the storage pond. Both values meet the suggested water quality objective for drip irrigation (21 NTU). However, it was exceeded in 3% of the effluent samples and in 24% of the storage pond samples.

Turbidity varied: from July 2013 until May 2014, mean turbidity was 8.2 FNU in the effluent of the lamella clarifier and 4.4 FNU in the effluent of the microscreen (Figure 2). Then, the mean turbidity increased to 19.4 FNU in the effluent of the lamella clarifier and to 12.1 FNU after passing through the microscreen (June 2014–January 2015). Retrofitting of the microscreen in February 2015 led to a lower mean turbidity value of 6.8 FNU in the effluent (March 2015–July 2015) despite higher turbidity levels in the

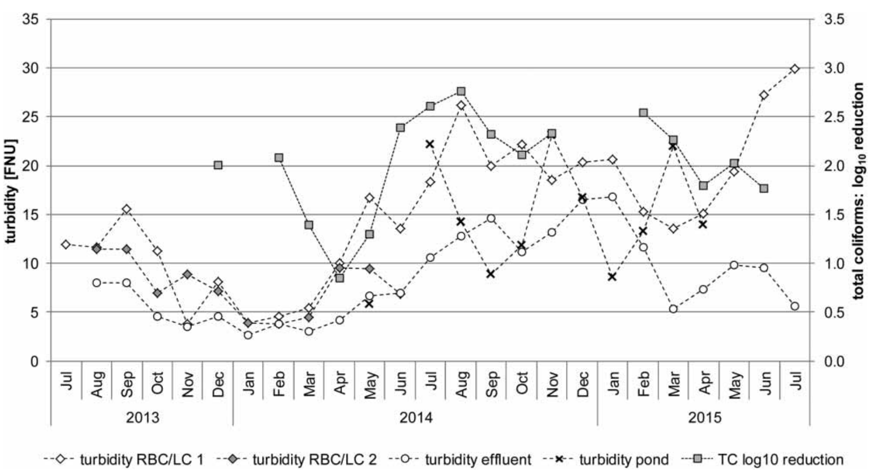

Figure 2 | Turbidity in the effluent of the rotating biological contactors and lamella clarifiers (RBC/LC 1 and 2), after passing the microscreen (effluent) and in the storage pond and log_{10} reduction of TC.

effluent of the RBC, respectively, lamella clarifier (17.1 FNU on average, up to 27.3 FNU in June 2015).

Regarding water quality requirements prior to UV disinfection, there is some room for improvement. Seventy-two per cent of all samples met the suggested limit of 10 NTU. Since retrofitting of the microscreen in February 2015, the turbidity prior to UV disinfection improved slightly: 88% of all samples were below 10 FNU.

There are several scale units and methods with which turbidity can be measured. Here, turbidity measurements are given in FNU (formazine nephelometric unit (ISO 7027 1999)), whereas EPA method 180.1 gives turbidity values in NTU (nephelometric turbidity unit). Both methods measure scattered light in a 90° angle, but at different wavelengths (ISO 7027 1999; Eaton & Franson 2005). Sadar (1999) found out that both methods deliver almost the same results for low turbidity samples, i.e. in a simplified way FNU~NTU. For a rough assessment, one can therefore use values stated either in FNU or NTU.

UV doses were very high (>100 mJ/m²) since flows were below the design value and UV disinfection was designed for higher (peak) flows. Still, the mean $\log_{10}$ reduction was only 2.2 for total coliforms (TC) and 0.9 for *E. coli*. Here, mean total coliform concentrations were 6,900 MPN/100 mL in the effluent (median = 200 MPN/100 mL, Table 1). A dose of 100 mJ/cm² should be sufficient to obtain mean total coliform concentrations of less than 2.2 MPN/100 mL (NWRI 2012).

The reason for the relatively low $\log_{10}$ reduction of TC and *E. coli* despite the high UV dose could have been incomplete removal of larger particles in the lamella clarifiers and the microscreen. The content of solids >20 μm was 12 mg/L in the influent of the microscreen and 4.1 g/L in the effluent of the microscreen ($n = 3$). Thus, the reduction was roughly 66% (and should be higher for TSS). This corresponds to the average turbidity reduction (57%) and is within the range of 10–80% TSS removal (55% in average) as reported in Tchobanoglous *et al.* (2004). However, by using a microscreen with a mesh size of 15 μm it should be possible to remove all particles >20 μm.

The results show that optimal $\log_{10}$ reduction rates of *E. coli* and TC have not been achieved. Clogging of the microscreen occurred, and the required additional maintenance probably caused leaky rubber foam strips of the screen baskets as well as incomplete removal of solids and HEs (see subsequent section). In spite of retrofitting the microscreen and additional training of the operating staff, the required maintenance of the lamella clarifier and microscreen exceeded the available capacities.

In existing guidelines, water quality requirements prior to UV disinfection are high. For instance, when irrigating food crops, the USEPA (2012) suggests a 24-hour average turbidity of ≤2 FNU, never to exceed 5 NTU at any time, and an average TSS of <5 mg/L. The achievable removal rates for microorganisms are lower for inferior water quality (i.e. higher particle content). In case UV disinfection is applied nevertheless, water quality objectives for unrestricted irrigation, as suggested in many standards, cannot be met. However, the WHO (2006) guidelines allow a lower degree of wastewater treatment, combined with other measures, to achieve the required $\log_{10}$ pathogen reduction for a certain HBT. Thus, even though the achieved $\log_{10}$ removal rates for *E. coli* and TC were rather low in this case, the achieved reduction contributed to meeting the required HBT (see subsequent section). All controls should achieve the required reduction (WHO 2015). If a limit is exceeded, previously defined remedial actions have to be undertaken (WHO 2015).

From a conceptual point of view, the installation of a UV disinfection system in the effluent of the storage pond should be considered. Emerick *et al.* (1999) investigated the number of bacteria-associated particles in different wastewater samples. They found out that between 4 and 31% of particles in samples from aerobic treatment steps (activated sludge process, trickling filter) contained embedded coliform bacteria. In aerated or facultative lagoons, this percentage was below 1%. The number of residual coliform bacteria surviving high UV doses was low despite high TSS concentrations. Another study found that polishing pond effluents can achieve a high $\log_{10}$ reduction for *E. coli* (2.8–3.4) and TC (2.6–3.1) despite a high TSS content (87–102 mg/L) and low absorbance (0.67–0.79) caused by algae. This was due to the high percentage (94%) of particles <10 μm in the effluent (Alves *et al.* 2012). Thus, if it is not possible or desired to provide the required water quality prior to UV disinfection, the disinfection system could be installed in the effluent of the storage pond. Like this, a high $\log_{10}$ reduction for *E. coli* and TC could be achieved despite high TSS concentrations and absorbance.

pH and alkalinity

Water with a low pH can be corrosive while water with a high pH might be scale-forming (Tchobanoglous *et al.* 2004). The FAO guidelines generally recommend a 'normal' range of pH 6.5–8.4 (Table 1). For drip irrigation systems, a range of pH 7.0–8.0 is recommended. For sprinkler irrigation, the pH should not be below 6.5 (Ayers & Westcot 1985).

In the presented case, the mean pH in the untreated wastewater was 7.8 (Table 1). After anaerobic pretreatment, the mean pH was 6.9 (±0.4), which is within the optimal range for methane-producing microorganisms (pH 6.6–7.4 (Chernicharo 2007). Alkalinity of the untreated wastewater was 10.3 (±2.1) mmol/L and 9.8 (±3.8) mmol/L after anaerobic pretreatment.

After the anaerobic pretreatment, the wastewater is treated aerobically. Rotating biological contactors were designed for COD removal. After implementation, flows have been much lower than planned (30.4 m^3/d instead of 90 m^3/d). Since nutrients should remain in the water for fertigation, no denitrification was implemented. This caused a further decrease of the pH during (unintended) nitrification (mean pH = 6.8, Table 1) although only one out of two RBCs was operated, and, most notably, a decrease of alkalinity (effluent: 1.5 (±1.5) mmol/L). As a consequence, variation of the pH after aerobic treatment was relatively high (±0.6).

In the presented case, water is applied via surface drip irrigation. Thus, the pH should be between 7.0 and 8.0 (Ayers & Westcot 1985). In most cases, the effluent did not meet the required pH for drip irrigation (65% of the measured values are below pH 7.0, no exceedance of pH 8.0). Overall, the combination of anaerobic pretreatment and nitrification during aerobic treatment led to low effluent pH values with a high variation. This should be considered whenever reclaiming waters with low alkalinity.

In the storage pond, the pH increased since algae consumed CO_2 and HCO_3^- during photosynthesis. The average pH was 8.0, but varied: 30% of the measured values fell below pH 7.0 and 55% exceeded pH 8.0. Since its start-up in April 2014 (Figure 3), the pH increased continuously in the storage pond. Alkalinity remained very low (1.6 (±0.4) mmol/L). Thus, the water was not expected to cause scaling despite the high pH.

Liming would be an easily implementable solution for pH control in order to prevent corrosion. Implementation of a denitrification step would also lead to a higher pH and lower standard deviation. Because the pond water was

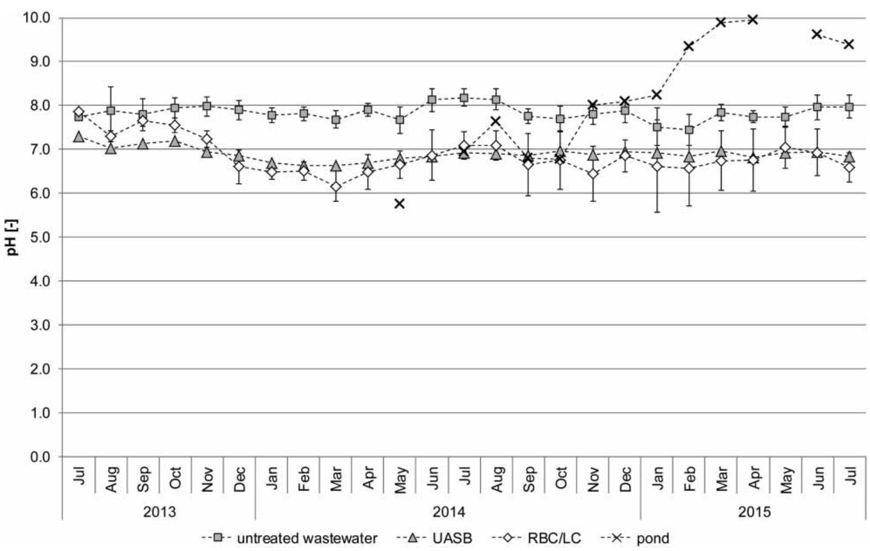

Figure 3 | pH in the untreated wastewater, after sedimentation and anaerobic pretreatment (UASB), after aerobic treatment and separation of solids via lamella clarifiers (RBC/LC) and in the storage pond (bars represent standard deviation of the mean).

less aggressive than the effluent of the wastewater treatment plant, it should be more suitable for irrigation.

COD and BOD

The BOD_5 was reduced from 196 mg/L in the untreated wastewater to 5.5 mg/L in the effluent (Table 1). Thus, the effluent was stabilized to a large degree. In the storage pond, the BOD increased to 16.0 mg/L because organic matter was added by algae growth and animals.

Total COD was 57.7 mg/L in the effluent and 64.9 mg/L in the storage pond. Consequently, the BOD_5/TCOD ratio was 0.1 in the effluent (5.5 mg/L ÷ 57.7 mg/L = 0.1) and 0.25 in the storage pond (16.0 mg/L ÷ 64.9 mg/L = 0.25). Thus, assuming a stable ratio and a BOD_5 limit of 15 mg/L, the adapted TCOD limit is 150 mg/L for the effluent (15 mg/L ÷ 0.1 = 150 mg/L) and 60 mg/L for the storage pond (15 mg/L ÷ 0.25 = 60 mg/L). None of the effluent's total COD concentrations exceeded 150 mg/L. However, in the storage pond, 53% of the samples showed values >60 mg/L. To prevent the clogging of drip lines, disc filters were installed in the irrigation system. Regarding the TCOD to BOD_5 ratio, the effluent of the wastewater treatment plant is more suitable for drip irrigation than the water extracted from the storage pond.

Nitrogen, phosphorus and potassium

The mean total N content of the effluent water was 33.5 mg/L. Almost the same mean concentration was measured in the storage pond (32.6 mg/L). Thus, the concentrations slightly exceeded the recommended FAO limit of 30 mg/L and also exceeded the requirements of most crops (Table 2).

The mean total P was 8.4 mg/L in the effluent and 9.9 mg/L in the storage pond. For most crops compiled in Table 2, the P loads applied via the irrigation water exceeded the requirements.

The same applied to potassium with mean concentrations of 18.8 mg/L in the effluent and 24.2 mg/L in the storage pond. While this was not enough to supply sufficient amounts to tomatoes, most crops require less K (Table 2).

In this case, mainly maize, peppers and tomatoes were cultivated. Compared to the adapted water quality objectives for these crops, the TP and K concentrations measured in this study met the requirements of cultivated crops. TN concentrations were lower than expected, but still slightly exceeded crop requirements. Irrigation management should consider alternate irrigation with tap water and reclaimed water to prevent adverse effects of nitrogen in plants.

Sodium, calcium and magnesium

Excessive Na^+ can cause dispersion of fine soil particles and clogging. This might be the case when irrigating with low conductivity water that leaches Mg^{2+} and Ca^{2+} out of the soil, or when Na^+ concentrations are very high compared to Mg^{2+} and Ca^{2+}. This can be assessed with the sodium adsorption ratio (SAR) and the EC ($SAR = c_{Na+} \div \sqrt{(c_{Ca^{2+}} + c_{Mg^{2+}}) \div 2}$, concentrations in meq/L) (Ayers & Westcot 1985). For water with high carbonate and bicarbonate contents, the SAR should be adjusted (Ayers & Westcot 1985).

The SAR was 5.9 in the effluent and 8.6 in the storage pond. For SAR values ranging between 6 and 12, no negative effects are expected for EC >1,900 μS/cm. For EC <500 μS/cm, severe infiltration problems will occur (Ayers & Westcot 1985). The EC of the irrigation water was between 527 μS/cm (effluent) and 596 μS/cm (storage pond). Thus, moderate to severe infiltration problems could be expected. Soil properties need to be monitored.

If infiltration rates are low, remedial actions are only required if the crop water demand or leaching requirements cannot be met (Ayers & Westcot 1985). There are chemical and physical remedial measures such as adding of gypsum to the soil, blending of the reclaimed water with other water sources or tillage that may be applied (Ayers & Westcot 1985).

Boron, manganese and heavy metals

High boron concentrations are toxic to plants (Ayers & Westcot 1985). As household detergents might contain boron, B concentrations could be an issue when irrigating with reclaimed water (Pescod 1992). Manganese can cause clogging and be toxic to plants while heavy metals can accumulate in soil and plants (Tchobanoglous *et al.* 2004). Those parameters were monitored in the irrigation water in Outapi, however they never reached FAO limits.

E. coli

E. coli is the indicator organism for pathogens suggested by WHO (2006). Depending on the irrigation method and the kind of crops, WHO (2006) recommends an overall $\log_{10}$ reduction between 2 and 7 units for *E. coli* in order to achieve a HBT of $\leq 10^{-6}$ DALYs per person per year (cf. WHO 2006). For the unrestricted irrigation of crops with above-ground harvested parts, the recommended reduction is 6 $\log_{10}$ units (WHO 2006).

The mean $\log_{10}$ reduction for *E. coli* was 3.1 during wastewater treatment (prior to UV disinfection) and 0.9 after UV disinfection. Die-off in the storage pond was about 1.7 $\log_{10}$ units. Local drip irrigation of low-growing crops further reduced pathogens by assumed 2.0 $\log_{10}$ units (WHO 2006). This led to an overall $\log_{10}$ reduction of 7.7 units when all barriers (anaerobic + aerobic wastewater treatment, UV disinfection, storage pond and drip irrigation) were working properly. Other barriers might have existed and provided additional reduction of pathogens (e.g. produce washing at home, die-off during storage), but could not be controlled under the local conditions and were therefore not considered.

An average reduction of 6 $\log_{10}$ units could still be achieved, when only three barriers were operating (e.g. $\log_{10}$ reduction for wastewater treatment + die-off in storage pond + drip irrigation $= 3.1 + 1.7 + 2.0 = 6.8$); thus UV disinfection would not have been necessary. In practice, however, these barriers were often bypassed. Farmers might have irrigated vegetable crops with hoses or extracted irrigation water from the effluent of the wastewater treatment plant or the storage pond for soil preparation. UV disinfection occasionally experienced operational problems. Water might have been pumped directly from the effluent to high level tanks without retention in the storage pond.

During normal operation, the required water quality was exceeded. The question arose as to whether the 7.7 $\log_{10}$ reduction was reasonable since every barrier consumed resources in one way or another. In theory, the circumvention of barriers could be avoided by improved infrastructure management. However, since operational malfunctions (human and technical) cannot be avoided and in order to achieve the desired HBT for sufficient public health protection, all barriers were necessary to achieve an *E. coli* reduction of 6 $\log_{10}$ units at any time.

HEs and larvae

WHO (2006) recommends a maximum of one HE per liter (and 0.1 HE/L when children under 15 years are exposed). For localized irrigation of high-growing crops, no water quality objective is necessary. The guidelines refer to the human intestinal nematodes *Ascaris lumbricoides* (human roundworm), *Trichuris trichiura* (human whipworm), *Ancylostoma duodenale* and *Necator americanus* (human hookworms) (Mara & Kramer 2008). The final hosts of *Hymenolepsis nana* are humans and mice (WHO 2004). *Hymenolepsis nana* is not included in the relevant helminths for the WHO (2006) water quality objectives, but can also infect humans (WHO 2004).

Three hundred and eight HE/L (including hookworm larvae) were counted in the effluent of the wastewater treatment plant. Hookworm eggs and hookworm larvae (presumably *Necator americanus*) constituted 99% of counts. Roundworm species (0.3 HE/L), *Taenia* sp. (0.7 HE/L, presumably *Taenia saginata*) and *Hymenolepsis nana* (0.9 HE/L) were less frequent. *Trichuris trichiura* was not found at all. The microscreen reduced HEs only by an average of 33% – probably due to the reasons discussed in the previous section – and thus failed to provide the required water quality.

The standard deviation was high (±359), whereas mean concentrations, collected from July 2014 to October 2014 in effluent samples, ranged from 127 to 773 HE/L, the mean concentration in samples collected between March 2015 and April 2015 ranged from 0.4 to 5.8 HE/L. It is unknown whether this was due, for example, to changed sedimentation patterns in the plant or due to lower concentrations in the untreated wastewater. Since analyses for HEs are very time-consuming, they were only conducted in the influent and effluent of the microscreen.

Because HEs could not be retained sufficiently (the recommended limit of ≤1 HE/L (WHO 2006) was exceeded), direct use of the effluent of the wastewater treatment plant was only possible for localized irrigation of high-growing crops. As *Taenia saginata* requires cows or pigs as intermediate host, irrigation of, for example, fodder crops or pasture, is only an alternative if there is a gap of at least 14 days between irrigation and use as fodder (WHO 2004). However, this procedure is seen critically since *Taenia* eggs can survive up to six months on grass and soil (WHO 2004).

HEs were completely retained in the storage pond. The pond is therefore the most important barrier for the retention of pathogens. Irrigation water should always be extracted from the pond.

Storage and water quality

As outlined in the previous sections, storage influenced the water quality. TCOD, BOD_5, EC, TDS, TSS, turbidity and SAR increased during storage. The increase of TSS, TCOD, BOD_5 and turbidity could be remedied by using common automatic backwash disc filters. pH also increased, but in contrast to the previously mentioned parameters, in this project this was beneficial for the water quality as the stored water was less aggressive than the effluent of the wastewater treatment plant.

In addition, the storage pond is important for protection of public health. It equalized the variation in *E. coli* and total coliform concentrations which led to a more uniform water quality. Die-off during storage further reduced *E. coli* and total coliform concentrations. Most notably, the pond was indispensable for retention of HEs.

Altogether, the benefits by HE retention, lower *E. coli* and total coliform concentrations and the higher pH outweighed the disadvantages caused by increasing TCOD, BOD_5, EC, TDS, TSS, turbidity and SAR. Hence, it is recommended to extract the irrigation water exclusively from the storage pond.

CONCLUSIONS

In this study, the FAO (1985) and WHO (2006) guidelines were used for monitoring irrigation water quality. It was discussed which parameters should be modified or added considering the water quality requirements for agricultural irrigation and considering the local conditions. Like this, water quality limits were developed that are tailored to the site-specific needs. Emphasis was put on water quality requirements prior to UV disinfection and drip irrigation systems and the nutrient requirements of cultivated crops. In order to meet the requirements of water reuse projects, additional water quality objectives for turbidity, BOD_5, TCOD, TP, and K were suggested. Depending on the water reuse concept and disinfection step, the objectives for TN and TSS may need modification.

The WHO (2006) guidelines provide a comprehensive approach for public health protection in water reuse projects. In this case, to achieve the required *E. coli* log_{10} reduction at any time, an additional barrier was needed. Thus, during normal operation the required water quality was exceeded. However, this was necessary since operational malfunctions could not be avoided. This finding conflicts with the objective to provide the required water quality efficiently. Nevertheless, public health protection is a priority and needs to be guaranteed. Redundancy assures the reliability of *E. coli* reduction.

Possible water reuse purposes are primarily determined by whether successful removal of HEs is achievable or not. HEs could not be removed to the required degree during wastewater treatment, but were completely retained in the storage pond. Thus, the HE concentrations are decisive and, for irrigation of crops eaten raw, the water should only be extracted from the storage pond. If irrigation water contains HEs and no storage is possible, or the pond is frequently bypassed, the water should only be used for drip irrigation of high-growing crops. Irrigation of fodder crops and pasture is an option for effluent water without prevalence of *Taenia* spp.

Anaerobic pretreatment of domestic sewage consumes alkalinity and leads to an effluent pH between 6.6 and 7.4 (Chernicharo 2007). Alkalinity is further reduced during nitrification. If the alkalinity of untreated wastewater is low, the pH can drop significantly and show a high variation. A low pH may be harmful to irrigation equipment. Considering expected excess N and a low pH, a denitrification step should be included when planning treatment plants for the reclamation of nitrogen-rich water with a low alkalinity. If N should remain in the water, liming or blending with other water sources could be used for pH adjustment. The effect of anaerobic pre-treatment on pH and alkalinity needs to be considered.

Initially, the storage pond was included in the water reuse project to compensate the gap between irrigation water supply and demand. However, it turned out to be a necessity to achieve the required water quality. Public health aspects and lower corrosiveness of the water determine that irrigation water is only extracted from the storage pond. It is therefore recommended to consider storage facilities as an additional water treatment step that contributes to the reliability of the water reclamation process.

The general approach for defining water quality criteria for a specific project should be to use the limits presented in the FAO (1985) guidelines for prevention of soil salinization (EC, TDS) and prevention of toxic effects on plants (Na, B, Mn, Cl, trace elements), for protection of irrigation infrastructure (TSS, pH) and to maintain sufficient soil infiltration (SAR). The WHO (2006) guidelines should be used for choosing an adequate approach for public health protection and defining limits regarding *E. coli* and HEs. The recommendations in this study should be used to include wastewater-related parameters and to develop site-specific water quality limits for protection of irrigation infrastructure (turbidity, TCOD, BOD_5), the required water quality prior to UV disinfection (turbidity, TSS, particle size) and prevention of eutrophication and negative effects on plants (TN, TP and K). Water storage facilities should be considered as an additional treatment step to reliably provide the required water quality.

Realization of water reuse projects can be facilitated by providing more detailed information on water quality requirements to relevant stakeholders. The parameters contained in the FAO (1985) guidelines provide a basis for monitoring irrigation water quality and should be further extended to include the wastewater-related parameters presented in this study. More detailed information on the required maximum particle content and suitable monitoring parameters prior to disinfection steps (UV, chlorine, chlorine dioxide, ozone) and for different types of irrigation infrastructure (drip irrigation, subsurface irrigation, sprinkler systems) is needed. Further characteristics of the irrigation site, such as soil conditions and climate, should be taken into account. This will facilitate water quality monitoring in water reuse schemes and assist in providing adequate irrigation water.

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