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ORIGINAL ARTICLE

Application of water quality guidelines and water quantity calculations to decisions for beneficial use of treated water

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Abstract Water reuse guidelines were compiled as a decision-analysis screening tool for application to potential water reuse for irrigation, livestock watering, aquaculture, and drinking. Data compiled from the literature for water reuses yielded guideline values for over 50 water quality parameters, including concentrations of inorganic and organic constituents as well as general water chemistry parameters. These water quality guidelines can be used to identify constituents of concern in water, to determine the levels to which the constituents must be treated for water reuse applications, and assess the suitability of treated water for reuse. An example is provided to illustrate the application of water quality guidelines for decision analysis. Water quantity analysis was also investigated, and water volumes required for producing 16 different crops in 15 countries were estimated as an example of applying water quantity in the decision-making process regarding the potential of water reuse. For each of the countries investigated, the crop that produces the greatest yield in terms of weight per water volume is tomatoes in Australia, Brazil, Italy, Japan, Saudi Arabia, Turkey, USA; sugarcane in Chad, India, Indonesia, Sudan; watermelons in China; lettuce in Egypt, Mexico; and onions (dry) in Russia.

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Introduction

The need for water reuse is becoming critical as water supplies are dwindling and becoming increasingly contaminated (Asano et al. 2007; Meybeck and Helmer 1996). During the times of drought, water treated for reuse can serve as an essential, additional source of water. From a socio-economic standpoint, increasing water resources by reuse can strengthen the infrastructure of a country and improve the lives of its people. Reuse options for a specific location must take into account the water quantity, water quality, latitude, longitude, altitude, and local climatic conditions, as well as criticality and prioritization of needs (e.g. drinking, irrigation, livestock watering, industry, augmentation of surface flow). Multiple reuses may be feasible at a specific site depending upon the water quantity and the constituents in need of treatment.

Water supply is a worldwide issue that is becoming increasingly evident in many countries. Due to the geography and climate variations around the world, approximately 70% of the renewable water resources are unavailable for human use (Postel 2000; Shiklomanov 2000). Lack of a sufficient quantity of water suitable for irrigation and drinking can lead to food shortages and health concerns for millions. In addition, water scarcity can stifle a nation's economy, fuel conflicts, and negatively impact the environment (Asano et al. 2007). The global water supply is being stressed further as human population continues to grow exponentially (Qadir et al. 2003, 2007). Consequently, there is an urgent need to increase water quantity for drinking and food production (e.g. irrigation and livestock watering).

The aim of water quality management is to minimize the health risks associated with either direct or indirect use of water. The need for standards and guidelines in water quality stems from the need to protect human health. Many countries have adopted guidelines or set standards for water quality for various uses. Guidelines are values set for specific parameters based on studies (e.g. toxicity and epidemiological) and field observations that typically represent the upper limit deemed safe for the use by receiving organisms or receptors (i.e. plants and animals). The main difference between the guidelines and standards is that the guidelines are recommendations while standards are enforceable by law. Commonly, standards apply to potable water due to direct consumption by people.

No single set of water quality guidelines is universally applicable. Many factors, including the level of technology, economic status, relative associated risk, and field conditions, influence the variability of guidelines among nations (Asano et al. 2007; Bixio et al. 2008; Jensen et al. 2001). Due to the inherent range among the available water quality guidelines, there is a need for an accepted set of guideline values that can be utilized for decision-making when dealing with water reuse issues. These guideline values are needed to identify the constituents of concern, determine the levels to which the constituents must be treated for water reuse, and assess the water reuse applications following the treatment.

With effective and efficient treatment, a variety of waters with impaired quality can potentially be beneficially used in many applications. The level of treatment required depends on the intended water usage (de Koning et al. 2008). Numerous crops have been successfully grown with treated wastewater including over twenty crop types (Asano et al. 2007). Application of water for growing crops requires an understanding of crop water requirements as water demand differs among the crops. Another potential use of treated wastewater is in rearing animals such as fish and livestock. Studies are being done to assess the feasibility of maintaining aquaculture with reused water (Nijhawan and Myers 2006). Expanded uses of water for cultivating fish and raising livestock can provide additional food sources for countries suffering from food shortages.

For efficient water reuse, a systematic approach is needed that considers both water quality and quantity. Therefore, the objectives of this investigation were: (1) compile water quality guidelines, which can be used in decision analysis, for irrigation, livestock watering, aquaculture, and drinking (potable water) and (2) develop estimations of water quantity required for crop production as an approach to assessing water quantity in the decision-making process regarding the potential of water reuse. This study provides an approach that considers both the water quality and water quantity with examples incorporating a database of multiple guidelines and calculations to assist in water reuse decisions.

Methods

Compilation of water quality guidelines

Existing water quality guidelines were compiled from government and non-government reports, books, and journals. The guidelines and references were entered into a Microsoft Excel spreadsheet with separate worksheets for four reuse purposes: irrigation, livestock watering, aquaculture, and drinking. Guideline values for inorganic, organic, and various general chemistry parameters were entered for each reuse. A user interface for interactive data comparison between the user-input data and water quality guidelines was created within the spreadsheet. Concentration data were entered for constituents specific to the water composition, and the values entered were compared interactively to the guideline values for water reuse. Results of the data comparison indicated if input values met or exceeded the guideline values for each reuse purpose. An example is provided to illustrate application of the interactive spreadsheet as a screening tool in decision analysis regarding possible use options for untreated and treated water.

Water quantity required for crop production

Data compilation for selected crops and countries

Water volumes required for crop irrigation were estimated from calculations and published data. In order to demonstrate the application for potential beneficial use, various crops and several countries were selected for investigation. Data for average crop yield (hg/ha) (1997–2001) and crop water requirement (mm/crop period) by country were compiled from Chapagain and Hoekstra (2004). Crop water requirement (CWR) is equivalent to the amount of water needed for evapotranspiration (also termed crop evapotranspiration) for one growing period (i.e. planting to harvesting) under standard conditions, whereby conditions are free of pests, nutrient restrictions, and water restrictions (Allen et al. 1998). In order to obtain CWR, Chapagain and Hoekstra (2004) summed daily crop evapotranspiration over the crop growing period. Crop evapotranspiration is the product of crop coefficient and reference evapotranspiration (Eq. 1, from Chapagain and Hoekstra 2004).

$$\mathrm{ET_c} = K \times \mathrm{ET_o} \qquad (1)$$

Table 1 Compilation of water quality guidelines for irrigation, livestock, aquaculture, and drinking[1,2]

Parameter	Irrigation	Livestock	Aquaculture[13]	Drinking
Aluminum	5[c,e,h,j,k,n,p]	5[e,h,k,p]	0.005[7,j,s]; 0.1[8,j,s] 0.01[7,d]; 0.03[8,d] 0.03[h]	0.05–0.2[l] 0.1–0.2[o,u] 0.15[h] 0.2[i,m,q]
Antimony	–	–	0.03[j]	0.003[m] 0.005[i,q] 0.006[l,u] 0.02[o]
Arsenic	0.1[c,e,h,j,k,n,p]	0.025[p] 0.2[e] 0.5[k] 1[h]	0.005[s] 0.05[h,d,j,r]	0.007[m] 0.01[h,i,l,o,q,u] 0.05[j]
Benzene	–	0.01[j]	0.3[j] 0.37[s]	0.001[i,m,q] 0.005[l] 0.01[o,j]
Benzo(a)pyrene	–	0.00001[j]	0.000015[s]	0.00001[i,j,m,q] 0.0002[l] 0.0007[o]
Beryllium	0.1[c,e,h,j,k,n,p]	0.1[e,j,p]	–	0.004[l]
BOD	10[c]	–	15[g]	–
Boron	0.5[c,h,k] 0.5–6[p] 0.75[n]	5[e,h,k,p]	–	0.5[o] 1[i,j,q] 4[m]
Cadmium	0.0051[p] 0.01[c,e,h,j,k,n]	0.01[h,k] 0.05[e] 0.08[p]	0.0002–0.0018[h] 0.0002–0. 002[j] 0.003[r]	0.002[m] 0.003[o] 0.005[h,i,j,l,q]
Chloride	100[h] 100–700[p] 178–710[j] 280[c]	–	–	100[h] 250[i,l,m,q]
Chromium[12]	0.008[p] (VI) 0.1[c,e,n] 1[j]	0.05[11,p] 1[e,j,k]	0.001[s](VI) 0.01[j] 0.02[h] (VI) 0.1[r]	0.05[i,j,m,o,q] 0.1[l]
Cobalt	0.05[c,e,h,j,k,n,p]	1[e,h,k,p]	–	–
Copper	0.2[e,h,j,k,n] 0.2–1.0[p] 0.4[c]	0.4–5[k] 0.5[e,j] 0.5–5[p]	0.002–0.004[s] 0.002–0.005[j] 0.005[h] 0.006[r]	1[h] 1.3[l] 2[i,m,o,q]
Cyanide	0.05[c]	–	0.005[d,j,r,s]	0.05[i,q] 0.07[o] 0.1[j] 0.2[l]
Fluoride	1[e,j,k,n,p] 2[c,h]	2[e,h,k]	0.02[a]	1[h] 1.5[i,m,o,q,u] 2 [l]
Iron	0.2[k] 1[j] 5[c,e,h,n,p]	–	0.01[d,h] (II) 0.5[r] 1[j]	0.1[h] 0.2[i,q] 0.3[l,m,u]

Table 1 continued

Parameter	Irrigation	Livestock	Aquaculture[13]	Drinking
Lead	0.1[c] 0.2[h,j,p] 2[k] 5[e,n]	0.1[e,h,k,p]	0.001–0.005[j] 0.001–0.007[a,s] 0.01[h] 0.03[r]	0.01[h,i,m,o,u] 0.015[l] 0.025[q] 0.05[j]
Magnesium	–	250–500[e] 500[h] 600[j]	15[d]	–
Manganese	0.02[h] 0.2[c,e,j,k,n,p]	0.05[e] 10[h]	0.01[d,r] 0.1 [h]	0.05[h,i,l,q,u] 0.4[o] 0.5[m]
Mercury	0.001[c] 0.002[j,k]	0.002[k] 0.003[p] 0.01[e]	0.000026[s] 0.00005[r] 0.0001[j] 0.001[k]	0.001[h,i,j,m,o,q,u] 0.002[l]
Molybdenum	0.01[c,e,h,j,k,n] 0.01–0.05[p]	0.01[h,j] 0.15[k] 0.5[p]	0.073[s]	0.05[m] 0.07[o]
Nickel	0.02[c] 0.2[e,h,j,k,n,p]	1[h,k,p]	0.01[k] 0.01[5,r]; 0.04[6,r] 0.015–0.15[j] 0.025–0.15[s] 0.1[d]	0.02[i,m,q] 0.07[o] 0.1[j]
Nitrate	10[c]	100[h] 133[j] 400[k]	1–100[r] 13[s] 50[g] 1,330[h]	10[l] 45[j,u] 50[i,m,o,q]
Nitrite	–	30[k] 33[e,j,p]	0.06[s] 0.1[b,d,r] 0.17[h]	0.5[i,q] 1[l] 3[m,o] 3.2[j,u]
Oil and Grease	35[t]	35[t]	0.3[g]	–
pH[3,14]	4.5–9.0[j] 6.0[n] 6.0–8.4[c] 6.0–8.5[k] 6.5–8.4[h]	–	5.0–9.0[k] 6.5–9.0[h,j,s] 6.8–9.5[r]	6.0–9.0[h] 6.5–8.5[l,m,u] 6.5–9.5[i] 6.5–10[q]
Selenium	0.02[c,e,h,j,k,n] 0.02–0.05[p]	0.02[k] 0.05[e,h,p]	0.001[s] 0.01[d] 0.3[h](VI)	0.01[i,j,m,o,q,u] 0.02[h] 0.05[l]
Silver	–	–	0.0001[j,s] 0.003[d]	0.05[j] 0.1[l,m,o]
Sodium	70[h]	2,000[h]	–	100[h] 180[m] 200[i,q]
Sulfate	–	1,000[h,j,k,p]	–	200[h] 250[i,l,o,q] 500[m,u]
TDS	500–2,000[n] 500–3,500[p]	3,000[p] 3,000–13,000[k] 5,000–15,000[j]	3,000[f]	450[h] 500[l,m,u] 1,200[o]

Table 1 continued

Parameter	Irrigation	Livestock	Aquaculture[13]	Drinking
Thallium	–	–	0.004[j]	0.002[l]
Turbidity[4]	1[c]	–	25[h]	1[i]
			80[r]	4[q]
				5[m]
Uranium	0.01[h,j,k,p]	0.2[k,p]	–	0.015[o]
				0.02[m,u]
				0.03[l]
Vanadium	0.1[e,h,j,k,n,p]	0.1[e,j,p]	0.1[d]	–
		1[h]		
Zinc	1[h]	20[h,k]	0.005[d]	3[m,o]
	1[9,p]; 5[10,p]	24[e]	0.005–0.05[j]	5[l,u]
	2[n,p,q,s]	50[p]	0.03[s]	
	4[c]		0.03–0.06[5,r]; 1–2[6,r]	

[1] Units in mg/L unless noted, [2]Values listed are upper limits unless indicated otherwise, [3]Standard unit, [4]Unit of nephelometric turbidity units (NTU), [5]Soft water, [6]Hard water, [7]Water pH < 6.5,[8]Water pH > 6.5,[9]Soil pH < 6.5, [10]Soil pH > 6.5, [11]III or VI, [12]Total chromium unless indicated otherwise, [13]Freshwater environment, [14]Guideline values are within the ranges listed

References: [a] (Tebbutt 1977), [b] (Coche 1981), [c] (Kalthem and Jamaan 1985), [d] (Meade 1989), [e] (Ayers and Westcot 1985), [f] (Lawson 1995), [g] (Schlotfeldt and Alderman 1995), [h] (DWAF 1996), [i] (EC 1998), [j] (SAEPA 1999-adapted from ANZECC 1992), [k] (ANZECC and ARMCANZ 2000), [l] (USEPA 2003), [m] (NHMRC and NRMMC 2004), [n] (USEPA 2004-adapted from Rowe and Adbel-Magid 1995), [o] (WHO 2004), [p] (CCME 2005), [q] (CIDWI 2006), [r] (QGEPA 2006), [s] (CCME 2007), [t] (Wilson 2007), [u] (CDW 2008)

where $ET_{c.}$ is the crop evapotranspiration (mm/day), K is crop coefficient (dimensionless), and ET_o is reference evapotranspiration (mm/day).

$ET_{c.}$ includes evaporation due to solar radiation and transpiration by plants (Allen et al. 1998). K is a value that incorporates crop transpiration and soil evaporation, which varies with plant growth stage (i.e. initial, crop development, mid, and late-season) (Allen et al. 1998; Ko et al. 2009; Piccinni et al. 2009). ET_o varies by climate and is independent of crop type and soil characteristics (Chapagain and Hoekstra 2004).

Calculation of water volume requirements and crop yields

Compiled values of average crop yield and crop water requirement (CWR) were used in calculations to quantify water requirements for the selected crops and countries. The calculations incorporated one crop growth period to obtain the following: (1) water volume (m^3) required to grow one hectare of crop; (2) crop yield (kg) per 1,000 m^3 (264,172 gal) water volume; (3) total water volume (m^3) required per metric ton of crop produced; (4) daily water volume (m^3) required per metric ton of crop produced; and (5) land area (ha) required per metric ton of crop.

Water volume required (m^3) to grow one hectare of crop for one crop period was calculated by converting CWR from mm/crop period to m/crop period and then multiplying by 10,000 m^2, which equals one hectare, using the following equation:

$$V_w = (\mathrm{CWR}) \times (0.001\ \mathrm{m/mm}) \times (10{,}000\ \mathrm{m}^2) \quad (2)$$

where V_w is water volume (m^3 per ha per crop period), and CWR is crop water requirement (mm/crop period).

Crop yield (kg) per 1,000 m^3 (264,172 gal) water volume during one crop growth period was calculated using Eq. 3:

$$\mathrm{CY} = (\mathrm{Cy}/V_w) \times 1000 \times (\mathrm{kg}/10\ \mathrm{hg}) \quad (3)$$

where CY is crop yield (kg/1,000 m^3), and Cy is average crop yield (hg/ha) for 1997–2001 (Chapagain and Hoekstra 2004).

As shown by Eq. 3, crop yield (hg/ha) was divided by water volume (m^3/ha), and the result was multiplied by 1,000 to obtain hg/1,000 m^3, which was then converted to kg/1,000 m^3 by multiplying by kg/10 hg. To calculate total water volume (m^3) required per metric ton of crop production (TWV), the following equation was used:

$$\mathrm{TWV} = [\mathrm{CY} \times (\mathrm{metric\ ton}/1{,}000\ \mathrm{kg})]^{-1} \quad (4)$$

Using this equation, the units of crop yield were converted from kg/1,000 m^3 to m^3/metric ton. TWV is equivalent to average virtual water content as used by Chapagain and Hoekstra (2004). The approximate average daily water volume (m^3) required per metric ton of crop production was calculated by dividing the TWV by the approximate duration of one plant growth period (Eq. 5).

Table 2 Guideline values used in this investigation for water quality decision analysis[a,g]

Parameter	Irrigation[b]	Livestock[b]	Aquaculture[b]	Drinking[b]
Alkalinity[c,e]	–	–	130	–
Aluminum	5	5	0.005	0.05
Ammonium	–	–	–	0.5
Antimony	–	–	0.03	0.003
Arsenic	0.1	0.025	0.005	0.007
Barium	–	–	–	0.7
Benzene	–	–	0.3	0.001
Benzo(a)pyrene	–	–	0.000015	0.00001
Beryllium	0.1	0.1	–	0.004
BOD	10	–	15	–
Boron	0.5	5	–	0.3
Cadmium	0.0051	0.01	0.0002	0.002
Calcium	–	1000	–	–
Chloride	100	–	–	100
Chromium[f]	0.1	0.05	0.01	0.05
Cobalt	0.05	1	–	–
COD	–	–	40	–
Copper	0.2	0.4	0.002	1
Cyanide	0.05	–	0.005	0.05
DO[e]	–	–	5	–
Fluoride	1	2	0.02	1
Hardness[c,e]	–	–	150	200
Hydrogen sulfide	–	–	0.001	–
Iron	0.2	–	0.5	0.1
Lead	0.1	0.1	0.001	0.01
Lithium	0.07	–	–	–
Magnesium	–	250	15	–
Manganese	0.02	0.05	0.01	0.05
Mercury	0.001	0.002	0.000026	0.001
Molybdenum	0.01	0.01	0.073	0.07
Nickel	0.02	1	0.01	0.02
Nitrate	10	100	1	10
Nitrite	–	30	0.06	0.05
Nitrate-nitrite	–	100	–	–
Nitrogen	5	–	–	–
Oil and grease	35	35	0.3	–
Phosphate	–	–	0.1	–
Phosphorus	0.05	–	–	–
Potassium	–	–	–	50
Selenium	0.02	0.02	0.001	0.01
Silver	–	–	0.0001	0.05
Sulfate	–	1000	–	200
TDS	500	3000	3000	450
Thallium	–	–	0.004	0.002
Tin	–	–	0.001	–
TSS	10	–	–	–
Turbidity[d]	1	–	25	1
Uranium	0.01	0.2	–	0.015
Vanadium	0.1	0.1	0.1	–
Zinc	1	20	0.005	3

[a] Lower concentration from among values listed in Table 1 unless indicated otherwise

[b] Concentration in mg/L, unless indicated otherwise

[c] Concentration in mg/L as $CaCO_3$

[d] Unit of Nephelometric Turbidity Units (NTU)

[e] Median concentration

[f] Total chromium

[g] References are listed in Table 1

$$\mathrm{DWV} = \mathrm{TWV}/\mathrm{DPG} \tag{5}$$

where DPG = approximate duration of growth period (days).

The DPG for each crop was obtained by averaging the growth period values reported by Allen et al. (1998) (Table 11). Eq. 6 was used to calculate A the approximate land area (ha) required per metric ton of crop. In equation 6, the average crop yield (hg/ha) was inverted, and the result was converted to ha/metric ton by multiplying by 10,000 hg/metric ton, where hg is hectogram (1 hg = 100 g).

$$A = (\mathrm{Cy})^{-1} \times (10,000\ \mathrm{hg/metric\ ton}) \tag{6}$$

Results

Compilation of water quality guidelines

Compilation of guideline values for the four water reuse purposes yielded 36 water-quality parameters having guidelines for at least two of the reuse purposes (Table 1). The parameters include inorganic and organic constituents of concern (COCs) as well as general water chemistry parameters. The guidelines are summarized in Table 2, with the most stringent values listed for each constituent. Included in Table 2 are the guidelines for parameters pertinent for a specific reuse purpose, such as nitrogen for crop irrigation. A water quality parameter not listed in the guideline compilation does not imply that it cannot be a constituent of concern, but only that it was not among those found in the literature reviews conducted for this investigation. Guidelines compiled in this paper pertain to the water quality; guidelines for soil quality are available from other sources (e.g. WHO 2006).

For the majority of parameters the concentrations are most conservative for aquaculture (i.e. most stringent;

Table 3 Average crop yield (hg/ha) by country (1997–2001) from Chapagain and Hoekstra (2004)

Country	Barley	Cassava	Lettuce	Maize	Millet	Onions, Dry	Potatoes	Rice (paddy)
Australia	19,787	nr	248,023	50,828	12,765	431,889	307,752	87,873
Brazil	20,249	131,162	nr	28,554	nr	147,638	165,421	29,202
Chad	nr	85,138	nr	8,684	4,180	200,000	66,605	13,271
China	29,588	159,836	217,277	47,807	17,932	206,387	142,580	62,830
Egypt	23,459	nr	269,091	74,781	nr	259,386	229,849	88,638
India	19,330	246,268	65,822	18,279	8,075	106,707	177,820	29,892
Indonesia	nr	124,024	nr	27,078	nr	86,705	148,989	43,340
Italy	35,782	nr	187,883	95,469	nr	295,479	242,186	60,692
Japan	34,697	nr	246,146	24,579	10,000	473,747	313,002	64,774
Mexico	20,752	123,239	201,741	24,477	7,079	122,723	222,843	43,723
Russia	16,491	nr	nr	21,260	9,337	114,351	103,916	30,199
Saudi Arabia	49,527	nr	nr	17,253	13,701	224,764	226,687	nr
Sudan	nr	17,793	nr	6,653	2,282	70,885	73,261	9,952
Turkey	21,981	nr	182,914	41,154	17,164	214,702	257,001	55,234
USA	31,916	nr	366,002	84,103	16,849	466,646	400,672	67,690

Country	Seed Cotton	Sorghum (grain)	Soybean	Sugar Cane	Sweet Potatoes	Tomatoes	Watermelons	Wheat
Australia	36,196	27,853	19,282	920,649	171,429	469,583	181,796	19,454
Brazil	20,562	17,345	24,267	686,927	107,125	486,106	79,129	17,325
Chad	6,174	6,484	nr	883,341	25,671	Nr	nr	18,767
China	31,571	34,545	17,235	684,949	197,564	251,887	309,477	38,556
Egypt	23,944	56,009	26,784	1,167,293	249,073	340,304	260,242	61,272
India	6,401	7,895	10,161	690,703	88,583	161,762	129,947	26,482
Indonesia	12,801	nr	12,119	666,020	95,567	117,279	nr	nr
Italy	nr	60,635	36,454	Nr	146,406	518,162	339,447	31,477
Japan	nr	nr	17,711	665,065	243,587	576,002	338,152	35,839
Mexico	29,849	31,608	15,705	742,135	195,643	275,237	214,355	46,550
Russia	nr	9,740	8,898	Nr	nr	121,674	33,924	16,887
Saudi Arabia	nr	12,608	nr	Nr	nr	213,848	182,008	44,747
Sudan	11,642	6,097	nr	778,447	134,282	119,063	286,661	20,608
Turkey	31,124	nr	26,744	Nr	nr	401,774	277,581	20,842
USA	18,582	41,051	25,844	787,093	169,863	646,274	258,927	27,930

nr = not reported
hg = hectogram
ha = hectare

generally, the lowest concentration values) with the least conservative values for livestock (Tables 1, 2). For example, concentration guidelines for aluminum, cadmium, copper, lead, mercury, selenium, silver, and zinc are lower for aquaculture than for the other water reuse purposes. One of the most stringent guideline values (Table 1) is for mercury in aquacultural water, which is 0.026 µg/L (CCME 2007). A probable reason for such a strict limit is the concern of mercury bioaccumulation in fish tissue and ultimately in humans (USEPA 1997).

Oil and grease limits were not incorporated for drinking water because the limits are listed separately for specific polycyclic aromatic hydrocarbons. The United States Environmental Protection Agency (USEPA) has subdivided the oil and grease category into specific components, each with its own maximum contaminant level (MCL), which represents the highest level of contaminant permissible for drinking water (USEPA 2003). Most notable is benzo(a)pyrene because it is a known carcinogen in addition to causing other adverse effects on human health even with short-term exposure at relatively low doses (USEPA 2002). The maximum contaminant level goal (MCLG) for benzo(a)pyrene is set at zero by the USEPA (2003). However, the MCL is 0.2 µg/L for drinking water (USEPA 2003). In comparison, four other references reported 0.01 µg/L as a concentration limit for benzo(a)pyrene in drinking water (CIDWI 2006; EC 1998; NHMRC and NRMMC 2004; SAEPA 1999-adapted from ANZECC 1992). The WHO (2004) drinking water guideline for benzo(a)pyrene is 0.7 µg/L, which is the least stringent value reported among references used for this study.

Table 4 Crop water requirement (mm/crop period) for selected countries (from Chapagain and Hoekstra 2004)

Country	Barley	Cassava	Lettuce	Maize	Millet	Onions, dry	Potatoes	Rice (paddy)
Australia	282	Nr	486	378	249	944	463	898
Brazil	278	525	Nr	337	Nr	653	398	900
Chad	Nr	1,016	Nr	562	413	1,014	641	1,385
China	251	552	329	383	334	505	394	830
Egypt	518	Nr	209	771	Nr	670	707	1,387
India	380	696	170	354	264	574	378	852
Indonesia	Nr	570	Nr	348	Nr	661	410	932
Italy	652	Nr	348	506	Nr	673	506	1,019
Japan	242	Nr	282	367	310	451	355	791
Mexico	440	770	241	427	321	676	453	954
Russia	389	Nr	Nr	297	270	324	342	725
Saudi Arabia	805	Nr	Nr	1,234	1,027	1,035	1,082	Nr
Sudan	Nr	1,131	Nr	618	461	1,212	791	1,495
Turkey	299	Nr	422	630	546	699	624	1,137
USA	224	Nr	319	411	361	505	424	863

Country	Seed cotton	Sorghum (grain)	Soybean	Sugarcane	Sweet potatoes	Tomatoes	Watermelons	Wheat
Australia	683	301	406	1,297	625	440	521	309
Brazil	571	279	261	1,065	420	353	388	280
Chad	882	497	Nr	1,776	532	Nr	Nr	569
China	448	298	451	798	455	424	303	266
Egypt	725	509	754	1,634	860	550	550	570
India	529	320	419	1,101	245	488	471	438
Indonesia	570	Nr	246	1,092	391	398	Nr	Nr
Italy	Nr	353	549	Nr	551	548	370	762
Japan	Nr	Nr	412	795	415	407	265	263
Mexico	635	383	499	1,272	331	504	506	496
Russia	Nr	232	350	Nr	Nr	368	255	401
Saudi Arabia	Nr	755	Nr	Nr	Nr	822	844	890
Sudan	968	553	Nr	1,998	612	847	873	639
Turkey	722	Nr	717	Nr	Nr	683	473	319
USA	471	321	483	1,023	486	451	327	237

Nr not reported

Guideline concentrations of TDS are greater than those of other constituents, particularly for irrigation and livestock watering. TDS guidelines are an order of magnitude higher for irrigation and livestock watering than for drinking water.

The species and age of the receiving organism influence its tolerance for TDS. TDS guideline concentrations for livestock range from 3,000 to 15,000 mg/L depending on the specific type of livestock (ANZECC and ARMCANZ 2000; CCME 2005 SAEPA 1999-adapted from ANZECC 1992). Tolerance of TDS varies among the crops, ranging from 500 mg/L for carrots to 3,500 mg/L for wheat (CCME 2005).

Several guideline parameters are pH dependent, such as concentration limits for aluminum and zinc. Aluminum guideline concentrations for aquaculture are based on pH of the water, while zinc guideline concentrations in water used for irrigation depend on soil pH. Although other parameters listed in Table 1 do not indicate pH dependence, they may be impacted by pH to some degree. For example, concentrations of many metals in solution are pH-dependent (Brookins 1988).

Water quantity required for crop production

Data compilation for selected crops and countries

For representation of different geographic regions and climatic conditions, 15 countries from around the world were selected for investigation: Australia, Brazil, Chad,

Table 5 Water volume (m^3) required to grow one hectare of crop per crop period

Country	Barley	Cassava	Lettuce	Maize	Millet	Onions, dry	Potatoes	Rice (paddy)
Australia	2,820	Na	4,860	3,780	2,490	9,440	4,630	8,980
Brazil	2,780	5,250	Na	3,370	Na	6,530	3,980	9,000
Chad	Na	10,160	Na	5,620	4,130	10,140	6,410	13,850
China	2,510	5,520	3,290	3,830	3,340	5,050	3,940	8,300
Egypt	5,180	Na	2,090	7,710	Na	6,700	7,070	13,870
India	3,800	6,960	1,700	3,540	2,640	5,740	3,780	8,520
Indonesia	Na	5,700	Na	3,480	Na	6,610	4,100	9,320
Italy	6,520	Na	3,480	5,060	Na	6,730	5,060	10,190
Japan	2,420	Na	2,820	3,670	3,100	4,510	3,550	7,910
Mexico	4,400	7,700	2,410	4,270	3,210	6,760	4,530	9,540
Russia	3,890	Na	Na	2,970	2,700	3,240	3,420	7,250
Saudi Arabia	8,050	Na	Na	12,340	10,270	10,350	10,820	Na
Sudan	Na	11,310	Na	6,180	4,610	12,120	7,910	14,950
Turkey	2,990	Na	4,220	6,300	5,460	6,990	6,240	11,370
USA	2,240	Na	3,190	4,110	3,610	5,050	4,240	8,630

Country	Seed cotton	Sorghum (grain)	Soybean	Sugarcane	Sweet potatoes	Tomatoes	Watermelons	Wheat
Australia	6,830	3,010	4,060	12,970	6,250	4,400	5,210	3,090
Brazil	5,710	2,790	2,610	10,650	4,200	3,530	3,880	2,800
Chad	8,820	4,970	Na	17,760	5,320	Na	Na	5,690
China	4,480	2,980	4,510	7,980	4,550	4,240	3,030	2,660
Egypt	7,250	5,090	7,540	16,340	8,600	5,500	5,500	5,700
India	5,290	3,200	4,190	11,010	2,450	4,880	4,710	4,380
Indonesia	5,700	Na	2,460	10,920	3,910	3,980	Na	Na
Italy	Na	3,530	5,490	Na	5,510	5,480	3,700	7,620
Japan	Na	Na	4,120	7,950	4,150	4,070	2,650	2,630
Mexico	6,350	3,830	4,990	12,720	3,310	5,040	5,060	4,960
Russia	Na	2,320	3,500	Na	Na	3,680	2,550	4,010
Saudi Arabia	Na	7,550	Na	Na	Na	8,220	8,440	8,900
Sudan	9,680	5,530	Na	19,980	6,120	8,470	8,730	6,390
Turkey	7,220	Na	7,170	Na	Na	6,830	4,730	3,190
USA	4,710	3,210	4,830	10,230	4,860	4,510	3,270	2,370

Calculated using equation 2 and values from Table 4

Na not available (crop water requirement not reported by Chapagain and Hoekstra (2004)

China, Egypt, India, Indonesia, Italy, Japan, Mexico, Russia, Saudi Arabia, Sudan, Turkey, and the United States of America. The following crops were selected based on global production data or for their importance as a food source in impoverished, rural communities: rice (paddy), maize, soybean, wheat, sweet potatoes, potatoes, tomatoes, watermelons, lettuce, onion, sorghum, and millet (FAO 2005). Cassava was selected because it is the third largest source of carbohydrates for human consumption in the world, particularly prominent in Africa (Cleaver et al. 2008). Seed cotton was selected because of the importance of cotton as a textile fiber, accounting for approximately 35% of the total world fiber use (USDA 2011), and cotton is one of the most widely grown agricultural crops (Watkins and Sul 2002). Only crops with crop yield data available (from Chapagain and Hoekstra 2004) for more than half of the selected countries were used for the analysis. Average crop yields (hg/ha) by country for the 16 selected crops are listed in Table 3, and crop water requirements in Table 4.

Water volume requirements and crop yields

The water volume required to grow one hectare of crop for the 16 selected crops ranges from 1,700 m^3 (lettuce in India) to 19,980 m^3 (sugarcane in Sudan) (Table 5).

Table 6 Crop yield (kg) per 1000 m^3 (264,172 gal) water volume during crop growth period (i.e. total water volume over duration of crop growth)

Country	Barley	Cassava	Lettuce	Maize	Millet	Onions, dry	Potatoes	Rice (paddy)
Australia	702	Na	5,103	1,345	513	4,575	6,647	979
Brazil	728	2,498	Na	847	Na	2,261	4,156	324
Chad	Na	838	Na	155	101	1,972	1,039	96
China	1,179	2,896	6,604	1,248	537	4,087	3,619	757
Egypt	453	Na	12,875	970	Na	3,871	3,251	639
India	509	3,538	3,872	516	306	1,859	4,704	351
Indonesia	Na	2,176	Na	778	Na	1,312	3,634	465
Italy	549	Na	5,399	1,887	Na	4,390	4,786	596
Japan	1,434	Na	8,729	670	323	10,504	8,817	819
Mexico	472	1,601	8,371	573	221	1,815	4,919	458
Russia	424	Na	Na	716	346	3,529	3,038	417
Saudi Arabia	615	Na	Na	140	133	2,172	2,095	Na
Sudan	Na	157	Na	108	50	585	926	67
Turkey	735	Na	4,334	653	314	3,072	4,119	486
USA	1,425	Na	11,473	2,046	467	9,241	9,450	784

Country	Seed cotton	Sorghum (grain)	Soybean	Sugarcane	Sweet potatoes	Tomatoes	Watermelons	Wheat
Australia	530	925	475	7,098	2,743	10,672	3,489	630
Brazil	360	622	930	6,450	2,551	13,771	2,039	619
Chad	70	130	Na	4,974	483	Na	Na	330
China	705	1,159	382	8,583	4,342	5,941	10,214	1,449
Egypt	330	1,100	355	7,144	2,896	6,187	4,732	1,075
India	121	247	243	6,273	3,616	3,315	2,759	605
Indonesia	225	Na	493	6,099	2,444	2,947	Na	Na
Italy	Na	1,718	664	Na	2,657	9,456	9,174	413
Japan	Na	Na	430	8,366	5,870	14,152	12,760	1,363
Mexico	470	825	315	5,834	5,911	5,461	4,236	939
Russia	Na	420	254	Na	Na	3,306	1,330	421
Saudi Arabia	Na	167	Na	Na	Na	2,602	2,156	503
Sudan	120	110	Na	3,896	2,194	1,406	3,284	323
Turkey	431	Na	373	Na	Na	5,882	5,869	653
USA	395	1,279	535	7,694	3,495	14,330	7,918	1,178

Calculated using equation 3 and values from Tables 3 and 5

Na not available

The crop yield per 1,000 m^3 water volume ranges from 50 kg (millet in Sudan) to 14,330 kg (tomatoes in USA) (Table 6). For each of the 15 countries investigated, the crop that produces the greatest yield in terms of weight per water volume is tomato in Australia, Brazil, Italy, Japan, Saudi Arabia, Turkey, USA; sugarcane in Chad, India, Indonesia, Sudan; watermelon in China; lettuce in Egypt, Mexico; and onion (dry) in Russia (Table 6). The range of total water volume required per metric ton of crop produced is 70 m^3 (tomatoes in USA) to 20,202 m^3 (millet in Sudan) (Table 7). The volume of water required to produce a metric ton of a specific crop varies greatly among the countries. For example, the volume of water required to produce a metric ton of crop is more than an order of magnitude greater for eight of the crops in Sudan compared with the country in which the smallest volume of water is required. The range for daily water volume required per metric ton of crop produced is 0.2 m^3 (sugarcane in China and Japan) to 165.6 m^3 (millet in Sudan) (Table 8). The approximate land area required per metric ton of crop ranges from 0.01 ha (sugarcane for Australia, Brazil, Chad, China, Egypt, India, Mexico, Sudan, and USA) to 4.38 ha (millet in Sudan) (Table 9). In terms of land requirement among the 15 countries, sugarcane requires the least amount while millet requires the most.

Table 7 Total water volume (m^3) required per metric ton of crop production

Country	Barley	Cassava	Lettuce	Maize	Millet	Onions, dry	Potatoes	Rice (paddy)
Australia	1,425	Na	196	744	1,951	219	150	1,022
Brazil	1,373	400	Na	1,180	Na	442	241	3,082
Chad	Na	1,193	Na	6,472	9,880	507	962	10,436
China	848	345	151	801	1,863	245	276	1,321
Egypt	2,208	Na	78	1,031	Na	258	308	1,565
India	1,966	283	258	1,937	3,269	538	213	2,850
Indonesia	Na	460	Na	1,285	Na	762	275	2,150
Italy	1,822	Na	185	530	Na	228	209	1,679
Japan	697	Na	115	1,493	3,100	95	113	1,221
Mexico	2,120	625	119	1,744	4,535	551	203	2,182
Russia	2,359	Na	Na	1,397	2,892	283	329	2,401
Saudi Arabia	1,625	Na	Na	7,152	7,496	460	477	Na
Sudan	Na	6,356	Na	9,289	20,202	1,710	1,080	15,022
Turkey	1,360	Na	231	1,531	3,181	326	243	2,059
USA	702	Na	87	489	2,143	108	106	1,275

Country	Seed cotton	Sorghum (grain)	Soybean	Sugarcane	Sweet potatoes	Tomatoes	Watermelons	Wheat
Australia	1,887	1,081	2,106	141	365	94	287	1,588
Brazil	2,777	1,609	1,076	155	392	73	490	1,616
Chad	14,286	7,665	Na	201	2,072	Na	Na	3,032
China	1,419	863	2,617	117	230	168	98	690
Egypt	3,028	909	2,815	140	345	162	211	930
India	8,264	4,053	4,124	159	277	302	362	1,654
Indonesia	4,453	Na	2,030	164	409	339	Na	Na
Italy	Na	582	1,506	Na	376	106	109	2,421
Japan	Na	Na	2,326	120	170	71	78	734
Mexico	2,127	1,212	3,177	171	169	183	236	1,066
Russia	Na	2,382	3,933	Na	Na	302	752	2,375
Saudi Arabia	Na	5,988	Na	Na	Na	384	464	1,989
Sudan	8,315	9,070	Na	257	456	711	305	3,101
Turkey	2,320	Na	2,681	Na	Na	170	170	1,531
USA	2,535	782	1,869	130	286	70	126	849

Calculated using equation 4 and values from Table 6

Na not available

Discussion

Water quality and reuse decisions

A benefit of compiling water reuse guidelines in a single database is that multiple guidelines are incorporated from different sources to provide specific values that can be used to assist in water reuse decisions. There are several applications to decision-making using the guideline values: to help identify COCs, determine the levels to which the constituents need to be treated for water reuse, and evaluate the water reuse applications following the treatment. Minimum acceptable concentrations can be established for the treated water based on a specific reuse (de Koning et al. 2008). Post-treatment concentrations can be compared to the guideline concentrations, which indicate whether the treated water can be reused and the potential uses of the renovated water.

The guideline values can be used with or without a specific, predefined reuse purpose. The concentration comparison can help to identify an option for water reuse (i.e. irrigate crops, raise livestock, rear fish, or use as drinking water). As an example of using the guideline values for identifying the reuse options, pre-treatment and post-treatment water quality data for a specific produced water were compared with the guideline values to identify COCs and to determine the possible water reuse options (Table 10). The comparison indicated that Cd, Cu, Zn, and

Table 8 Approximate average daily water volume (m^3) required per metric ton of crop production

Country	Barley	Cassava	Lettuce	Maize	Millet	Onions, dry	Potatoes	Rice (paddy)
DPG	160	286	107	152	122	180	140	165
Australia	8.9	Na	1.8	4.9	16.0	1.2	1.1	6.2
Brazil	8.6	1.4	Na	7.8	Na	2.5	1.7	18.7
Chad	Na	4.2	Na	42.6	81.0	2.8	6.9	63.3
China	5.3	1.2	1.4	5.3	15.3	1.4	2.0	8.0
Egypt	13.8	Na	0.7	6.8	Na	1.4	2.2	9.5
India	12.3	1.0	2.4	12.7	26.8	3.0	1.5	17.3
Indonesia	Na	1.6	Na	8.5	Na	4.2	2.0	13.0
Italy	11.4	Na	1.7	3.5	Na	1.3	1.5	10.2
Japan	4.4	Na	1.1	9.8	25.4	0.5	0.8	7.4
Mexico	13.3	2.2	1.1	11.5	37.2	3.1	1.5	13.2
Russia	14.7	Na	Na	9.2	23.7	1.6	2.4	14.5
Saudi Arabia	10.2	Na	Na	47.1	61.4	2.6	3.4	Na
Sudan	Na	22.3	Na	61.1	165.6	9.5	7.7	91.0
Turkey	8.5	Na	2.2	10.1	26.1	1.8	1.7	12.5
USA	4.4	Na	0.8	3.2	17.6	0.6	0.8	7.7

Country	Seed cotton	Sorghum (grain)	Soybean	Sugarcane	Sweet potatoes	Tomatoes	Watermelons	Wheat
DPG	202	135	118	500	137	157	95	160
Australia	9.3	8.0	17.8	0.3	2.7	0.6	3.0	9.9
Brazil	13.7	11.9	9.1	0.3	2.9	0.5	5.2	10.1
Chad	70.7	56.8	Na	0.4	15.1	Na	Na	18.9
China	7.0	6.4	22.2	0.2	1.7	1.1	1.0	4.3
Egypt	15.0	6.7	23.9	0.3	2.5	1.0	2.2	5.8
India	40.9	30.0	34.9	0.3	2.0	1.9	3.8	10.3
Indonesia	22.0	Na	17.2	0.3	3.0	2.2	Na	Na
Italy	Na	4.3	12.8	Na	2.7	0.7	1.1	15.1
Japan	Na	Na	19.7	0.2	1.2	0.5	0.8	4.6
Mexico	10.5	9.0	26.9	0.3	1.2	1.2	2.5	6.7
Russia	Na	17.6	33.3	Na	Na	1.9	7.9	14.8
Saudi Arabia	Na	44.4	Na	Na	Na	2.4	4.9	12.4
Sudan	41.2	67.2	Na	0.5	3.3	4.5	3.2	19.4
Turkey	11.5	Na	22.7	Na	Na	1.1	1.8	9.6
USA	12.5	5.8	15.8	0.3	2.1	0.4	1.3	5.3

Calculated using equation 5 and values from Table 7. DPG equals approximate duration of growth period (days). Water requirement varies with local conditions

Na not available

Pb concentrations in the influent (pre-treatment water) exceeded guideline concentrations for all four of the water reuse purposes with the exception of Zn for livestock and Cu for drinking. Therefore, Cd, Cu, Zn, and Pb were identified as COCs. Based on the comparison with guideline concentrations (Table 10), post-treatment concentrations of the COCs indicated that the treated water could be used for watering livestock, but not for aquaculture. In addition, the treated water can potentially be used for irrigation, with Cd still being a concern. Since some crops are more tolerant to metals than other crops, the decision to use the treated water is case-specific. The treated water can potentially be used as a drinking water; however, there is a concern due to the elevated concentrations of Cd and Pb. From a decision-making standpoint, further treatment would be necessary to lower the concentrations of Cd and Pb if the water were to be used for irrigating crops or drinking water.

Another application of the guideline compilation is for decisions regarding the treatment for a specific reuse.

Table 9 Approximate land area (ha) required per metric ton of crop production

Country	Barley	Cassava	Lettuce	Maize	Millet	Onions, dry	Potatoes	Rice (paddy)
Australia	0.51	Na	0.04	0.20	0.78	0.02	0.03	0.11
Brazil	0.49	0.08	Na	0.35	Na	0.07	0.06	0.34
Chad	Na	0.12	Na	1.15	2.39	0.05	0.15	0.75
China	0.34	0.06	0.05	0.21	0.56	0.05	0.07	0.16
Egypt	0.43	Na	0.04	0.13	Na	0.04	0.04	0.11
India	0.52	0.04	0.15	0.55	1.24	0.09	0.06	0.33
Indonesia	Na	0.08	Na	0.37	Na	0.12	0.07	0.23
Italy	0.28	Na	0.05	0.10	Na	0.03	0.04	0.16
Japan	0.29	Na	0.04	0.41	1.00	0.02	0.03	0.15
Mexico	0.48	0.08	0.05	0.41	1.41	0.08	0.04	0.23
Russia	0.61	Na	Na	0.47	1.07	0.09	0.10	0.33
Saudi Arabia	0.20	Na	Na	0.58	0.73	0.04	0.04	Na
Sudan	Na	0.56	Na	1.50	4.38	0.14	0.14	1.00
Turkey	0.45	Na	0.05	0.24	0.58	0.05	0.04	0.18
USA	0.31	Na	0.03	0.12	0.59	0.02	0.02	0.15

Country	Seed cotton	Sorghum (grain)	Soybean	Sugarcane	Sweet potatoes	Tomatoes	Watermelons	Wheat
Australia	0.28	0.36	0.52	0.01	0.06	0.02	0.06	0.51
Brazil	0.49	0.58	0.41	0.01	0.09	0.02	0.13	0.58
Chad	1.62	1.54	Na	0.01	0.39	Na	Na	0.53
China	0.32	0.29	0.58	0.01	0.05	0.04	0.03	0.26
Egypt	0.42	0.18	0.37	0.01	0.04	0.03	0.04	0.16
India	1.56	1.27	0.98	0.01	0.11	0.06	0.08	0.38
Indonesia	0.78	Na	0.83	0.02	0.10	0.09	Na	Na
Italy	Na	0.16	0.27	Na	0.07	0.02	0.03	0.32
Japan	Na	Na	0.56	0.02	0.04	0.02	0.03	0.28
Mexico	0.34	0.32	0.64	0.01	0.05	0.04	0.05	0.21
Russia	Na	1.03	1.12	Na	Na	0.08	0.29	0.59
Saudi Arabia	Na	0.79	Na	Na	Na	0.05	0.05	0.22
Sudan	0.86	1.64	Na	0.01	0.07	0.08	0.03	0.48
Turkey	0.32	Na	0.37	Na	Na	0.02	0.04	0.48
USA	0.54	0.24	0.39	0.01	0.06	0.02	0.04	0.36

Calculated using equation 6 and crop yield data in Table 3. Land requirement varies with local conditions

Na not available

For instance, a farmer wanting to use treated water to irrigate crops can identify COCs and set target concentrations for the post-treatment water using the guideline concentrations for irrigation. Design and construction of the treatment system can then be based on achieving those target concentrations. Following the treatment, concentrations of COCs can be compared to guideline values to determine if the water can be used for the intended purpose.

In the decision-making process, guidelines for water use developed by one country may not be suitable for another due to the limitations such as technology and economic status (Asano et al. 2007). Without compromising the safety of organisms within the receiving system, guideline values may require adjustment based on case-specific treatment goals and the available technology. Many countries have adopted and/or modified water quality guidelines outlined by the World Health Organization (WHO). Recently, the WHO has made modifications to their proposed guidelines for the reuse of water in agriculture based on the findings from epidemiological studies and quantitative microbial risk assessments (Brissaud 2008). To determine water quality guidelines, the WHO takes into account the cost of water treatment prior to reuse as well as health risks (Asano et al. 2007). Both cost and health risks largely determine the potential beneficial use of

Table 10 Example of applying water use guidelines (Table 2) to decision analysis for potential water use purposes

Constituent	Concentration	Irrigation	Water use purpose		Drinking
			Livestock	Aquaculture	
Pre-Treatment					
Cadmium	0.312	No	No	No	No
Copper	0.703	No	No	No	Yes
Lead	0.744	No	No	No	No
Zinc	5.180	No	Yes	No	No
Post-Treatment					
Cadmium	0.008	No	Yes	No	No
Copper	<0.010[a]	Yes	Yes	No	Yes
Lead	<0.015[b]	Yes	Yes	No	No
Zinc	0.367	Yes	Yes	No	Yes

Pre-treatment and post-treatment natural gas storage produced waters (NGSPW) are compared

Yes meets criteria for use (i.e. below guideline concentration)

No does not meet criteria for use (i.e. exceeds guideline concentration)

Concentrations (mg/L) are for NGSPW simulated to represent actual produced waters (freshwaters) in a study of a pilot-scale constructed wetland treatment system (Johnson et al. 2008)

[a] Measured concentration below detection limit (0.010 mg/L)

[b] Measured concentration below detection limit (0.015 mg/L)

Table 11 Recommended crops based on crop yield per 1,000 m^3 (264,172 gal) water volume during one crop growth period

Country	Recommended crops
Australia	Tomatoes, sugarcane, potatoes, lettuce, onions (dry)
Brazil	Tomatoes, sugarcane, potatoes, sweet potatoes, cassava
Chad	Sugarcane, onions (dry), potatoes, cassava, sweet potatoes
China	Watermelons, sugarcane, lettuce, tomatoes, sweet potatoes
Egypt	Lettuce, sugarcane, tomatoes, watermelons, onions (dry)
India	Sugarcane, potatoes, lettuce, sweet potatoes, cassava
Indonesia	Sugarcane, potatoes, tomatoes, sweet potatoes, cassava
Italy	Tomatoes, watermelons, lettuce, potatoes, onions (dry)
Japan	Tomatoes, watermelons, onions (dry), potatoes, lettuce
Mexico	Lettuce, sweet potatoes, sugarcane, tomatoes, potatoes
Russia	Onions (dry), tomatoes, potatoes, watermelons, maize
Saudi Arabia	Tomatoes, onions (dry), watermelons, potatoes, barley
Sudan	Sugarcane, watermelons, sweet potatoes, tomatoes, potatoes
Turkey	Tomatoes, watermelons, lettuce, potatoes, onions (dry)
USA	Tomatoes, lettuce, potatoes, onions (dry), watermelons

Crops listed starting from crop having greatest yield per 1,000 m^3 water volume

the treated water. Because of these factors, the guideline values from the WHO may be less stringent than values from other sources.

Water quantity for reuse

The following were calculated from crop water requirement (CWR) and average crop yield as explained in the Methods: (1) water volume required to grow one hectare of crop; (2) crop yield per 1000 m^3 water; (3) total water volume required per metric ton of crop produced; (4) daily water volume required per metric ton of crop produced; and (5) land area required per metric ton of crop. CWR varies by climate and is independent of soil characteristics. Average crop yield depends upon the factors such as farming practices, use of pesticides, fertilizers, and soil conditions. These factors differ among countries and may be related to infrastructure, technological development, and economic stability. Most average crop yields are greater in developed countries than in less developed countries, which results in greater total water volume (m^3) required per metric ton of crop production in the less developed countries. Qadir et al. (2007) noted that the average volume of water needed to grow cereal crops in developed countries is less than that required in developing countries. Two (Chad and Sudan) of the 15 countries studied are among the least developed countries (LDCs) according to the United Nations (UN 2011). As an example from the results of our study, CWR for wheat in Egypt is approximately equal to that in Chad (Table 4), whereas average crop yield for wheat is 61,271 hg/ha in Egypt and only 18,767 hg/ha in Chad (Table 3). The difference in average crop yield results in a much greater calculated volume of water

Table 12 Approximate water volumes and approximate land area required for growing one metric ton of selected crops in United States of America (USA)

Crop	Duration of crop growing period (days)[a]	Total calculated water volume required (m^3)	Daily water volume required during crop growing period (m^3/day) (gal/day)[b]		Land area required (ha)[b]
Barley	160	702	4.4	1,162	0.31
Lettuce	107	87	0.8	211	0.03
Maize	152	489	3.2	845	0.12
Millet	122	2,143	17.6	4,649	0.59
Onions, dry	180	108	0.6	159	0.02
Potatoes	140	106	0.8	211	0.02
Rice (paddy)	165	1,275	7.7	2,034	0.15
Seed cotton	202	2,535	12.5	3,302	0.54
Sorghum (grain)	135	782	5.8	1,532	0.24
Soybean	118	1,869	15.8	4,174	0.39
Sugarcane	500	130	0.3	79	0.01
Sweet potatoes	137	286	2.1	555	0.06
Tomatoes	157	70	0.4	106	0.02
Watermelons	95	126	1.3	343	0.04
Wheat	160	849	5.3	1,400	0.36

Values obtained from Tables 7, 8, 9

[a] Approximate total time of growth includes all growth stages; can vary widely due to local conditions. After Allen et al. (1998)

[b] Depends on local conditions

required per metric ton of wheat produced in Chad (3,032 m^3) than in Egypt (930 m^3) (Table 7).

Based on calculated crop yield per 1,000 m^3 water volume required (Table 6), crops are recommended for the most effective utilization of water for each of the 15 countries examined (Table 11). Recommended crops included cassava, lettuce, maize, onions (dry), potatoes, sugarcane, sweet potatoes, tomatoes, and watermelons. Potatoes and tomatoes are the most commonly recommended crops (Table 11) because they require the least amount of water to grow based on our analysis.

As an example of application to a specific country, calculated estimates of land and water requirements for growing specific crops in the United States are listed in Table 12. Using the calculation approach followed in this study, the land area needed and the water volume required to grow specific crops in other countries can be estimated, and a table similar to Table 12 generated for the use in decisions regarding crop selection and water use. Local conditions (weather, soil, etc.) and agricultural practices (fertilizers, pesticides, mechanization, etc.) influence crop yield (Tolk et al. 1997) and should be considered in decision analysis. Other local variations that can affect crop yield include water losses, such as infiltration and runoff (Tolk and Howell 2008).

Conclusions

Water quality guidelines were compiled for application to decision analysis based on water characteristics and reuse in irrigation, livestock, aquaculture, and drinking. The results can be used as a screening tool for water reuse. Specific applications to decision analysis include identifying COCs, determining target concentration levels for the COCs, and assessing suitability of treated water for reuse.

An approach to assessing water quantity for decision analysis was investigated for application of water reuse, and calculations for selected crops and countries were made to illustrate this approach. The quantity of water needed for crop production was calculated to give an estimate of the potential yield from reusing treated water for irrigation. The approach developed can assist in crop planning based on water availability, as illustrated by calculations leading to recommended crops for several countries.

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