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.

Keywords Water use · Water quality · Water quantity · Guidelines · Crops · Decision support

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).

\[ ET_c = K \times ET_o \] (1)
Table 1 Compilation of water quality guidelines for irrigation, livestock, aquaculture, and drinking

| Parameter      | Irrigation | Livestock | Aquaculture | Drinking |
|----------------|------------|-----------|-------------|----------|
| Aluminum       | 5<sup>c,e,h,j,k,p</sup> | 5<sup>c,h,k,p</sup> | 0.005<sup>3,j,6</sup>, 0.1<sup>8,j,6</sup> | 0.05–0.2<sup>2</sup> |
|                |            |           | 0.01<sup>1,2,3</sup>, 0.03<sup>8,d</sup> |          |
|                |            |           | 0.03<sup>3</sup> |          |
|                |            |           | 0.15<sup>6</sup> |          |
|                |            |           | 0.2<sup>1,12</sup> |          |
| Antimony       | –          | –         | 0.03<sup>3</sup> | 0.003<sup>2</sup> |
|                |            |           | 0.004<sup>2</sup> |          |
|                |            |           | 0.02<sup>2</sup> |          |
| Arsenic        | 0.1<sup>c,e,h,j,k,n,p</sup> | 0.025<sup>e</sup> | 0.005<sup>s</sup> | 0.007<sup>7</sup> |
|                |            | 0.2<sup>e</sup> | 0.05<sup>8,d,<i>r</i></sup> |          |
|                |            | 0.5<sup>k</sup> | 0.01<sup>1,h,l,o,q,u</sup> |          |
|                |            | 1<sup>b</sup> | 0.05<sup>3</sup> |          |
| Benzene        | –          | 0.01<sup>1</sup> | 0.3<sup>3</sup> | 0.001<sup>4,m,q</sup> |
|                |            |           | 0.37<sup>3</sup> | 0.005<sup>3</sup> |
|                |            |           | 0.01<sup>3</sup> | 0.0002<sup>1</sup> |
| Benzo(a)pyrene | –          | 0.00001<sup>i</sup> | 0.000015<sup>s</sup> | 0.00001<sup>4,m,q</sup> |
| Beryllium      | 0.1<sup>c,e,h,j,k,n,p</sup> | 0.1<sup>e,j,p</sup> | – | 0.004<sup>1</sup> |
| BOD            | 10<sup>e</sup> | –         | 15<sup>g</sup> | – |
| Boron          | 0.5<sup>c,h,k</sup> | 5<sup>c,h,k,p</sup> | – | 0.5<sup>s</sup> |
|                | 0.5–6<sup>o</sup> |           | 1<sup>1,i-q</sup> |          |
|                | 0.75<sup>n</sup> |           | 4<sup>m</sup> |          |
| Cadmium        | 0.0051<sup>n</sup> | 0.01<sup>h,k</sup> | 0.0002–0.0018<sup>h</sup> | 0.002<sup>m</sup> |
|                | 0.01<sup>c,e,h,j,k,n</sup> | 0.05<sup>3</sup> | 0.0002–0.002<sup>3</sup> | 0.003<sup>a</sup> |
|                |            | 0.08<sup>n</sup> | 0.003<sup>2</sup> | 0.000<sup>k,i,j,l,q</sup> |
| Chloride       | 100<sup>h</sup> | –         | – | 100<sup>b</sup> |
|                | 100–700<sup>p</sup> |           | – | 250<sup>i,l,m,q</sup> |
|                | 178–710<sup>i</sup> |           | – |          |
|                | 280<sup>o</sup> |           | – |          |
| Chromium<sup>12</sup> | 0.008<sup>n</sup> (VI) | 0.05<sup>1,1,j,p</sup> | 0.001<sup>k</sup>(VI) | 0.05<sup>s,j,m,o,q</sup> |
|                | 0.1<sup>c,e,n</sup> | 1<sup>e,j,k</sup> | 0.01<sup>s</sup> | 0.1<sup>i</sup> |
|                | 1<sup>1</sup> |           | 0.02<sup>k</sup> (VI) |          |
|                |            |           | 0.1<sup>r</sup> |          |
| Cobalt         | 0.05<sup>c,e,h,j,k,n,p</sup> | 1<sup>e,h,k,p</sup> | – | – |
| Copper         | 0.2<sup>c,h,k</sup> | –         | – | – |
|                | 0.4–5<sup>4</sup> |           | 0.002–0.004<sup>1</sup> | 1<sup>h</sup> |
|                | 0.2–1.0<sup>o</sup> | 0.5<sup>i</sup> | 0.002–0.005<sup>0</sup> | 1.3<sup>1</sup> |
|                | 0.4<sup>c</sup> | 0.5–5<sup>p</sup> | 0.005<sup>1</sup> | 2<sup>1,m,o,q</sup> |
|                |            |           | 0.006<sup>r</sup> |          |
| Cyanide        | 0.05<sup>s</sup> | –         | 0.005<sup>3,i,r,s</sup> | 0.05<sup>1,q</sup> |
|                |            |           | 0.07<sup>2</sup> |          |
|                |            |           | 0.1<sup>s</sup> |          |
|                |            |           | 0.2<sup>n</sup> |          |
| Fluoride       | 1<sup>e,j,k,n,p</sup> | 2<sup>e,h,k</sup> | 0.02<sup>s</sup> | 1<sup>h</sup> |
|                | 2<sup>e,h</sup> |           | 1.5<sup>1,m,o,q,u</sup> |          |
| Iron           | 0.2<sup>4</sup> | –         | 0.014<sup>b</sup> (II) | 0.1<sup>b</sup> |
|                | 1<sup>1</sup> |           | 0.5<sup>r</sup> | 0.2<sup>4</sup> |
|                | 5<sup>c,e,h,n,p</sup> | 1<sup>i</sup> | 0.3<sup>3,m,u</sup> |          |
Table 1 continued

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

| Parameter | Irrigation | Livestock | Aquaculture\(^{13}\) | Drinking |
|-----------|------------|-----------|-----------------------|----------|
| Thallium  | –          | –         | 0.004\(^{d}\)         | 0.002\(^{d}\) |
| Turbidity | 1\(^{h}\)  | –         | 25\(^{h}\)            | 1\(^{i}\) |
|           |            |           | 80\(^{f}\)            | 4\(^{g}\) |
|           |            |           | 5\(^{m}\)             |          |
| Uranium   | 0.01\(^{j}\) \(^{k}\) \(^{l}\) \(^{p}\) | 0.2\(^{k}\) | –                     | 0.015\(^{o}\) |
|           |            |           |                      | 0.02\(^{m,u}\) |
|           |            |           |                      | 0.03\(^{l}\) |
| Vanadium  | 0.1\(^{c}\) \(^{h}\) \(^{j}\) \(^{k}\) \(^{n}\) \(^{p}\) \(^{q}\) | 0.1\(^{j}\) \(^{p}\) | 0.1\(^{d}\) | – |
|           |            |           |                       |          |
| Zinc      | 1\(^{h}\)  | 20\(^{h}\) | 0.005\(^{d}\)         | 3\(^{m,o}\) |
|           | 1\(^{p}\) \(^{n}\) \(^{q}\) \(^{s}\) | 24\(^{e}\) | 0.005–0.05\(^{j}\)    | 5\(^{u}\) |
|           |            |           | 0.03\(^{s}\)          |          |
|           |            |           | 0.03–0.06\(^{s}\)     |          |

\(^{1}\) 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 Jampa 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), \(^{q}\) (CDWI 2006), \(^{r}\) (QGPEA 2006), \(^{s}\) (CCME 2007), \(^{t}\) (Wilson 2007), \(^{u}\) (CDW 2008).

where \(E_{Tc}\) is the crop evapotranspiration (mm/day), \(K\) is crop coefficient (dimensionless), and \(E_{To}\) is reference evapotranspiration (mm/day).

\(E_{Tc}\) 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). \(E_{To}\) 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:

\[ V_w = (CWR) \times (0.001 \text{ m/mm}) \times (10,000 \text{ m}^2) \]  

(2)

where \(V_w\) is water volume (m\(^3\)/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:

\[ CY = (C_y/V_w) \times 1000 \times (\text{kg/10 hg}) \]  

(3)

where \(CY\) is crop yield (kg/1,000 m\(^3\)), and \(C_y\) 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:

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

(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).
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 1). 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).

\[
A = (\text{Cy})^{-1} \times (10,000 \text{ hg/metric ton})
\]  

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;
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 g/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 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 | 206,707 | 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 | 7,097 | 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 |

nr = not reported  
hg = hectogram  
ha = hectare
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

| 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
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) 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 m³ (lettuce in India) to 19,980 m³ (sugarcane in Sudan) (Table 5).

### Table 5 Water volume (m³) 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      | 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)
The crop yield per 1,000 m\(^3\) (264,172 gal) 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 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    | 10,241      | 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     | 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
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...
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.

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

### 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      | 9.2     | 6.8   | Na     | 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     | Soybean | Sugarcane | Sweet potatoes | Tomatoes | Watermelons | Wheat |
|-------------|---------|-----------|----------------|----------|-------------|-------|
| DPG         | 202     | 118       | 500            | 137      | 157         | 95    |
| Australia   | 9.3     | 17.8      | 0.3            | 2.7      | 0.6         | 3.0   |
| Brazil      | 13.7    | 9.1       | 0.3            | 2.9      | 0.5         | 5.2   |
| Chad        | 70.7    | Na        | 0.4            | 15.1     | Na          | Na    |
| China       | 7.0     | 22.2      | 0.2            | 1.7      | 1.1         | 1.0   |
| Egypt       | 15.0    | 23.9      | 0.3            | 2.5      | 1.0         | 2.2   |
| India       | 40.9    | 34.9      | 0.3            | 2.0      | 1.9         | 3.8   |
| Indonesia   | 22.0    | 17.2      | 0.3            | 3.0      | 2.2         | Na    |
| Italy       | Na      | 12.8      | Na             | 2.7      | 0.7         | 1.1   |
| Japan       | Na      | 19.7      | 0.2            | 1.2      | 0.5         | 0.8   |
| Mexico      | 10.5    | 26.9      | 0.3            | 1.2      | 1.2         | 2.5   |
| Russia      | Na      | 33.3      | Na             | Na       | 1.9         | 7.9   |
| Saudi Arabia| Na      | 44.4      | Na             | Na       | 2.4         | 4.9   |
| Sudan       | 41.2    | 67.2      | Na             | 3.3      | 4.5         | 3.2   |
| Turkey      | 11.5    | 22.7      | Na             | Na       | 1.1         | 1.8   |
| USA         | 12.5    | 15.8      | 0.3            | 2.1      | 0.4         | 1.3   |

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.
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 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
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.
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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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                                      | 841                                            | 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
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