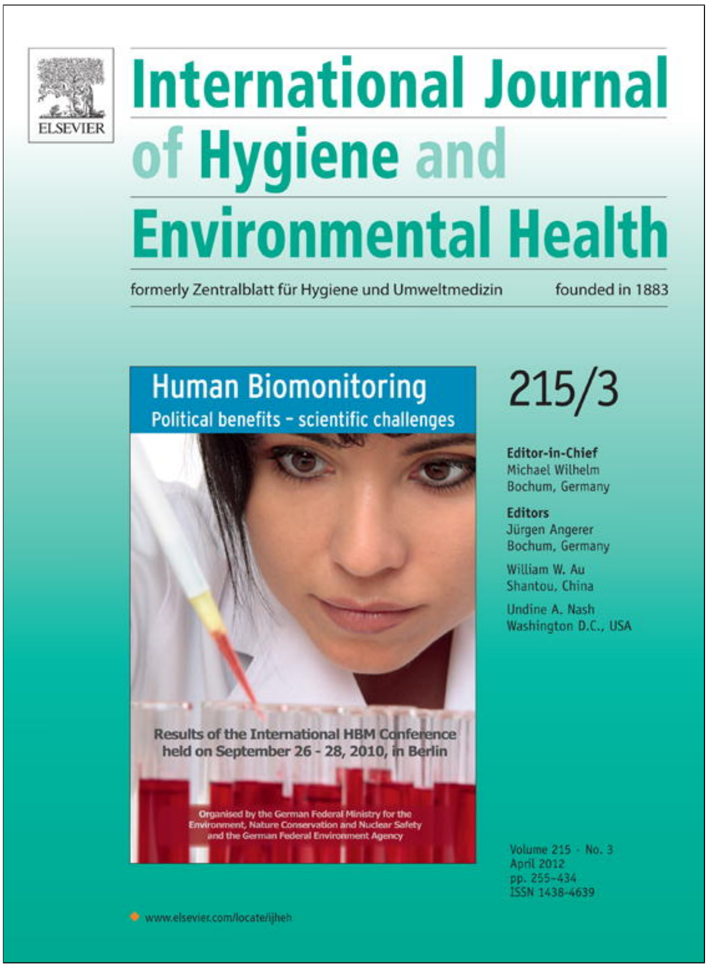
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Wastewater irrigation and environmental health: Implications for water governance and public policy

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ABSTRACT

Climate change is a large-scale and emerging environmental risk. It challenges environmental health and the sustainability of global development. Wastewater irrigation can make a sterling contribution to reducing water demand, recycling nutrients, improving soil health and cutting the amount of pollutants discharged into the waterways. However, the resource must be carefully managed to protect the environment and public health. Actions promoting wastewater reuse are every where, yet the frameworks for the protection of human health and the environment are lacking in most developing countries. Global change drivers including climate change, population growth, urbanization, income growth, improvements in living standard, industrialization, and energy intensive lifestyle will all heighten water management challenges. Slowing productivity growth, falling investment in irrigation, loss of biodiversity, risks to public health, environmental health issues such as soil salinity, land degradation, land cover change and water quality issues add an additional layer of complexity. Against this backdrop, the potential for wastewater irrigation and its benefits and risks are examined. These include crop productivity, aquaculture, soil health, groundwater quality, environmental health, public health, infrastructure constraints, social concerns and risks, property values, social equity, and poverty reduction. It is argued that, wastewater reuse and nutrient capture can contribute towards climate change adaptation and mitigation. Benefits such as avoided freshwater pumping and energy savings, fertilizer savings, phosphorous capture and prevention of mineral fertilizer extraction from mines can reduce carbon footprint and earn carbon credits. Wastewater reuse in agriculture reduces the water footprint of food production on the environment; it also entails activities such as higher crop yields and changes in cropping patterns, which also reduce carbon footprint. However, there is a need to better integrate water reuse into core water governance frameworks in order to effectively address the challenges and harness the potential of this vital resource for environmental health protection. The paper also presents a blueprint for future water governance and public policies for the protection of environmental health.

Backdrop

Global socio-demographic and environmental change poses unprecedented challenges to mankind. Drivers of global change such as climate change, population growth, urbanization, industrialization, and rising income, living standard, and water and energy demand will all characterize wastewater futures in the developing countries. These forces will be confounded by slowing productivity growth, falling investment in irrigation and agriculture worldwide, loss of biodiversity, risks to public health, soil salinity, land degradation, land use and land cover changes and water scarcity (Molden, 2007) as well as potential disruptions to virtual water trade (Wichelns, 2011). Future population growth and water scarcity pose significant risks to global food security (Hanjra and Qureshi, 2010). Population growth and water scarcity also drive the need to reuse wastewater for irrigation and other uses in many countries (Scheierling et al., 2010). For instance, water scarcity is a major driver of farmer's willingness to use recycled water (Menegaki et al., 2007). Poor households often rely on this resource for their livelihood and food security (Ensink et al., 2004). They may accept the environmental and health risks due to the economic benefits of using wastewater for irrigation (Wichelns and Drechsel, 2011). Wastewater is both a resource and

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a problem (Rutkowski et al., 2007). It is a drought-proof, renewable supply of water that can keep water resources from shrinking and waterways from becoming polluted. For instance, fertilizer and energy cost savings arising from recycling of nutrients in the wastewater and the water content are a direct benefit to the farmers as well as to the environment. Wastewater irrigation can supply plant food nutrients inexpensively, mitigate water scarcity, save disposal costs, reduce pumping energy cost and thus minimise carbon emissions to the environment. Fertiliser availability is constrained in a resource-limited world. It is essential that phosphorus that sits in wastewater is recycled to avoid exhaustion of reserves of this unsubstitutable nutrient (Dawson and Hilton, 2011).

However there are negative health and environmental risks of wastewater irrigation that need to be addressed, such as excess nutrients (Kalavrouziotis et al., 2008), pathogens (Kazmia et al., 2008), saline salts and heavy metals (Li et al., 2009). These can negatively impact human health (Toze, 2006), biosafety (Feldlite et al., 2008), soil and groundwater resources (Khan et al., 2008a; Walker and Lin, 2008), and the natural and built environment (Rongguang et al., 2008). These can also result in negative consumer attitude towards the use of wastewater for irrigation. Research findings compiled from studies around the globe (Keraita et al., 2010) suggest that awareness of health risks is not high among farmers. However, 89% of the farmers interviewed in two case studies in Nepal linked untreated wastewater use with negative health outcomes, specifically skin irritations (Rutkowski et al., 2007). Wastewater governance issues, due to weak institutions and policy failures that plague most developing countries, compound these environmental and health risks (Asano and Levine, 1996).

In the future the volume of wastewater generated by domestic, industrial and commercial sources will continue to increase with population growth, urbanization, economic development and improvements in living standards. The demand for wastewater for irrigation will also continue to increase, especially by the millions of small farmers who depend on wastewater irrigation to produce high valued crops for urban markets. These farmers would have fewer alternative sources of irrigation water or livelihoods outside agriculture (Qadir et al., 2010). Improved management of wastewater use can offer positive-sum solutions in human welfare and the environment. Reliable estimates of future wastewater supply and demand are needed for better planning and risk management, but the limited information available on wastewater use and the informal agriculture that uses it makes future projections difficult (Asano and Levine, 1996). The fact that wastewater continues to be excluded from water accounting also adds to this difficulty (Arntzen and Setlhogile, 2007).

Concern about the sustainability of water use for feeding future human population is the strong motivation to understand the potential of wastewater use and nutrient energy recycling in irrigated agriculture. It may also provide useful information to develop various innovative governance strategies to meet the current and future water demand, and new approaches for adjusting to the urbanization and developing mega cities in Asia. The socio-economic benefits from wastewater use in agriculture have so far been inadequately differentiated and quantified. A better understanding of the positive and negative environmental health impacts of wastewater use in agriculture can lead to a better understanding of the significance of wastewater as a resource and can highlight implications of its use on livelihoods and social equity in developing countries.

This paper builds on our previous works (Hanjra, 2000a,b, 2001) – that were the basis of two working papers (Hussain et al., 2001, 2002) and a recent paper (Hanjra et al., 2011) that focussed on the economic valuation of biophysical and socioeconomic impacts of wastewater management in an age of climate change. This paper offers a perspective on drivers of global change such as population growth, urbanization, rising income and improving living standard, industrialization, and urban water demand to characterize wastewater futures in developing countries. Empirical evidence is presented on the benefits and risks of wastewater irrigation on crop productivity, soil resources, groundwater quality, aquaculture, property values, environmental health, public health, infrastructure constraints, social concerns and risks, and poverty and social equity. It also demonstrates that how wastewater management can reduce the water footprint and energy footprint of food production on the environment and offer the possibility to earn carbon credits. Future opportunities to address water scarcity and food security issues by beneficial use of wastewater in agriculture under changing climate are identified.

Wastewater as a resource

Wastewater is composed of 99% water and 1% suspended, colloidal and dissolved solids. Municipal wastewater contains organic matter and nutrients (N, P, K); inorganic matter or dissolved minerals; toxic chemicals; and pathogens (Asano et al., 1985). The pollutants belonging to the same category exhibit similar water quality impacts (NRC, 1996). The composition of typical raw wastewater (Table 1; Hussain et al., 2001, 2002; Carr et al., 2011) depends on the socioeconomic characteristics of the residential communities and number and types of industrial and commercial units, such that global demographic and economic change also has implications for environmental health protection and wastewater governance approaches. The paper does not discuss the agricultural wastewater or irrigation return flows.

Guidelines for wastewater reuse in agriculture – wastewater governance

Wastewater contains microbes and chemicals that pose risk to human and environmental health. Wastewater governance refers to the guidelines, regulations, policies and laws that have been developed to guide wastewater use for agricultural and other uses, and to minimize the risk to public health and the environment.

Microbial guidelines

Wastewater contains a high concentration of excreted pathogens such as viruses, bacteria, heliminth, and fecal coliforms (Abu-Ashour and Lee, 2000). Intestinal nematodes, including the human roundworm (*Ascaris lumbricoides*), human hookworm (*Anclyostoma duodenale* and *Necator americanus*), and the human whipworms (*Trichuris*), pose the highest risk. Communicable diseases such as cholera and typhoid fever can be transmitted by wastewater irrigation of vegetable crops, if consumed raw (Shuval et al., 1997).

To protect public health, WHO (1989) guidelines recommended no more than one viable human intestinal nematode egg per liter for *restricted irrigation*; plus no more than one thousand fecal coliform/100 ml for *unrestricted irrigation*. These guidelines were stringent (Shuval et al., 1997) and hence revised. The revised guidelines (Table 2; WHO, 2006a,b) are based on the target approach and tolerable burden of disease expressed as Disability-Adjusted Life Years. This approach gives developing countries greater flexibility in applying the guidelines through treatment and non-treatment options (WHO, 2006a,b). Future guidelines may bundle economic and social incentives with regulations to better protect public health. Too little emphasis on water quality requirements will lead to situations of unacceptable impact, while too stringent

Table 1
Composition of raw wastewater for selected countries.

Parameters	USA	France	Morocco (Boujaad)	Pakistan (Faisalabad)	Jordan Khirbet As-Mara
Biological oxygen demand (BOD)	110–400	100–400	45	193–762	152
Chemical oxygen demand (COD)	250–1000	300–1000	200	83–103	386
Suspended solids (SS)	100–350	150–500	160	76–658	–
Total potash and nitrogen (TKN)	20–85	30–100	29	–	28
Total phosphorous (TP)	4–15	1–25	4–5	–	36

Data source: Hussain et al. (2001, 2002) except for Jordan (Carr et al., 2011).

requirements will make treatment costs commercially non viable for low and middle income countries.

Chemical guidelines

Chemical guidelines were developed for the protection of public health and the environment (WHO, 2006a,b). Two approaches were used: preventing pollutant accumulation in waste receiving soil, and maximizing the soil's capacity to assimilate and detoxify harmful chemicals. The first approach sets numerical limits on pollutant loadings based on the principle of ecological sustainability; such limits are difficult to achieve for most poor communities. The second approach generates maximum permissible limits on pollutant concentration by taking into account multiple exposure pathways and pollutant transfer rates. Chemical guidelines will become more important in the future as industrialization growth will increase the proportion of industrial effluents in the developing countries. Also, the release of new microbiological and chemical substances such as estrogens, endocrine disrupters, and surfactants that cannot be removed by conventional wastewater treatment plants will pose additional risks to public health (Emmanuel et al., 2009).

Effluent guidelines for the protection of public health in Australia are outlined in Table 3 (DEC, 2004). It also outlines suggested levels of treatment and monitoring frequency which are a means of achieving endpoint microbial and chemical safety guidelines (ACT-AUS, 1997; ARMCANZ-ANZECC, 1996, 2000; EPA-NSW, 2004). Effluent irrigation policy guidelines for environment protection in Australia are outlined in Table 4. The environmental and health performance objectives of these two guidelines are (DEC, 2004): protection of surface waters; protection of groundwater; protection of lands; protection of plant and animal health; prevention of public health risks; resource reuse and recycling; and protection of community amenity (EPA-NSW, 1995a,b, 2004).

Benefits and risks of wastewater irrigation

Treated wastewater can be used for irrigation if public health and environmental protection concerns are fully addressed. Best management practices and supportive policy frameworks are necessary to minimize the risks. The socioeconomic benefits and costs of wastewater irrigation also need assessment to achieve ecologically sustainable development (Lutz and Munasinghe, 1994).

Since wastewater use has several benefits, a huge water volume would be utilized for various purposes such as industrial washing, water-cooling, toilet flushing, groundwater recharge, urban greenbelts, ecological rehabilitation, waterway restoration and creation of recreational waterfront. Again, the benefits and risks must be carefully evaluated. This section presents a summary of the benefits and risks of wastewater irrigation based on our previous work (Hanjra, 2000a,b, 2001) and its advanced version (Hussain et al., 2001, 2002). Our recent paper examined the basic biophysical and socioeconomic aspects (Hanjra et al., 2011); this paper extends the analysis to the environmental health and governance issues.

Crop productivity

Wastewater is widely used in agriculture in most developing counties because it provides additional water for crop production and is also a rich source of nutrients for crop growth. Wastewater is also more reliable than surface water and continual supply of wastewater from treatments plants and community sources enables the farmers to cultivate multiple crops through out the year, raising cropping intensity and output. Wastewater irrigation has a critical role in reducing water shortages and scarcity and maintaining crop productivity. Most crops give higher yield with wastewater irrigation; and reduce the need for chemical fertilizer resulting in net income gains to farmers.

The nutrients present in effluent which are most likely to be utilized by plants are N, P, and K. The P (∼10 mg/L) and K (usually low) in effluent are normally present at concentrations which are advantageous for plant growth. But plant nutrients in wastewater are available in concentrations and proportions that may not always be ideal for *direct* crop production and these proportions cannot be readily manipulated to suit crop nutrient requirements. Often,

Table 2
Health-based targets for treated wastewater use in agriculture.

Type of irrigation	Target for viral, bacterial and protozoa	Microbial reduction target for helminth eggs	Health protection measures
Unrestricted	$\leq 10^{-6}$ DALY per person per year (achievable by a 6–7 log units pathogen reduction)	≤1/L (arithmetic mean – determined throughout irrigation season for at least 90% of samples)	Wastewater treatment Health and hygiene promotion Chemotherapy and immunization
Restricted	$\leq 10^{-6}$ DALY per person per year (achievable by a 2–3 log units pathogen reduction)	≤1/L (arithmetic mean – as above)	Produce restriction Food handling and preparation Cooking foods Irrigation timings
Localized (e.g. drip irrigation)	$\leq 10^{-6}$ DALY per person per year	(a) Low-growing crops: ≤1/L (arithmetic mean) (b) High-growing crops: (include fruits trees, olives, etc. – no crops to be picked from the soil): no recommendation	Access control. Use of personal protective equipment. Intermediate host control Reducing vector contact (bed nets, repellents) Other site specific measures

Data source: WHO (2006a,b).
DALY is the Disability-Adjusted Life Years (expressed as per person per year).

Table 3
Wastewater reuse policy guidelines for the protection of public health in Australia.

Reuse option	Level of treatment	Reclaimed water quality	Monitoring <3 ML/year use	Remarks
Municipal with unrestricted public access: irrigation open spaces, parks, gardens, dust suppression, construction sites, ornamental water bodies	Secondary + pathogen reduction by disinfection, filtration or ponding	Thermotolerant coliforms <10 cfu/100 ml (median value) ≥1 mg/L Cl residual after 30 min or equivalent level of pathogen reduction pH 6.5–8.0 (90% compliance)	Weekly initially for 3 months, then monthly Weekly	Treatment systems using detention only do not reduce the coliform to <10 cfu/100 ml and are not suitable as sole means of pathogen reduction Salinity should be considered for irrigation
Municipal with restricted public access: Irrigation, dust suppression, firefighting	Secondary + pathogen reduction by disinfection, etc.	Thermotolerant coliforms <1000 cfu/100 ml	3 monthly	These guidelines are applicable with controlled public access, sub-surface irrigation and horticulture
Sub-surface irrigation for all purposes	Secondary	≥1 mg/L Cl after 30 min or equivalent pathogen reduction	Weekly	Irrigation during times of no public access
Horticulture	Secondary	Suspended solids or turbidity pH 6.5–8.0 (90% compliance)	Monthly Monthly	
Residential:	Secondary + filtration + pathogen reduction	Thermotolerant coliforms <10 cfu/100 ml	Weekly initially for 3 months, then monthly; at ownership change	Plumbing controls including maintenance plans, education of owner and operator Identification through purple color coding or marked – NOT FOR DRINKING
Garden watering Toilet flushing Car washing Path and wall washing		≥1 mg/L Cl residual after 30 min or equivalent level of pathogen reduction pH 6.5–8.0 (90% compliance)	Weekly Weekly	Guideline is based on the fact that the standard for primary contact recreation is 150 cfu/100 ml
Non food crops: Silviculture, turf and cotton, etc.	Secondary	Thermotolerant coliforms <10,000 cfu/100 ml PH 6.5–8.5	Monthly Weekly	Restricted public access Withholding period of 4 h
Fodder crops: Pasture and fodder for grazing animals (except pigs)	Secondary + pathogen reduction by disinfection or detention in ponds	Thermotolerant coliforms <1000 cfu/100 ml Disinfection systems pH 6.5–8.0 (90% compliance)	Weekly Weekly Weekly	Withholding period of 4 h for irrigated pasture. Drying of fodder. Helminth control. Grazing only where no ponding
Food crops: In direct contact with water (e.g. sprays)	Secondary + filtration + pathogen reduction	Thermotolerant coliforms <10 cfu/100 ml ≥1 mg/L Cl residual after 30 min or equivalent level of pathogen reduction pH 6.5–8.0 (90% compliance)	Weekly Daily Weekly	Minimum 25 days ponding or equivalent treatment (e.g. sand filtration for helminth control). NSW Health does not support reclaimed water use for salad vegetables if effluent is in contact with the edible part of the plant.
Food crops: Raw human food not in direct contact with water (e.g. use tricke irrigation) or sold to consumers cooked or processed	Secondary + pathogen reduction	Thermotolerant coliforms <1000 cfu/100 ml Biological oxygen demand/suspended solids pH 6.5–8.0 (90% compliance)	Weekly Monthly Weekly	Not for food crops consumed raw or direct. Crops must be cooked (>70 °C for 2 min), commercially processed or peeled before consumption Dropped crops not to be harvested from the ground
Ornamental waterbodies – restricted access	Secondary	Thermotolerant coliforms <1000 cfu/100 ml Disinfection systems	Monthly Weekly	Surface films must be absent
Aquaculture: Non-human food chain	Secondary + maturation ponds (5 days retention)	Thermotolerant coliforms <10,000 cfu/100 ml TDS <1000 mg/L	Monthly Monthly	Applies to aquaculture for non-human food chain
Aquaculture: Human food chain	Secondary + filtration Pathogen reduction	Thermotolerant coliforms <10 cfu/100 ml pH 6.5–8.0 (90% compliance) ≥1 mg/L Cl residual after 30 min or equivalent level of pathogen reduction	Weekly Daily	Toxicant, dissolved oxygen and salinity controls may be required
Indirect potable reuse: Groundwater recharge by spreading into aquifiers	Secondary + disinfection at least	pH Turbidity Coliform Cl residual	Daily Continuous Daily Continuous	Buffer distance is 30 m if spray irrigation Must meet drinking water standards after percolation through vadose zone

Data source: Adapted from various sources (ARMCANZ-ANZECC, 1996, 2000; ACT-AUS, 1997; DEC, 2004).
Note: In all types of reuse options, the applications rates must be limited to protect groundwater quality.

Table 4
Effluent irrigation policy guidelines for environment protection in Australia.

Parameter	Effluent standard	Effluent monitoring <3 ML/year use	Impact and monitoring
Nutrients	Balance excess nutrient with plant requirements	Initial and 6 monthly monitoring of effluent for P and N	Nutrient balance calculations must be done to determine N and P Excess nitrates in groundwater may render it unfit for livestock and domestic use. Nitrate is a health risk to humans at 10 mg N/L and animals at 30 mg N/L Groundwater should be monitored annually for nitrate
Total dissolved solids	500 mg/L	Initial and 6 monthly monitoring for TDS or EC	Due to poor leaching and drainage, salts may accumulate at the soil surface Periodically monitor soil salinity at suitable depth Groundwater quality to be monitored periodically
Sodium adsorption ratio (SAR)	<6	Initial monitoring of SAR	Soil clay structure can be damaged if ratios of sodium/calcium to magnesium, combined with salinity are high. This leads to permeability and aeration problems. Effluent with an SAR of >3 can cause structural damage Effluents with SAR >6 should only be used with caution Monitor soil structure and permeability to detect deterioration
Biochemical oxygen demand	Organic load ≤40 kg/ha/day	Initial monitoring of BOD	High organic loading reduce soil's infiltration. Annually monitor organic matter and soil structure to detect the deterioration
Acidity (pH)	6.5–8.5	See public health guidelines	Soil pH affects the availability of nutrients. Monitor every 5 years or if plant growth problems arise
Chlorine residual	<0.5 mg/L if runoff can enter receiving waters	Should be dechlorinated or held until Cl residual is <0.5 mg/L	Effluent should be either dechlorinated or held until the chlorine degrades to <0.5 mg/L. This guidelines is thus stringent than the public health guideline (Cl ≥1.0 mg/L)
Heavy metals and other restricted substances	Al 5.0 mg/L; CU, Pb, Mn, Ni 0.2 mg/L; Cr, Ar, Co 0.1 mg/L; Br 0.05 mg/L	Monitoring required only for effluents from industrial units	Monitoring of the top 100 mm of soil is required if effluent comes from industrial units. Although some metals are essential for plant growth, they are also toxic at high levels. This requirement should be seriously observed as most developing countries lack separate treatment systems for effluents from industrial units.

Data source: Adapted from various sources (EPA-NSW, 1995a,b, 2004).

satisfying one nutrient requirement may imbalance another nutrient level. Thereby a nutrient deficiency or oversupply may cause toxicity and adverse effects on crop yield. Wastewater can meet 75% of the fertilizer requirements of a typical farm in Jordan (Carr et al., 2011) but excess nutrients can also reduce productivity, depending upon the crop. Careful nutrient management is essential to reduce fertilizer costs and prevent a reduction in crop yield due to excess nutrients in wastewater.

Nitrogen may be present at concentrations ranging from 10 to 50 mg N/L. If the total nitrogen delivered via wastewater irrigation exceeds the recommended dose for the crop, it may stimulate vegetative growth but delay ripening and maturity and even cause yield losses. Nitrate in excess of plant requirements may also be carried through the soil to the groundwater causing environmental pollution (Akber et al., 2008; Bond, 1999). Review of global studies (Hussain et al., 2001, 2002) shows that treated wastewater can often be used for producing better quality crops with higher yields than fresh water irrigation. Irrigation with effluent can also lead to greater water use efficiency (Hassanli et al., 2009).

Irrigation with untreated wastewater as practiced in many developing counties poses a set of different challenges. For example, urea factory effluents are a rich source of liquid nutrients but through unregulated discharges they can adversely affect rice and corn yields (Singh and Mishra, 1987). Continued overloading of organic matter from food factories effluents may clog the soil pores and favour anaerobic microbiological growth in the soil due to aeration problems. Pests carried in the water such as nematodes may be carried to the land, needing additional pesticides to counter these additional pathogens. Pesticide effectiveness may also be affected due to high pH of the wastewater.

Farmers who passively use wastewater due to its provision via rivers are a more serious concern. The nutrient content of wastewater is recognized by most farmers, yet many continue to apply chemical fertilizers in recommended or excess quantities resulting in over-fertilization in Bangladesh (Mojid et al., 2010) and Pakistan (Ensink et al., 2004) with consequences for human and environmental health. Provisioning of information on the nutrient content through formal and informal channels remains a key challenge for determining the optimal fertilizer requirements.

Soil health

Municipal sewage effluent contains around 500 mg/L of TDS or an EC of 8 dS m^{-1}. Treated wastewater is even slightly saline (EC exceeds 2 dS m^{-1}). Prolonged use of saline and sodium rich wastewater has the potential to cause soil sodicity (Lal, 2009) to destroy the soil structure (Ghafoor et al., 2010) and affect productivity, making the land unsuitable for crop production in the long run. Irrigation water with an SAR of 3 has the potential to cause soil sodicity. Permeability and aeration problems can occur when irrigation water has an SAR above 6. Soil salinity and sodicity issue can be managed by adequate leaching, or the application of natural (green manure) or artificial soil amendments (gypsum). Wastewater irrigation may have long term impacts on soil quality which may reduce the market price of land. Thus, periodic monitoring of soil salinity levels is needed for effective and lasting effluent irrigation scheme (Weber et al., 1996).

Wastewater induced salinity may reduce crop production due to general growth suppression at the early seedling stage, nutritional imbalance, and growth suppression by toxic ions (Kijne, 2006). Some crops such as cucumbers are more sensitive than tomatoes.

Although some metals are essential for plant growth, many are toxic. For example, Boron, used in detergents is highly toxic to some plants (Vidal et al., 2000). Boron may also be present in domestic wastewater as it is commonly added to cleaning products such as laundry and dishwasher powder. Metals are a serious issue if effluent is derived from industrial plants.

Wastewater irrigation may lead to transport of heavy metals to fertile soils, affecting soil flora and fauna and may result in crop contamination. Some of these heavy metals may bio-accumulate in the soil while others such as Cd and Cu may be redistributed by soil fauna such as earthworms (Kruse and Barrett, 1985). Studies conducted in Mexico (Assadian et al., 1998, 1999), where wastewater mixed with river water has been used for crop irrigation for decades, show that polluted water irrigation may account for up to 31% of soil surface metal accumulation (Cd, Pb, Ni, Zn, Cr, and Co). Heavy metal concentrations in alfalfa were about five times less than the soil but posed no risk to animals or human health. Heavy metals from industrial effluents have contaminated the agricultural lands in People Victory Canal area in China (personal communication, 2011). Serious health impacts have forced the farmers to abandon paddy lands, with consequences for livelihoods and food security of the communities.

Overall, the impact of wastewater irrigation on soil resources may be mediated by a number of factors such as soil properties (Monnett et al., 1996); plant characteristics and cropping strategies (Kim and Burger, 1997); sources of wastewater (Degens et al., 2000); and water management strategies (Carr et al., 2011).

Groundwater quality

Wastewater irrigation can add excess salts and nutrients to the soil and these have the potential to affect groundwater quality through leaching below the root zone. The actual impact depends on a host of factors including depth to watertable, quality of groundwater, soil drainage, hydraulic conductivity, scale of wastewater irrigation, and agronomic practices (Khan and Hanjra, 2008). The depth to watertable may determine the magnitude of impact from nitrate leaching. In areas with shallow watertable (<2 m) and poor drainage, the effects of nitrate leaching on groundwater quality are likely to be higher than in areas with deep watertable and better drainage.

Groundwater is a major source of drinking water for communities in the developing world. Poor wastewater management practices have the potential to impair groundwater quality. All of the ten wells sampled within one km radius of a wastewater drain in Faisalabad, Pakistan contained total dissolved salt concentration higher than the maximum permissible limit for irrigation water (Hanjra and Hussain, 1993). Wastewater irrigation also has the potential to translocate pathogenic bacteria and viruses to groundwater (Asano and Cotruvo, 2004). The nitrate pollution of groundwater has serious economic, environmental, and public health implications. Hence the risk of groundwater pollution should be carefully evaluated in any wastewater irrigation initiative.

In Lugo, Spain, the principal sources of saline contamination of rural well and urban spring water are livestock farms and the municipal water supply network (Vidal et al., 2000). In the Greater Cairo region where untreated or primary treated wastewater has been used for irrigation since 1915, the long term impact has been a "decreasing impact on salinity of groundwater" (Farid et al., 1993). They also found evidence of coliform contamination of groundwater. Others (Downs et al., 2000) did not detect the influence of the practice on groundwater quality in Mexico. Where wastewater is used for drought mitigation through artificial storage and recovery of groundwater, the environmental guidelines must protect the quality of groundwater (Table 3) by addressing the issue (Bouwer, 1996; Khan et al., 2008b). For instance, municipal wastewater has been used for the recharge of groundwater in the Dan Region, Israel with positive environmental and economic impacts. The aquifer treatment system produced effluent of very high quality which is suitable for a variety of non potable uses including unrestricted irrigation, industrial, municipal, and recreational use (Kanarek and Michail, 1996).

Aquaculture

Fish and aquaculture is an important source of food and livelihood for the poor (Béné et al., 2009). Wastewater aquaculture may pose risks to public health as fish is often consumed directly after catch and any pathogens or heavy metals in the fish tissues would be ingested (El-Gohary et al., 1995). The fact that fish concentrate bacteria and other microbes (viruses and protozoa) in their intestines is, however, of greater concern to public health. Cross-contamination from the gut contents to the edible fish parts during unhygienic fish processing poses greater risk to consumers. Unhygienic fish processing can increase the levels of microbial contamination by 100-fold in the edible parts. A recent systematic literature review shows that food borne nematode infections were on the rise in areas where freshwater aquaculture is also increasing (Keiser and Utzinger, 2005).

Potential health effects can be avoided if wastewater is adequately treated before use for aquaculture (Feldlite et al., 2008). Fish feeding on nutrient rich wastewater can recycle and convert these nutrients into protein rich food. Farm, farmhouse, and domestic effluents can be used for integrated crop-aquaculture production to enhance water use efficiency, optimal resource utilization, and promote an environment friendly and ecologically sustainable farming system (Feldlite et al., 2008). Studies in Suez, Egypt (Shereif et al., 1995) show that wastewater treatment stabilization ponds can be used for growing fish with average yield as high as 5–7 metric tonnes/ha/year. Nutrient rich effluent from the fish ponds can then be used to grow trees and crops like barley, maize, beet root, and ornamentals. The health benefits from wastewater aquaculture may include, at least, the increase in protein supply and potential reduction in protein deficiency and malnutrition in developing countries (Verdegem and Bosma, 2009).

Property values

Wastewater related environmental pollution may affect property values in two ways. First, the discount for discomfort associated with odor, nuisance, noise, aesthetics, hazard, and poor hygienic conditions. Costs may include health risks and damage claims, clean up costs, loss of tax revenue, and legal liability for the municipality (Page and Rabinowitz, 1993). Residential properties located along a polluted stream have significantly lower property values than those along clean streams (Epp and Al-Ani, 1979). Pollution related beach closings in New Jersey reduced property values by a margin of about 23% (Sanchirico et al., 2000).

Second, depending upon the eventual use one might make of the polluted land its market value may be lower. Page and Rabinowitz (1993) estimate the impact of groundwater contamination with toxic chemicals on properties compared to adjacent properties with no contamination. Groundwater pollution negatively affected the value of industrial and commercial properties but not residential properties. Leggett and Bockstael (2000) show a 'significant and defensible' effect of fecal coliform levels on residential property values. Carson and Mitchell (1993) indicate a decline in price premium for declining water quality from boatable to swimmable to fishable such that people discount the risk of water pollution. Another example is the effect of wastewater induced salinity on land productivity, which affect land rent and sale prices (Renkow, 1993). Alternatively, wastewater availability might raise the value of the land because it will increase productivity (provide "free" fertilizer and provide irrigation water year-round) especially in water scarce areas.

Infrastructure constraints

Well functioning irrigation infrastructure is instrumental for improved performance of irrigation systems. Dysfunctional infrastructure can reduce the accessibility and reliability of water supplies, resulting in yield and income loss. Off-farm irrigation canals and supply channels may get clogged or chocked due to the practice of disposing waste materials into the channels. Dedicated wastewater conveyance systems are often lacking in most developing countries such that supply channels used for freshwater irrigation are also used for wastewater irrigation – a challenge for water laws and institutions. This dual use practice clearly conflicts with canal water irrigation scheduling apart from impairing the quality of fresh irrigation water that latter runs into the same channels. This is a serious social issue where irrigation water has multiple uses such as drinking, bathing and domestic use (Meinzen-Dick and van der Hoek, 2001). Wastewater irrigators are often free-riders and do not contribute towards the maintenance cost of the canals; they even have no obligation to participate in seasonal cleaning of surface water canals they make use for wastewater conveyance. This undermines collective action and limits the capacity of formal institutions and canal water user associations to provide well functioning canal irrigation infrastructure to its members.

Even in the developed countries there are difficulties to using a unique system for both fresh and wastewater. Hydraulic structures such as flume gates and gages may be damaged, resulting into more frequent maintenance and early replacement. Damage to on-farm irrigation infrastructure may result into higher costs and reduced profits. For instance, farmers in Jordan reported that drip irrigation emitters became clogged due to suspended solids, mineral precipitation or algal growth (Carr et al., 2011). This affected the life of pipes and emitters and necessitated earlier emitter replacement. Mineral precipitation is often due to the high pH of wastewater (Liu and Huang, 2009). High pH of wastewater also reduces the effectiveness of pesticides, and farmers cope by purchasing freshwater for pesticide mixing or by adding phosphoric acid to the irrigation water to lower the pH (Carr et al., 2011). Corrosion of metal structures in the irrigation network and reduced life span of irrigation equipment and additional operation and maintenance cost is likely to be an associated problem.

Environmental health

Ecological impacts associated with the increasing wastewater use for irrigation under the influence of global change are least understood. Surface drainage from wastewater irrigation schemes may contain excess nitrogen, phosphate, orthophosphate or organics causing eutrophication of receiving water bodies (Smith et al., 1999). Excess phosphorous may translocate to various parts of the ecosystem; excess nitrogen may accumulate in soils, translocate to surface water, enter the atmosphere via volatilization, or leach to groundwater. This causes imbalances in microbiological communities, and nitrogen enrichment which affects terrestrial ecosystems (Table 5; Hanjra, 2000a,b, 2001). These ecological effects can translate into environmental health issues. For example, reduction of dissolved oxygen can cause fish death and reduce food supply from fish. Loading of heavy metals may contaminate the ecosystem and affect the food chain, posing a higher risk to food safety and public health (Whitall et al., 2007).

Social concerns and risks

Impacts of wastewater irrigation may often be localized, but may assume social dimensions if they affect a large number of people. Wastewater irrigation having a negative effect on a farmer's health and productivity is an economic impact. But if majority of the farmers in the area are negatively affected, the economic impacts become a social issue due to wider consequences for income levels, health, and wellbeing of the community. Sensitive receptors of wastewater irrigation schemes and impacts that are of public concern are given in Table 6. Among the public concerns are the general concerns regarding wastewater irrigation that include nuisance, odor, poor environmental quality, poor hygiene, and reduced visibility during morning hours in winter. Social concerns include food safety, health and wellbeing, quality of life, and environmental degradation issues. Natural resource concerns include pollution of community water supplies, and loss of fish, wildlife, and protected species (Hussain et al., 2001, 2002).

Table 5
Effects of nitrogen enrichment on terrestrial ecosystems.

- Increased production of vascular plants
- Increased susceptibility of some plant species to disease, cold stress and herbivory
- Changes in plant and microbial community structure
  - Decreased dominance by legumes
  - Increased dominance by grasses
  - Decreases in symbiotic nitrogen fixing bacteria
- Changes in animal community structure
  - Increase in deer, wild boar, winter geese and swans, wood pigeons, and ducks
  - Decrease in quail, partridge, rabbit, hare, and open vegetation birds

Source: Authors, based on literature survey (Hanjra, 2000a,b, 2001; Hussain et al., 2001, 2002).

Public backlash towards the use of wastewater for irrigation may create business risks. For instance, Saudi Arabia imposed a ban on the import of some Jordanian fruits and vegetables during the early 1990s, based on concerns about the use of reclaimed water for irrigation (Carr et al., 2011). Such public concerns can be addressed through public education and awareness programs. Business risks and potential liability can be covered by insurance instruments.

Public health

Wastewater contains pathogenic microorganisms such as viruses, bacteria and parasites which have the potential to cause disease and impact human health. Protozoa and helminth eggs are most virulent and they are most difficult to remove by treatment processes; they are often implicated in a number of infectious and gastrointestinal diseases in developing and even developed countries (Shuval et al., 1997; Shuval, 2000). Except for the use of raw sewage for crop production, there have not been any documented cases of infectious disease caused by reclaimed wastewater use in North America or Australia (Weber et al., 2006) but investigations

Table 6
Sensitive receivers in wastewater irrigation schemes.

Sensitive area	Impacts of concern
Natural water bodies (e.g. rivers, lakes, streams, springs)	Water quality, aquatic ecosystems, related beneficial uses
Other waters (e.g. artificial water uses, drainage channels, small streams, farm dams)	Water quality, ecosystems, related beneficial uses
Domestic water wells used for household water	Water quality and household health
Town water supply bore	Water quality and public health
Hospitals, schools, playing fields, public open spaces, roads	Odour, insects, noise, water quality (pathogens, contaminants, etc.)
Environmentally sensitive areas (e.g. drinking water catchments, wetlands, native vegetation, heritage sites)	Water quality, ecosystems, soil and water nutrient status, protected species, biodiversity, heritage
Livestock, wildlife and crops	Pathogens, heavy metals, organic compounds

on public health effects of wastewater reuse in the Middle East and Mexico (Toze, 2006) provide mixed evidence.

Irrigation with untreated wastewater poses a greater risk to children and elderly (Alberini et al., 1996). For instance, irrigation with untreated wastewater leads to higher prevalence of ascariasis (Cifuentes et al., 2000) and hookworm infections among children (USEPA, 1998). An equivalent increase in fecal coliforms causing contamination of water sources poses a greater risk of diarrhea in infants (VanDerslice and Briscoe, 1993), than the contamination of potable water storage in-house, because family members are likely to develop immunity to pathogens commonly found in the house. Investigations on determinants of diarrhea disease in Jakarta (Alberini et al., 1996) also support these findings.

High concentrations of heavy metals in wastewater also pose a health risk when ingested in high quantities and can be fatal. Transfer of metals to humans through the food chain may have serious public health consequences. While a review of epidemiological studies on pathogenic disease transmission due to wastewater reuse is available (Shuval et al., 1997; Shuval, 2000) but there is, as yet, no comprehensive assessment of the risk of heavy metals to public health.

Public health risks will dominate the negative consumer attitude and decisions on consuming wastewater grown crops especially those grown on untreated wastewater and consumed raw. Risks from avian flu, mad cow disease, SARS and pandemics such as cholera and diarrhea will further heighten the risk associated with the consumption of wastewater irrigated crops. Extra risk factor may also be due to new wastewater regulations or marketing of produce, restrictions in access to markets and lower prices of the produce. Public policy for ensuring the safety of the produce and protecting consumer health will figure more prominently in the future but its integration with water policy and core water programs will pose immense challenges.

Poverty and social equity

Wastewater is a critical resource for livelihoods in peri-urban areas. More than 10% of the world's population consumes foods produced by irrigation with wastewater (WHO, 2006b). Wastewater irrigation in peri-urban neighborhoods acts as an epicenter of fresh produce supplies, on a daily and regular basis, to almost all towns and cities in India and Pakistan. About 60% of the vegetable supply in Accra, Ghana comes from wastewater agriculture that thrives in the fringes of the city. These wastewater epicenters also act as magnets that attract the poor and landless women and other workers either to work directly on the vegetable production farms or provide related support services such as processing and transportation. The epicenters are booming with wastewater agriculture that transforms the opportunity structure of the poor workers through employment and value addition. The benefits of wastewater irrigation are both direct and indirect. The direct benefits accrue due to more water for irrigation and inexpensive nutrients in wastewater, which together may result in higher cropping intensity, more cropped area, higher yield and production, additional employment, and enhanced food security for the local population (Hanjra and Gichuki, 2008). For instance, peri-urban areas that use wastewater for crop production also provide employment for women and other landless laborers. It also enables crop specialization and year-round production. Landless farmers who lease agricultural land for horticultural nurseries can afford a better standard of living for their families and contribute towards improving the quality of urban environment by supplying nursery plants for landscaping. Wastewater irrigation may have secondary or indirect benefits due to spin off at regional or national level. The indirect impacts of wastewater irrigation on employment, income levels and its distribution and social effects such as human capital and equity may be as equally important as the direct and immediate benefits. Often, the indirect benefits are several multiples of the direct benefits such that every dollar generated in direct income creates several dollars through indirect spin-off effects.

The studies on the socioeconomic impacts of wastewater reuse for crop production are rare. The least examined are the indirect impacts. Future research is needed to explore the impacts of reuse on poverty and social equity, with the aim of identifying how farmer involvement can be enhanced for inclusive wastewater governance.

Empirical evidence

Economic analysis of wastewater irrigation can be done from the perspective of a municipality (treatment cost minimization goal); a farmer (profit maximization objective); a region (income maximization goal); the environment (minimizing environmental impacts); and the ecosystem (minimizing ecosystem impacts) as outlined in our previous works (Hanjra, 2000a,b, 2001) and its advanced version (Hussain et al., 2001, 2002). This section extends that analysis. An analysis that considers comprehensive direct and indirect impacts across spatial, temporal and human scales has yet to be done.

Economic benefits of wastewater irrigation

There is quite dated literature on various aspects of economics of wastewater irrigation (Martijn and Redwood, 2005; Qadir et al., 2010; Raschid-Sally et al., 2005). Young and Epp (1980) show that costs of land based treatment depend on the degree of pretreatment, pumping costs, land rent, annual application rate, type of crops, and regulation governing wastewater reuse. Crop selection strongly affects the revenue, returns, and economics of the system. Alfalfa and corn have high return; forest plantations have lower nutrient removal rates and revenue, but can utilize year round wastewater supply. Wastewater can be used for growing pulpwood such as eucalyptus on public lands, along canal banks and roads (Ramlal et al., 2009); such plantations serve as natural air conditioners and greenhouse gas sinks to clean urban environment and improve its amenity value (Luttik, 2000). As forestry is included in the Kyoto Protocol emission reduction targets, such plantations can also earn carbon credit and provide additional income to communities.

Dinar and Yaron (1986) used a long run mathematical programming model to maximize regional income. Farmers can optimize income only if a subsidy was provided for wastewater irrigation to cover high transportation cost. The regional benefit was optimized at 50% subsidy. All entities, such as farmers, town, environment, and water ecosystem benefit from participating in the regional cooperative solution.

Linear programming model to maximize farmer's income in the Tyre region, Lebanon (Darwish et al., 1999) shows that the least to most profitable options were sea disposal, using wastewater on existing cropping pattern, and new cropping pattern. A dynamic model was used to determine the optimal cropping system capable of using all effluent water, recycle nutrients, and maximize revenue in Lubbock, Texas (Eduardo et al., 1996). Alfalfa, wheat-corn, wheat-grain sorghum, and cotton were crop combination to maximize net revenue. It also reduced the routine municipal treatment costs.

Social value

Wastewater irrigation has social aspects such that the costs and benefit extend beyond the scheme. A risk assessment model was used to predict the changes in water and soil quality (Scott

Table 7
Overall net profit of a water exchange scheme in Llobregat Delta of Spain.

	€ million/year
Costs	
Wastewater treatment	0.59
Wastewater conveyance	0.21
Freshwater conveyance	0.81
Total costs	1.61
Benefits	
Cost savings in water abstraction	0.06
Cost savings in fertilizers	0.01
Increase in yields	0.39
Farmers benefit	0.46
Value of released freshwater	8.13
Net benefits to the city	6.52
Overall net benefits to stakeholders	6.98

Data source: FAO et al. (2010).

et al., 2000) and to evaluate the economic value and risks of long term use of urban wastewater for crop irrigation in Guanajuato, Mexico. Field survey and simulation results show irrigation with raw wastewater results in higher salinity and soil coliforms. Cost savings on fertilizer and its application charges were a measure of nutrient value. Wastewater was shown to be a valuable resource for the community and reuse was a more economic alternative to expensive treatment (Scott et al., 2000). Case studies from Ghana, Bolivia, Pakistan, Tunisia and Mexico show (Martijn and Redwood, 2005) that farmers using wastewater in developing countries are often limited in adopting safeguards for human, animal and environmental health and in making beneficial use of water and nutrients.

Sharing responsibilities and costs across stakeholders can enhance the social value of wastewater reuse (Qadir et al., 2010), for instance through water exchanges. The social value of freshwater that can be saved and released for other human usage through the reuse of wastewater in agriculture can be a conduit for 'win–win–win' partnerships among farmers, industry and cities. To show the value of wastewater under water scarcity, a case study in Llobregat Delta of Spain quantified the overall net profit of a water exchange scheme, with farmers being compensated for using reclaimed water while 'releasing' high value freshwater for urban use (Table 7; FAO et al., 2010). The total costs were estimated at €1.61 million/year whereas total farmer benefits were €0.46 million/year, such that if only farmers pay the costs the reuse project would not be justified. If the value of freshwater released is accounted, the reuse project was fully justified with a net benefit of €6.98million/year (FAO et al., 2010). The city can pay the costs and still have a net benefit of €6.52 million/year, while farmer benefits are 0.46 million/year, a win–win situation for the stakeholders (Heinz et al., 2011). This approach can be potentially applied in many middle-income countries and in water-scarce areas with high value of water.

Aside these, there are also other social benefits such as the value of ecosystem services and carbon credits. For a community in the Venice Lagoon watershed in Italy, semi-natural wetlands have a development cost of €1.39–€1.75 million, whereas traditional treatment plant cost range from €2.0 to €2.50 million (Mannino et al., 2008). These constructed ecosystems effectively reduce BOD, nitrogen, and pathogens in secondary treated wastewater, and attract many wildlife species, thus improving habitat quality and wildlife biodiversity. Another example is that the cattail produced with wastewater in wetlands can be harvested and burned as a renewable bioenergy source, to displace the use of coal, thereby reducing greenhouse gas emissions and also producing the possibility for carbon credits (IISD, 2011).

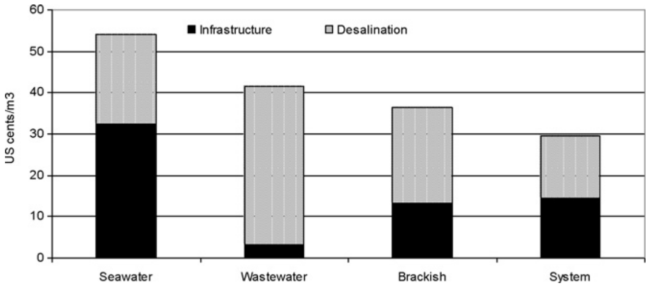

Fig. 1. Costs of water treatment in the Emek Heffer area in Israel.
Data source: Haruvy et al. (2008).

Global change and wastewater futures

Deriving beneficial uses from treated municipal and industrial wastewater is a thesis that will be strongly repeated during the future decades. Optimizing the benefits from wastewater uses entails minimizing the risks to public health and the environment and maximizing the benefits from its productive uses. The projected socioeconomic impacts will present significant challenges for affected communities and societies, particularly the wastewater dependent poor farmers in peri-urban and rural areas (Wichelns and Drechsel, 2011), who in many developing countries are already highly dependent on wastewater irrigation and vulnerable to changing political and socioeconomic circumstances, regionally and globally. Future water governance and policies must mainstream these issues by adopting core water programs to current and emerging challenges.

Future socio-economic impacts and vulnerabilities

Global population doubled during the last half century and is projected to increase by 50% by 2025. Much of the future population growth will come from the developing world; the proportion of the population living in cities will reach 50% for the first time (UNDP, 2007). Population growth, urbanization, industrialization, migration and urban economic growth will continue to increase urban water demand in the developing world. With municipal wastewater generation at about 75% of the supply, wastewater treatment infrastructure will come under intense pressure. With worsening water scarcity and higher urban water demand, wastewater recycling and reuse will be seen as an important water conservation and environmental management strategy. This also acknowledges that recycling is already a fact in many situations. Treatment and social incentives are the need.

Another issue that is not sufficiently addressed in water policy is the infrastructural requirements for conveying and delivering treated water to irrigable land. This could lead to feuds among farmers for the right to use wastewater and freshwater conveyance infrastructure for that purpose (Weckenbrock et al., 2011) and the potential social cost of water litigation is quite high. Often the infrastructure costs are a small component and offer high returns to public investments. For instance, the analysis of costs of treatment in the Emek Heffer area in Israel, Fig. 1 (Haruvy et al., 2008) shows that average wastewater treatment costs are lower than seawater desalinisation, and in particular the infrastructure costs are the lowest. The infrastructure may be the bottleneck for recycling wastewater for irrigation use. Alternatively, increasing treatment intensity, wastewater could be recycled for domestic use, reducing conveyance costs.

It is also not clear where in the hydrological framework wastewater should be set if integrated water resources management is advocated. For instance, while most of irrigation water is used and consumed, most of domestic or industrial water is used but not consumed; therefore, depending on the hydrological context, wastewater may be reused unintentionally. In one study, Hyderabad city water balance was used for dynamic modeling (Rooijen et al., 2005), where water inflows from rivers and dams, city water use, and urban water use in irrigated agriculture were considered. Potentially lost freshwater irrigated area and potentially gained wastewater irrigated area were uniquely modeled to estimate the city water balance. It showed that wastewater irrigation offsets about half of the freshwater irrigated area lost due to higher urban water use. Such work could serve as an example of where in the hydrological framework wastewater should be set in the context of urbanization issues.

A recent global assessment of water reuse provides an understanding of common practices of reuse of treated wastewater for municipal and industrial uses, and agricultural and groundwater recharge. Treated wastewater reuse is estimated at 43% in Tunisia and 11% in major cities in Australia, while wastewater reuse may approach 10–40% of total water use in water scarce arid and semiarid regions in the Middle East and Africa and parts of China, India, Pakistan, and USA (Jimenez and Asano, 2008).

According to the Comprehensive Assessment of Water Management in Agriculture (Molden, 2007) wastewater irrigation is a global phenomenon especially around large cities in the developing world. In four out of every five cities surveyed, wastewater is used in peri-urban agriculture (Raschid-Sally and Jayakody, 2008). Across the 53 cities surveyed, with a total population of 166 million, about 0.5 million ha are cultivated and irrigated with wastewater by 1.1 million farmers having 4.5 million dependents. Worldwide an estimated 20 million hectares are irrigated with wastewater by 200 million farmers (Raschid-Sally and Jayakody, 2008). Over the next 50 years the regions that are likely to become more dependent on wastewater use and recycling include arid areas in Australia, mid-west US, Middle East specifically Israel and Jordan, South and Southeast Asian countries including India, Pakistan, Vietnam, and parts of northern China such as the Yellow River Basin. The scale of wastewater irrigation in the future is difficult to assess because the knowledge of current and projected future supply of wastewater is incomplete and because it is not clear how future policy and technology will respond to global change challenges.

Wastewater irrigation is a key livelihood strategy around many large and small cities in the developing world. Case studies in Pakistan show that around one-quarter of the local vegetable production came from wastewater irrigation (Ensink et al., 2004). Farmers using wastewater for irrigation have higher gross margins, lower expenses on fertilizer but face higher risk from helminth infections (Ensink et al., 2007). Field visits show that buying and selling of wastewater is emerging among peri-urban communities and the farmers in the Punjab province of Pakistan (personal observation; January, 2010). The rates charged for wastewater use were found to be at least as high as the water rates payable for canal water but the farmers benefit from higher reliability and year-round supply of wastewater as well as free nutrients. Wastewater agriculture supports millions of farmers in the proximity of large cities such as Faisalabad, Lahore and Gujranawala in Pakistan, and Kolkata (Gupta and Gangopadhyay, 2006), Mumbai and Hyderabad in India (Bradford et al., 2003), and many others in China, Mexico, and Vietnam.

Wastewater irrigation will become a more important strategy in future to address the twin issues of increasing water scarcity and competition in agriculture, and pollution of waterways and the environment at local and national levels. For instance, estimates show that without contribution from wastewater reuse the 2050 water demand in India cannot be met for any population growth scenario (Gupta and Deshpande, 2004). Once utilizable surface water and rechargeable groundwater are used and measures for conservation, recycling and reuse of water have been put in place the Indian Linking of the Rivers Project may not be necessary (Gupta and Deshpande, 2004) and potential deleterious effects on the environment could be avoided. However, it is not clear if Gupta and Deshpande (2004) consider the hydrological context to avoid double accounting.

Global change and socioeconomic factors will continue to drive wastewater irrigation in the future. Poverty and rural to urban migration will be significant drivers of peri-urban agriculture and hence wastewater use for irrigation in the future. Poverty tends to be highly concentrated as these areas act as magnets to attract the rural poor, and the migrants tend to engage in peri-urban agriculture to gain a meager income. Where municipalities will be unable to treat wastewater due to lack of infrastructure and resources, they are forced to dispose of the municipal wastewater into waterways which then serve peri-urban irrigation needs or flow to the natural hydrological system. Under this scenario the potential risks to public health and the environment will be substantial. In many situations there are significant governance related barriers to action that could exacerbate these risks, including a lack of accountability, unclear property rights and corruption.

Regulatory frameworks and governance measures will be needed for collection, treatment and reuse of wastewater. Enforcement of standards for reducing environmental risks and protecting public health will be crucial. From the perspective of human health risk, new micro pollutants such as estrogens, endocrine disrupters and surfactants should also be considered as quality guideline parameter besides the conventional ones (Furumai, 2008). In particular, the measures chosen for any given area will depend on the local situation and the expected nature of risks. As a result there are no one-size-fits-all solutions. Local public and wastewater managers must have sufficient flexibility and capacity to choose the most appropriate suite of management measures for their local situation. The current failure to fully implement wastewater management guidelines is likely to limit such capacity. With rapid urbanization and continued influx of rural poor to urban areas, the challenges to public policy seem immense.

Peri urban communities are more prone to poverty. They usually have inadequate access to basic amenities such as safe drinking water, and healthcare and this coupled with poor sanitation exposes them to a higher risk than the average urban dweller. Wastewater irrigation is often practiced by these same communities, exposing them to higher risk of pathogens and disease vectors. Nevertheless, the economic benefits from wastewater dependant agriculture are inadequately quantified. There is growing interest and need to quantify economic benefits to better understand the importance of wastewater as a livelihood strategy for poverty reduction and social equity in the developing world.

Climate change and carbon credits

Wastewater reuse and recycling of its nutrients in agriculture can contribute towards climate change adaptation and mitigation. Benefits such as avoided cost of freshwater pumping and energy savings, the savings in fertilizer use, and prevention of mineral fertilizer extraction from mines can reduce carbon footprint and earn carbon credits. Wastewater reuse in agriculture entails activities such as higher crop yields and changes in cropping patterns, which also reduce carbon footprint. For instance, the conversion of dry wheat farming areas into irrigated maize fields using reclaimed water and its nutrients almost doubles the atmospheric CO_2 uptake (Muñoz and Sala, 2007). It can also reduce water footprint of food production. For instance, the volume of irrigation water needed to cover the daily food and related requirements for one person is estimated at 2700 L/day (Molden et al., 2007). Whereas, the basic physiological requirement for daily drinking water have been established at about 2 L/capita/day. However, a

Table 8

Nutrient addition, energy savings and carbon emissions reduction when irrigating with treated wastewater in India.

Nutrient	Concentration (mg/L)		Fertilizer contribution (kg/ha)				Energy equivalent (MJ/ha)				CO_2 equivalent (tCO_2)			
			Irrigation A		Irrigation B		Irrigation A		Irrigation B		Irrigation A		Irrigation B	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Nitrogen	16	62	48	186	80	310	3175	12,302	5291	20,503	0.159	0.615	0.265	1.025
Phosphorous	4	24	12	72	20	120	149	896	249	1493	0.009	0.054	0.015	0.090
Potassium	2	69	6	207	10	345	67	2308	112	3847	0.004	0.138	0.007	0.231
Calcium	18	208	54	624	90	1040								
Magnesium	9	110	27	330	45	550								
Sodium	27	182	81	546	135	910								

Source: Authors own calculations, based on data on nutrient concentrations as shown.

Note: Irrigation A, at 3000 m^3/ha; irrigation B, at 5000 m^3/ha. Low/high refer to the concentration.

daily supply of 140–160 L/capita is considered adequate to meet all domestic needs (Gleick, 2003) – the actual 'depleted fraction' is so small that almost all of this water returns back for recycling or as wastewater. This means that the volume of wastewater generated by 18–20 persons might be enough to cover the daily food production requirements for one person, potentially reducing the water footprint of food. While the potential volume of wastewater that may be reused for irrigation depends on many factors, this example helps to illustrate this important point. A similar budget could be done for wastewater nutrients and its associated energy and carbon footprint reduction. In Table 8, we demonstrate this partial budget for a case example setting in India. However, comprehensive studies on energy budgets and carbon balances using life-cycle approach are required for assessing the full impact on carbon balances to guide public policy decisions on wastewater reuse in agriculture. This is important because carbon tax/pricing will increase costs and impact investment decisions. A recent study shows that carbon tax will have implications for water pricing and urban water system design (MacLeod and Filion, 2011). Therefore, there is a need to quantify the opportunities and trade-offs under the emerging climate change carbon credits regime.

Strategies and incentives for risk reduction along the exposure pathway

Wastewater reuse in agriculture can capture nutrients and reuse water but environmental health risks are substantial. There is a need to reduce environmental and health risks along the exposure pathway – households and business, wastewater treatment, irrigation, food production, harvesting and transport, and distribution and retail to food preparation and consumers (Wichelns et al., 2011). A better differentiation is required between developed and developing countries, i.e. those which can build on treatment (centralized or decentralized) and those where in 50 years from now treatment would still be outpaced by population growth (Scheierling et al., 2010). The 2006 WHO guidelines which do no longer insist on treatment where treatment is unlikely to provide the needed coverage and impact on public health in the years to come, like in most of SSA. The related policy implication addressing the common reality of wastewater irrigation without treatment and risk reduction along the exposure pathway is therefore much more important in the low-income countries (Wichelns and Drechsel, 2011).

While in some Asian countries, like Pakistan the wastewater literature refers with the term wastewater indeed mostly to raw wastewater transported in sewers, with or without treatment, the term is used elsewhere (SSA, India, South-East Asia) also for diluted wastewater or water farmers fetch from streams polluted with wastewater. This gives wastewater irrigation a different dimension as it makes it a common practice around every town and city for example in SSA where pollution levels change every kilometre. This situation of farmers already farming since decades along severely polluted rivers and streams and not in vicinity of a sewer also requires a different set of strategies and incentives for reducing the risks arising from wastewater irrigation (Drechsel and Said, 2011). The strategy must consider the limitations and opportunities in individual countries, as reflected in their level of economic development based on GNI/capita data as done by the World Development Report 2010 (Scheierling et al., 2010). For instance, in high income countries (66 countries, >$11,906 GNI/capita) such as Australia the policy guidelines for environmental and public health protection are based on level of treatment, regulations and crop restrictions as outlined in Table 3, for instance. In lower middle income countries (55 countries, $976–$3855 GNI/capita – such wastewater use countries are Bolivia, China, Egypt, India, Iran, Jordan, Morocco, Pakistan, Sudan, Syria, Tunisia, West Bank and Gaza. Where treatment is not economically feasible, crop restrictions could work if regulations can be enforced; in low income countries (43 countries, <$975 GNI/capita – key wastewater use countries are Sub-Saharan Africa except South Africa, Vietnam, and Yemen) (Scheierling et al., 2010) where regulations are weak and difficult to enforce, farmers and traders need to adopt a set of alternative safety measures such as voluntary industry standards and 'consumer safe' labelling of the produce to minimise the risks. Financial incentives could include access to affordable credit for farmers and vendors or input subsidies (Wichelns et al., 2011). Data from Ghana shows that up to 90% of the DALYs can be from the use of untreated wastewater could be averted through low-cost interventions at on- and off-farm levels (Drechsel and Said, 2011). Therefore, future strategies must go beyond financial incentives and consider education and social incentives (such as improved tenure security for farmers, preferential sale license for vendors, and implementing voluntary food safety assurance programs run by trained professionals) that could enhance the adoption of safety measures to reduce the risks along the exposure pathway from farmers to consumers (Wichelns et al., 2011). Thus there is a need to move beyond regulatory aspects to consider other aspects that are important for achieving a more integrated approach to agricultural wastewater use, including institutional and policy, technological, economic, financial, and social incentives to move the wastewater management agenda forward (Scheierling et al., 2011).

Future water governance and public policies

Information needs and communication obstacles in current water policy are substantial. Wastewater irrigation has yet to be mainstreamed in the core water policies and programs. Public management remains the predominant model (IWA, 2010), yet public–private partnerships are making the way to "mutual management" of water resources. Most of the responsibilities can be transferred to private operators (Table 9; IWA, 2010). A key strategy

Table 9
Responsibilities for water supply in selected countries.

	High income countries[a] (>$11,906 GNI/capita)								Middle income countries ($976–$11,905 GNI/capita)					Low income countries (<$975 GNI/capita)		
	Australia	Austria	France	Germany	Netherlands	S/Korea	Spain	USA	Bulgaria[a]	China	India	Bangladesh	Pakistan	Vietnam	Ethiopia	Zambia
Responsibilities which can be transferred to private operators: yes/no?																
Water service operation	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Customer relation management	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Tes
Equipment renewal	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Existing infrastructure renewal	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Main infrastructure extension	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	No	No	No	No	No
Research and development	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	No	Yes	No
Responsibilities which can be transferred to private operators: do they exist yes/no?																
Water service operation	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Customer relation management	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Tes
Equipment renewal	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes
Existing infrastructure renewal	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Main infrastructure extension	No	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	No	No	No	No	No
Research and development	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	No	No	Yes

Source: Authors.

[a] The data for these countries are taken from IWA (2010).

applicable to all water management in the future will be adaptive co-management – a systematic process that recognizes the importance of stakeholder participation, cooperation and communication/dialogue and aims to continually improve water and wastewater management policies and practices by monitoring and learning from the outcome of core water programs.

Adaptive co-management could also help stakeholders to respond and adjust to emerging pressures and take advantage of the opportunities created by climate change related water quality and scarcity issues. Traditional governance focused on hierarchical top-down policy formation and implementation by the nation state and the use of regulatory policy instruments are insufficiently flexible to meet the future challenges posed by the global change (Garland, 2008). Moreover policies in other sectors, specifically agriculture, public health, energy, population, and urban and resource development will continue to have significant impacts on wastewater use, requiring improved intersectional policy coordination that is difficult to achieve in the current top-down water policy making model. The wide range of new actors and interest groups who are expected to become involved in policy making all pose challenges for the policy design. These challenges can be met by new and hybrid model of policy governance that makes greater use of policy networks. Network governance embraces the participation of multiple actors in wastewater policy formulation and implementation, seeking mutual solutions to common problems (Garland, 2008). National water policies and programs are the core instruments of new governance model. Flexible mixes of policy instruments with potential for rapid international convergence on best practice are required. The goal of wastewater policy adaptation should be added to the existing economic, ecological and social goals of sustainable water management, and positive interactions between international regimes for sustainable water management should be facilitated. Future policies must not ignore the many drivers of wastewater that originate in other sectors: developments in agriculture such as use of wastewater for growing of biofuel crops and forest plantations for soil carbon sequestration, transportation, energy, and resource conservation, industrial structure, institutional structure, economic regulation and contracts, tariffs and subsidies, public policies for rural communities and even exogenous factors such as macroeconomic policies, global economic outlook, and implications of globalization can have dramatic effects on the incentives to reuse and recycle wastewater. Improving inter-sector policy coordination will be the first step; alongside funding must improve to better target investments to wastewater hotspots and reduce current shortfalls in funding. Despite the risk of negative interactions, it is important to look for synergies with international funding programs for meeting the future funding shortfalls and restore official development assistance to water and wastewater sector.

Despite these policy changes, the future wastewater management will be substantially different from the past. The blueprint will be a mosaic of opportunities and challenges. For instance, the gap between per capita water demand in developed and developing countries will narrow; dewatering of economic growth will slow down the water consumption rate in the former and accelerate in the latter (Rock, 2000). The problems of water scarcity and pollution will be faced increasingly in developing areas of the world (Tsuzuki, 2008). Coastal cities may resort to desalinisation to ensure drinking water supplies; with technology advance the desalinisation costs may become competitive with wastewater treatment for reuse (Srinivasan et al., 2010; Younos, 2005). Freshwater demand for blending with wastewater will increase. Water has traditionally been managed as a local resource. No more. Water will become a global resource, both physically and virtually traded in international markets, requiring policy responses at both macro and micro scales. In the future, increasing water scarcity will lead to increasing value being placed on all water resources, including wastewater. Water in the future will be traded more frequently, with price fluctuating according to supply and demand. Spot wastewater markets will emerge in many arid regions, allowing seasonal water trade, and facilitating the emergence of permanent trade in wastewater. National 'water exchanges' will become a common feature in all countries. Water companies will be increasingly listed on global stock exchanges, offering higher than the average market returns to investors. Water will be allocated to everyone according to his purchasing power. Dollarization of freshwater will impact access to water and sanitation for low income households but will invite stronger investor interest in wastewater treatment and management companies. Tapping private markets for investments in wastewater will be commonplace. Sharing of transboundary polluted water resources will pose new challenges to public health, social equity and environmental quality (Giordano, 2003). Incorporating equity in transboundary water sharing agreements may have political and legal ramifications for peace and stability in affected regions (Giordano and Wolf, 2001). Water polluting industries may largely relocate to border areas, worsening the quality issues in transboundary poor nations (Fernandez, 2002). Water conflict may percolate to every level and the risk of millions revolting could be in the making as water scarcity and quality issues intensify.

By 2010, about half of the global population is already living in urban areas. Wastewater will therefore become a more valuable resource to be used where it is created, in turn reducing pressure on bringing alternative water supplies to people. Improvements in water conservation technologies, which are currently poor, may reduce the quantity of wastewater that is available; in the future it might happen that the quantity of wastewater will be so small that it will not be worthwhile bothering about recycling it. For example, new technologies such as the Ecosave and WaterIndus can make high levels of purification possible at domestic and industrial scales, respectively, with the use of relatively low-tech devices (Garland, 2008). Most of the domestic wastewater will be recycled through dual retrofitting and rainwater tanks (and this is already happening in Australia and South Africa through public subsidy). Wastewater recycling and purification legislation will be promulgated, and in conjunction with this, policy and economic incentives will be triggered for the initial avoidance of pollution of otherwise clean water resources. Wastewater discharge fees, treatment fees, and water pollution charges will become common incentive mechanism to curb discharges and pollution in the first place. The emphasis will be on water cycle charges rather than water charges (IWA, 2010). Policies for wastewater reuse will embrace the concept of joint water usability, as it will become more and more necessary to link the water sector with other sectors (e.g. agriculture, health, sanitation, environment, energy and climate change).

The need to promote effective wastewater policies in developing countries will become an integral part of the solution to stemming the water scarcity crisis. Global wastewater stewardship as a global social responsibility to address the issue will emerge. Without secure water and food supplies, a global social disaster will become inevitable as water based conflicts may escalate to water wars in the future. Efforts to explore and secure water supplies beyond the Earth will intensify. The scale of wastewater reuse will need to be considered at micro and macro levels simultaneously to enhance water and food security. A dramatic rise in domestic water reuse and home grown food will reduce the pressure on global levels of supply and demand. It will also lower the pressure on public sewage and water purification systems and lessen the financial costs associated with the maintenance of these infrastructure. At the same time on a wider scale, action will be taken to recognize wastewater as a valuable resource, prevent pollution, and integrate the wastewater sector into the mainstream in order to maximize its potential use closer to the point of generation. Wastewater will become a social resource – important for societal wellbeing and environmental sustainability.

Summary and environmental health policy implications

In a resource constrained world, wastewater reuse and recycling of its nutrients is essential. Wastewater reuse environment protection policy should promote more effective and efficient use of available water resources by assisting the beneficial use of wastewater. It must also ensure that public health and environmental concerns are fully addressed. Limitations include: nutrient management, choice of crops, soil properties, irrigation methods, health risk regulation, land and water rights and public education and awareness. Wastewater governance must improve. Sharing of costs and responsibilities between wastewater producers, government institutions and farmers can enhance water use efficiency, crop production, and nutrient recycling while protecting public health and the environment. This requires economic, financial and social incentives in low income countries to reduce the risks along the exposure pathway from irrigator to vendors to consumers. Policy frameworks are needed for mainstreaming the wastewater into core national water programs to help protect public health and the environment. Irrigation with wastewater can also reduce the water footprint and energy footprint of food production, earn carbon credits and potentially contribute to climate change adaptation and mitigation. For that, wastewater should be mainstreamed into the core programs on climate change.

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