Available online at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/jes

JES JOURNAL OF ENVIRONMENTAL SCIENCES

www.jesc.ac.cn

Wastewater reclamation and reuse in China: Opportunities and challenges

Sidan Lyu[1,2], *Weiping Chen*[1,*], *Weiling Zhang*[1], *Yupeng Fan*[1], *Wentao Jiao*[1]

1. *State Key Laboratory for Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China.* E-mail: lvsidan01@163.com
2. *University of Chinese Academy of Sciences, Beijing 100049, China*

ARTICLE INFO

Article history:
Received 31 July 2015
Revised 26 November 2015
Accepted 27 November 2015
Available online 30 December 2015

Keywords:
Wastewater reuse
Urbanization
Policy
Integrated water resource management
Public acceptance

ABSTRACT

The growing water stress both in terms of water scarcity and quality deterioration promotes the development of reclaimed water as a new water resource use. This paper reviewed wastewater reuse practices in China, and the opportunities and challenges of expanding reclaimed water use were analyzed. Rapid urbanization with the increasing of water demand and wastewater discharge provides an opportunity for wastewater reuse. The vast amount of wastewater discharge and low reclaimed water production mean that wastewater reuse still has a great potential in China. Many environmental and economic benefits and successful reclamation technologies also provide opportunities for wastewater reuse. In addition, the overall strategy in China is also encouraging for wastewater reuse. In the beginning stage of wastewater reclamation and reuse, there are many significant challenges to expand wastewater reuse in China including slow pace in adopting urban wastewater reuse programs, the establishment of integrated water resources management framework and guidelines for wastewater reuse programs, incoherent water quality requirements, the limited commercial development of reclaimed water and the strengthening of public awareness and cooperation among stakeholders.

Introduction

Many countries around the world are facing the increasing pressure of fresh water supply and that fresh water resources are becoming insufficient to satisfy water demand. As urban water scarcity is growing and water purification technology is advancing, wastewaters are being reclaimed in increasing volumes and being reused for more purposes around the world (Levine and Asano, 2004). The highest-ranked countries of the total wastewater reuse are the United States and Saudi Arabia, and Qatar, Israel, and Kuwait are the most remarkable countries based on the per capita wastewater reuse (Jimenez and Asano, 2008). In the United States, Florida and California represent the largest use of reclaimed water, and landscape irrigation use of reclaimed water increased rapidly from 44% in 2003 to 59% in 2009 in Florida (Chen et al., 2013b). More than 92% of wastewater is treated in Australia with the worse water scarcity problems. There are 580 municipal wastewater treatment plants which treat 2 billion m^3 of wastewater per year, and 21% of treated municipal wastewater is reused including 14% for irrigation in Australia (United Nations Environment Programme, 2015).

There are many severe water resource issues such as fresh water scarcity and unbalanced distribution in China which is one of the 13 lowest water availability countries (Yi et al., 2011). At the same time, its water demand and pollution also

* *Corresponding author.* E-mail: wpchen@rcees.ac.cn (Weiping Chen).

http://dx.doi.org/10.1016/j.jes.2015.11.012

quickly increase with the rapid development of urbanization. Thus China has ambitious plans to promote wastewater reuse and make that reclaimed water becomes a key element of nationwide water resource management scheme. Since the 1980s, comprehensive wastewater collection and treatment systems and recycling of reclaimed wastewater started to develop gradually (Yi et al., 2011). In 2010, reclaimed water production and use rate were 12.1 million tons per day and <10%, and they were planned to be 38.85 million tons per day and 15% in 2015 respectively according to the 12th Five-year National Urban Sewage Treatment and Recycling Facilities Construction Plan. In addition, environmental and economic benefits of wastewater reuse such as decreasing pollutants emission, improving soil health and saving cost, can also promote the development of wastewater reuse in China (Fan et al., 2013; Chen et al., 2015a).

The successful development of wastewater reuse has the close relationships with the installation of wastewater treatment plant, integrated water resource management, economic and financial analysis and public acceptance. Because the additional treatment of wastewater beyond secondary treatment and installation of pipeline networks for reuse are needed, expensive capital cost is a very important issue of wastewater reuse implementation (Asano et al., 2007). Bixio et al. (2006) reported that integrated water resources management considered that wastewater reuse was still at its infancy in many regions of European, and suggested that related specialists should renew own knowledge to promote the implementation of more conscious and sustainable wastewater reuse. In addition, integrated water resources management should involve all stakeholders in the whole processes of water reuse operations (Asano and Bahri, 2011).

So far, wastewater reclamation and reuse level in China is not high on the whole, whereas the potentiality of wastewater reuse is huge. The objectives of this paper are to compressively analyze the current status of wastewater reclamation and reuse in China, and to summarize the opportunities and the challenges of expanding wastewater reuse, and then to put forth recommends for future wastewater reclamation and reuse in China and possibly other regions experiencing the similar situations.

1. Opportunities and drivers for wastewater reuse

Many driving forces can be identified in practices of wastewater reuse such as water scarcity, environmental and economic consideration as well as technology improvement. In China, urbanization and consequential water demand drive directly the development of wastewater reuse. Since the implementation of 'Reform and Opening-up' policy in 1978, China entered a period of rapid urbanization. The rapid urbanization aggravates water demand and wastewater discharge, resulting in decease of water environment and water supply, and then the decreasing of water resource inhibits the development of urbanization at some extent. Under the above situation, a worse cycle between urbanization and water resource is formed in many cities. Wastewater reuse which can increase water supply and reduce pollutant discharge into surrounding water bodies, provides a chance to unbuckle this cycle (Fig. 1). This positive cycle can alleviate water crisis and promote the development of cleaner production and circular economy. In addition, current technologies applied in wastewater reuse such as ultraviolet radiation, maturation ponds, membrane filtration and electrochemical treatment can remove effectively the pollutants including salinity, pathogens, heavy metals and emerging contaminants. The advanced wastewater treatment technologies greatly reduce the risks associated with wastewater reuse. According to the current policies, regulations and investments on wastewater reuse, wastewater reuse in China is expected to expand greatly in the following decades.

Five opportunities driving reclaimed water use in China are analyzed as follows.

1.1. Urbanization

Urbanization is a historical process of urban quantity increasing and urban scale expanding due to populations transferring and the secondary and tertiary industries gathering from rural to urban (Chen, 2002). As the population and economy scales are gradually closed to or more than water resources carrying capacity, the relationships between urbanization and

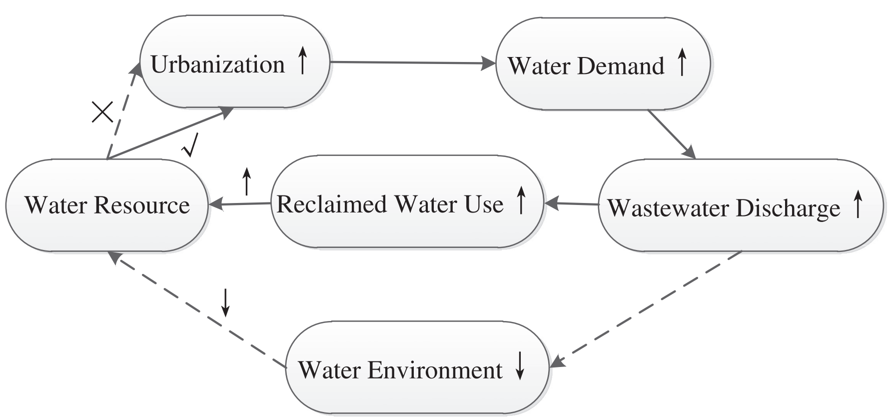

Fig. 1 – The relationship between urbanization and water resource. ↑ means increase, and ↓ means decrease. √ means the positive effects, and × means the negative effects.

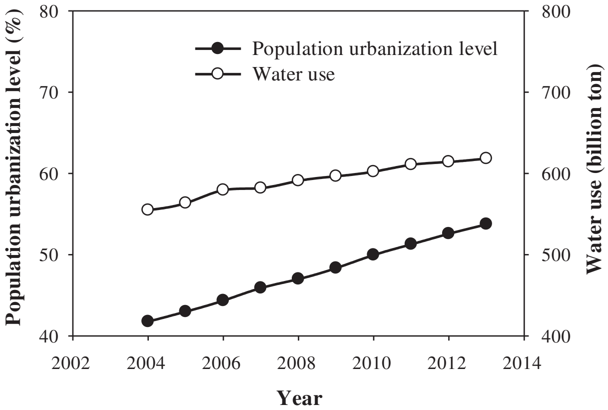

Fig. 2 – Population urbanization level (the ratio values of urban resident population and total resident population) and water use from 2004 to 2013 in China. Data are based on China Statistical Yearbook 2005–2014.

sustainable utilization of water resources are paid more and more attention to (Fitzhugh and Richter, 2004; Bao, 2014). Population urbanization level in China increased from 41.8% in 2004 to 53.7% in 2013, and the increasing rate every year was about 1.2% (Fig. 2). Based on China Statistical Yearbook, Gross Domestic Product (GDP) in China increased from 15,987.8 billion Yuan in 2004 to 56,884.5 billion Yuan in 2013. As the total population and economy increased, the total water use also increased from 555 billion tons in 2004 to 618 billion tons in 2013 (Fig. 2).

Some researchers think that the main reason of water crisis is the increasing of water resource demand caused by urbanization and the increasing of economy (Fitzhugh and Richter, 2004; Jenerette and Larsen, 2006). Ma et al. (2014) predicted that urbanization rate would be 60% in 2020 in China, and total water use would be 688 billion tons which exceeded the red line control requirements of total water use (670 billion tons). The current water resources carrying capacity could not support the rapid development of urbanization in China. However, rapid urbanization can stimulate the enhancement of water resource use efficiency as the development of economy and technology, and it provides a driver of wastewater reuse. For example, Beijing as the pioneer of wastewater reuse in China started to promote wastewater reuse in 2003 because of facing great water demand pressure from population increasing and economy developing. Its reclaimed water supply increased from 205 million tons in 2003 to 800 million tons in 2013, accounting for about 22% of the total annual water supply in Beijing (Beijing Water Authority, 2013).

In all, water resource has become a key factor of limiting urban development in many regions of China. By simultaneously creating an alternative water resource and reducing effluent discharges to the environment, wastewater reclamation and reuse are now recognized as key components of water and wastewater management by urban managers. Many cities are struggling to maximize the benefits of wastewater reuse, and the potential for wastewater reuse is vast.

1.2. Wastewater and reclaimed water production

Compared with the rapid development of urbanization, wastewater discharge increases proportionally. The total wastewater discharge in China increased from 48.2 billion tons in 2004 to 69.5 billion tons in 2013. Domestic wastewater charge increased from 26.1 billion tons in 2004 to 48.5 billion tons in 2013 (Fig. 3a). Based on Environmental Statistics Bulletin in 2013, there were 5364 municipal wastewater treatment plants, and the design treatment capacity of plants was 165.7 million tons per day. Municipal wastewater treatment plant operational cost increased from 7.37 billion Yuan in 2005 to 39.36 billion Yuan in 2013. The production of reclaimed water from municipal wastewater treatment plants increased from 1.3 billion tons in 2011 to 2.4 billion tons in 2013. The utilization ratio of reclaimed water decreased from 74.4% in 2011 to 63.1% in 2013, although the utilization amounts of reclaimed water increased. In all, while municipal wastewater treatment rate reached to 87.2%, the production of reclaimed water only was 5% of total domestic wastewater

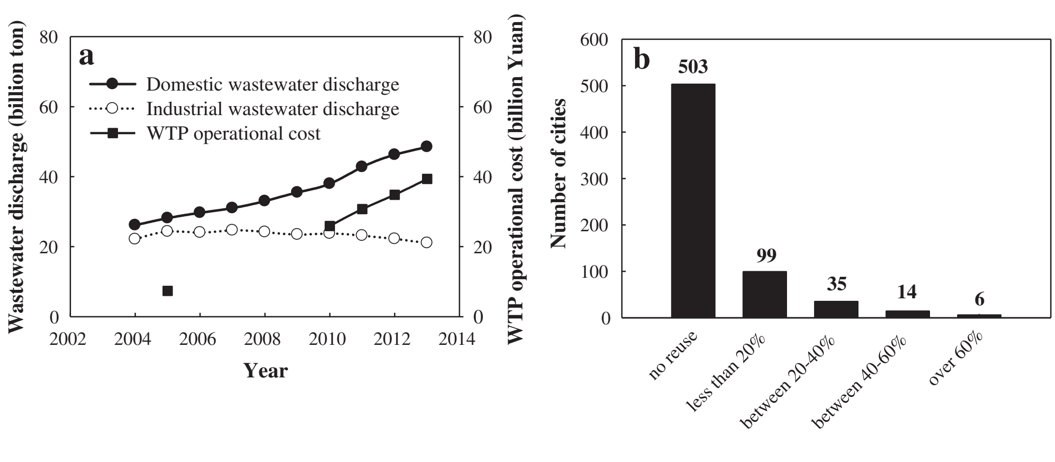

Fig. 3 – Wastewater reuse in China cities, (a) amounts of domestic and industrial wastewater discharge *vs.* wastewater treatment plants (WTP) operational cost; (b) number of cities with different reuse level. Data are based on Environmental Statistics Bulletin 2004–2013 and China Urban Construction Statistical Yearbook 2012.

in 2013. In this regard, there still has a great potential for domestic wastewater reuse in China.

Industrial wastewater discharge firstly increased and then decreased from 2004 to 2013, which might be attributed to the increasing of industrial water use efficiency and recycling rate (Fig. 3a). Based on China Water Resource Bulletin, the industrial water use recycling rate was about 80%, and water consumption per ten thousand Yuan industrial added value was 69 m^3 in 2012 which decreased by 64.8% compared with that in 2004. At present, industrial wastewater reuse level still in China is low, and most wastewater reuse is used for nonindustrial production such as washing floor, green space irrigation and flushing slag. During industrial production, a systemic engineering is necessary to integrate industrial wastewater reuse, cleaner production, resource recovery and the effluents of reaching water quality standard. The systemic engineering has the functions of saving water and decreasing pollutants emission, and it can also reduce the cost at a certain degree (Tong et al., 2013). In comparison to developed countries, there is still big development space for industrial wastewater reuse in China.

In general, the large increasing of wastewater discharge and treatment in the past decades provides a great opportunity for expanding wastewater reuse in China. However, the overall reuse rate is still low due to social, ecological and economic reasons.

1.3. *Environmental and economic benefits*

Reclaimed water is a treated effluent that is considered to be of appropriate quality for an intended water reuse application (Asano and Levine, 1996). Wastewater reuse stimulates the treatment efficiency of wastewater, and then it results in the decreasing of pollutants emission into natural environments. Roughly, the discharges of chemical oxygen demand (COD) and NH_4–N are reduced about 350,000 tons and 70,000 tons per year in China. When reclaimed water is used for irrigation, pollutants such as heavy metals and biochemical oxygen demand (BOD) can be decreased owing to purification and filtration functions of soil and plants.

Reclaimed water irrigation can improve soil fertility, and promote the growth of plants receiving reclaimed water. The concentration of total nitrogen in the secondary effluents is typically 10 to 20 mg/L (Chen et al., 2013a), which meets total annual nitrogen requirements of turf grasses between 10 and 28 mg/L recommended by Sevostianova and Leinauer (2014). In addition, most of the nitrogen and phosphorus in reclaimed water is found in forms that can be easily used by plants (Duncan et al., 2009). Soil enzyme activities with reclaimed water irrigation can also be improved due to the changes of related elements contents in soil (Chen et al., 2015a).

Because reclaimed water contains many nutrients such as nitrogen, phosphorus and potassium, agricultural irrigation with reclaimed water can decrease the use of fertilizer and save the cost of crop production (Jeong et al., 2014). For example, it was estimated that the uses of nitrogen and phosphorus could decrease 7140–8610 tons and 1119–1590 tons per year in Beijing with reclaimed water irrigation, respectively (Chen et al., 2014). The production cost of reclaimed water in Beijing is no more than 1 CNY/ton per year when using the coagulation–sedimentation–filtration treatment process, and 2.5 CNY/ton per year when using tertiary and advanced treatment (Chen et al., 2013a). The production cost of reclaimed water is much lower than that of seawater desalination and South-to-North Water Diversion. Reclaimed water provides an economical water resource for urban water uses such as car washing and road cleaning.

Above all, cost-benefit analysis of wastewater reclamation and reuse program in Beijing had demonstrated that wastewater reuse was economically feasible with considering all the related benefits (Fan et al., 2013). Based on the 2010 data in Beijing, reclaimed water use can generate a net annual benefit of 712 million CNY and the benefit to cost ratio was 1.7 (Table 1). The adverse impacts as well as low revenues from wastewater reuse (about 1/3 of total benefits) are two main obstacles to implement the wastewater reuse programs.

1.4. *Wastewater reclamation technology*

The successful development of wastewater reuse has a close relationship with the quality of treated wastewater which depends upon the development of wastewater reclamation technology. Current technologies applied in wastewater reuse include oxidants such as sodium hypochlorite, ultra-violet (UV) radiation and O_3, biological treatments such as anaerobic, maturation ponds and constructed wetlands, physical separations such as medium filtration and membrane filtration, and electrochemical treatments (Norton-Brandao et al., 2013). The most concerned pollutants in the reclaimed water include salinity, pathogens, heavy metals and emerging contaminants (Table 2).

Reverse osmosis (RO) has an excellent result of desalination, and it is the most frequently applied desalination technology (Al-Sahali and Ettouney, 2007). The results of Oron et al. (2008) showed an electro conductivity (EC) removal

Table 1 – Cost and benefit of wastewater reuse (Fan et al., 2013).

Cost category	Value (million CNY)	Benefit category	Value (million CNY)
Amortized investment	54	Revenues from wastewater reuse	680
Power consumption	167	Water resources saving, fertilizer	960.18
Chemical reagents	90.3	Water replacement savings	22.87
Maintenance	23.4	Wastewater discharge reduction	33.9
Manpower	50.2	Environmental improvement	205
Pipeline construction	611	Public health impacts	−339
		Groundwater pollution	−0.543
		Groundwater recharge	200
Total cost	996	Total benefit	1,708

Table 2 – Abilities, advantages and disadvantages of wastewater reuse technologies, based on Norton-Brandao et al. (2013) and Wei et al. (2014).

Technology	Abilities	Advantages	Disadvantages
Ozone	High bactericidal action Bixio and Wintgens (2006); the removal of 90%–99% for antibiotics and estrogens Huber et al. (2005)	Low formation of by-products	High operability, moderate operating costs, high investment costs
TiO_2	High inactivation of coliforms Rojas-Higuera et al. (2010); the removals of 33% for Cd and 75% for Co Pedrero et al. (2011); The removal of >90% for pharmaceuticals and personal care products Bernabeu et al. (2011)	Likely use of renewable energy in the case of solar photocatalysis, no formation of by-products, use of inexpensive catalysts and facilities Lydakis-Simantiris et al. (2010)	Lack of residual bactericidal action and slow kinetic behavior
Ponds and constructed wetlands	Bacterial removals between 1 and 6 log units Feigin et al. (1991)	Low maintenance costs and energy usage, no formation of by-products Brissaud (2007), Ghermandi et al. (2007)	Large footprint, efficiency depending on meteorological conditions
Membrane filtration	The removals of 81% for electro conductivity, 83% for Na^+ and 80% for Cl^- Oron et al. (2008); the removal of 61% for sodium absorption ratio Chang et al. (2005); a complete reduction of viruses Yim et al. (2007); the removal of 95% for heavy metals Hyun and Lee (2009); the removal of >89% for pharmaceuticals Xu et al. (2005)	Simultaneous disinfection and removal of electro conductivity and heavy metal	High investment costs, high operating costs Lazarova et al. (1999)
Electrolysis	*Escherichia coli* can be completely removed Cano et al. (2011)	Effective in killing a wide spectrum of microorganisms Drogui et al. (2001)	Formation of significant amounts of perchlorates Bergmann et al. (2009)

of 81% for an initial EC of 2020 μS/cm, a Na^+ removal of 83% for an initial Na^+ concentration of 280 mg/L and a Cl^- removal of 80% for an initial Cl^- concentration of 348 mg/L by RO. RO can remove sodium ions and divalent cations, and thus it is very effective for the decline of sodium adsorption ratio (SAR). Chang et al. (2005) found a SAR removal of 61% was observed for an initial SAR of 1.8 with the use of RO.

For disinfection namely the removal of pathogens, the recommended technology by several guidelines is ultraviolet treatment (Bixio and Wintgens, 2006). Researchers found that the pathogen contents of effluents can reach to the related standards after the ultra-violet treatment (Gomila et al., 2008; Melidis et al., 2009). Regarding biological treatments, maturation ponds have an excellent ability of pathogen removing. Madera et al. (2002) observed that 4 log units of *Escherichia coli*, 1 log unit of *Streptococcus* and 100% of helminth eggs were able to be removed after treatments in a series of anaerobic, facultative and maturation ponds. In addition, Yim et al. (2007) found that a complete reduction of viruses was possible with an ultrafiltration membrane treatment, and Cano et al. (2011) found that *E. coli* could be completely removed by the electrochemical treatment.

The removal technologies of heavy metal include chemical precipitation, biosorption, membrane filtration and electrochemical treatment *etc*. The results of Hyun and Lee (2009) showed the removal efficiencies of 95% for heavy metals such as Fe, Mn, Cu, Cr and Pb under optimal operating conditions after a series of anaerobic–oxic–anoxic biofilm filtration (AOBF) and membrane filtration processes, and the final concentrations of all heavy metals were suitable for the agricultural irrigation. The field treatment system (FTS) was also suitable for agricultural irrigation of wastewater reuse, and research results showed the FTS system including granulated ferric hydroxide adsorber, screen filter and UV lamp could remove 76% of As, 80% of Cd and Cu, 88% of Cr and Pb, and up to 97% of Zn (Battilani et al., 2010).

As for emerging contaminants, Nakada et al. (2007) studied the removal of 24 pharmaceuticals and personal care products and endocrine-disrupting chemicals in the secondary effluent of a municipal sewage treatment plant with sand filtration and ozonation, and found that the removal of most contaminants were more than 80%. The results of Huber et al. (2005) also found the removal of antibiotics and estrogens, which were 0.5–5 μg/L in the municipal wastewater treatment plant effluents, was 90%–99% after ozonation. In addition, solar photocatalysis has an excellent result of emerging pollutants removal. Bernabeu et al. (2011) found the concentrations of emerging pollutants were under the detection limit after solar photocatalysis with TiO_2. The removal of pharmaceuticals and personal care products was more than 90%, and the concentration was less than 10 ng/L after the treatment of biological activated carbon filter (Reungoat et al., 2011).

In all, with advances in technology, wastewater may be treated to meet the most stringent quality requirements and be used for any purposes desired, even including drinking water supply. The potential uses for reclaimed water are indeed unlimited. However, wastewater that has undergone the conventional treatments may contain some impurities which are of agronomic significance or of public health significance, and then its potential reuses are impacted. Combination of different treatment technologies is often necessary for certain types of reuse or multiple reuses.

1.5. Policy and regulation

Except the effects of water scarcity or economic factors on wastewater reclamation and reuse in China, the effects of policy factors are also very important. The overall strategy in

Table 3 – Wastewater reclamation and reuse polices at national level in China. [a]

Government sectors	Wastewater reclamation and reuse polices	Wastewater reclamation and reuse polices prescriptions Chang et al. (2013)
The State Council	The 12th Five-year Comprehensive Work Plan for Energy Conservation and Emissions Reduction (2011); The 12th Five-year National Urban Sewage Treatment and Recycling Facilities Construction Plan (2012)	1. Adopting reasonably the price of reclaimed water which should be lower than that of conventional water; providing the privileged policies of tax and fee reduction for reclaimed water producers 2. Encouraging reclaimed water to be used in industries, carwash, urban facilities and landscaping; forcing certain water users to use reclaimed water
MOHURD MOST	The Interim Procedures of Reclaimed Water Facilities Management in Urban (1995); The Regulation of Saving Water Management in Urban (1998); The Policy of Wastewater Reclamation and Reuse Technology in Urban (2006); The 12th Five-year Development Plan of National Science and Technology (2011)	1. Using actively reclaimed water; Issuing the technology policy of wastewater reclamation and reuse 2. Considering preferentially the landscaping use of reclaimed water; using the secondary effluent from municipal wastewater treatment plants in agriculture irrigation 3. Making policies to encourage wastewater reclamation and reuse by related central and local governments; offer financial supports for wastewater recycling by local governments 4. Establishing gradually reasonable water price system and water utilization structure
MEP GAQSIQ	The 12th Five-year National Environmental Protection Regulations and Environmental Economic Policy Construction Plan (2011); Series water quality standards for different reclaimed water reuses	1. Making the water quality standards for different reclaimed water uses
MOF NDRC	The Notice of Implementing the Policy without Value-added Tax for Reclaimed Water and Others (2008); The Notice of Suggestion about Supporting the Investment and Financing Policy of the Circular Economy Development (2011)	1. Reaching to wastewater reuse rates of 20–25% for the cities with water scarcity in North China and 10–15% for coastal areas of South China in 2015 2. Encouraging wastewater reclamation and reuse to increase water resource development efficiency

[a] MOHURD, MOST, MEP, GAQSIQ, MOF and NDRC mean the Ministry of Housing and Urban–Rural Development, the Ministry of Science and Technology, the Ministry of Environmental Protection, General Administration of Quality Supervision, Inspection and Quarantine, the Ministry of Finance and the National Development and Reform Commission.

China is encouraging for wastewater reuse (Table 3). Based on the 12th Five-year National Urban Sewage Treatment and Recycling Facilities Construction Plan, 30.4 billion CNY will be invested to upgrade or construct reclaimed water production facilities. Wastewater reclamation rates (reclaimed wastewater quantity/treated wastewater quantity) will increase over 5%, and the production scale of reclaimed water will increase from 12.1 million tons per day in 2010 to 38.8 million tons per day. In 2012, the Ministry of Housing and Urban–Rural Development (MOHURD) issued Technical Guidelines for Municipal Wastewater Reclamation and Reuse (draft) which covered planning, construction, operation, maintenance and risk management during productions and end uses to promote the wastewater reuse. In the Performance Evaluation and Assessment Measure of Low Impact Design or Development (draft) issued by MOHURD in 2015, wastewater reuse rate should be more than 20% in the cities where water resource per capita is less than 500 m^3 and water quality in water environment is higher than the IV-class standard.

For supporting the development of wastewater reclamation and reuse, the Ministry of Construction and Standardization Administration issued a series of regulations and standards such as Quality Acceptance Code for Municipal Sewage Treatment Plant Engineering (GB 50334-2002) and the Reuse of Urban Recycling Water–Water Quality Standard for Urban Miscellaneous Water Consumption (GB/T 18920-2002). To enlarge the wastewater reclamation and reuse, series water quality standards for different wastewater reuses (Table 4) including for environment reuse (GBT 18921-2002), miscellaneous urban reuse (GBT 18920-2002), industrial reuse (GBT 19923-2005), farmland irrigation reuse (GB20922-2007), and green space irrigation reuse (GB/T 25499-2010) was enacted by the Ministry of Environmental Protection (MEP) and the General Administration of Quality Supervision, Inspection and Quarantine (GAQSIQ). In addition, the combined actions of water price reform and water consumption quota promote the development of water saving measures and wastewater reuse in the areas of industrial, agricultural and domestic water.

In general, facing serious water crisis around China, the central government has great ambition to expand wastewater reuse. Many policies, regulations and standards on reclaimed water had been issued. Some national plans involving reclaimed water have been made. All these actions provide great chances for enlarge wastewater reuse nationally, but the efficiency and execution capability still need to be improved.

2. Challenges for expanding wastewater reuse

China is still in a primary stage of wastewater reclamation and reuse, and the extensive reuse practices have not been

Table 4 – Series water quality standards for different reclaimed water use in China.

Values	Industrial use			Agricultural irrigation [e]				Non-potable water use				
Indexes [a]	Cooling	Washing	Boiler	Fiber crop	Dry land grain and oil crop	Paddy grain	Field vegetables	Toilet flushing	Road sweeping and fire	Urban greening [e]	Carwashing	Construction
Chroma (°)	≤30	≤30	≤30	–	–	–	–	≤30	≤30	≤30	≤30	≤30
Turbidity (NTU)	≤5	≤30	≤30	–	–	–	–	≤5	≤10	≤5, 10 [d]	≤5	≤20
pH	6.5–8.5	6.5–9.0	6.5–8.5	5.5–8.5	5.5–8.5	5.5–8.5	5.5–8.5	6.0–9.0	6.0–9.0	6.0–9.0	6.0–9.0	6.0–9.0
TDS (mg/L)	≤1000	≤1000	–	≤1000, ≤2000 [c]	≤1000, ≤2000 [c]	≤1000, ≤2000 [c]	≤1000	≤1500	≤1500	≤1000	≤1000	≤1500
SS (mg/L)	≤30	≤30	≤5	≤100	≤90	≤80	≤60	–	–	–	–	–
DO (mg/L)	–	–	–	–	–	≥0.5	≥0.5	≥1.0	≥1.0	–	≥1.0	≥1.0
BOD_5 (mg/L)	≤10	≤30	≤10	≤100	≤80	≤60	≤40	≤10	≤15	≤20	≤10	≤15
COD_{Cr} (mg/L)	≤60	≤60	≤60	≤200	≤180	≤150	≤100	–	–	–	–	–
NH_3–N (mg/L)	≤10 [b]	≤10	≤10	–	–	–	–	≤10	≤10	≤20	≤10	≤20
LAS, (mg/L)	–	–	–	≤8.0	≤8.0	≤5.0	≤5.0	≤1.0	≤1.0	≤1.0	≤0.5	≤1.0
Hg (mg/L)	–	–	–	≤0.001	≤0.001	≤0.001	≤0.001	–	–	≤0.001	–	–
Cd (mg/L)	–	–	–	≤0.01	≤0.01	≤0.01	≤0.01	–	–	≤0.01	–	–
As (mg/L)	–	–	–	≤0.1	≤0.1	≤0.05	≤0.05	–	–	≤0.05	–	–
Cr (mg/L)	–	–	–	≤0.1	≤0.1	≤0.1	≤0.1	–	–	≤0.1	–	–
Pb (mg/L)	–	–	–	≤0.2	≤0.2	≤0.2	≤0.2	–	–	≤0.2	–	–
Fe (mg/L)	≤0.3	≤0.3	≤0.3	≤1.5	≤1.5	≤1.5	≤1.5	≤0.3	–	≤1.5	≤0.3	–
Mn (mg/L)	≤0.1	≤0.1	≤0.1	≤0.3	≤0.3	≤0.3	≤0.3	≤0.1	–	≤0.3	≤0.1	–
Fecal coliform groups (MPN/L)	≤2000	≤2000	≤2000	≤40000	≤40000	≤40000	≤20000	≤200	≤200	≤200, 1000 [d]	≤200	≤200

[a] TDS, SS, DO, BOD, COD, LAS and SAR mean the total dissolved solids, suspended matter, dissolved oxygen, biochemical oxygen demand, chemical oxygen demand, sodium dodecylbenzene sulfonate and sodium adsorption ratio, respectively.
[b] NH3-N about circulating water of steel heat exchanger is 1 mg/L.
[c] Less value is in the areas with non-saline soils, and larger values is in the areas with saline soils.
[d] Less values are in non-restrictive green space, and larger values are in restrictive green space.
[e] Others indexes in agricultural and urban greening use with reclaimed water include olfaction, sodium absorption ratio, chloride, residual chlorine, Be, Co, Cu, Mo, Ni, Se, Zn, B, fluoride, cyanide, vanadium, chloral, formaldehyde, benzene, and ascarid eggs.

carried out until 2000 and later. There are many significant challenges to expand wastewater reuse and make it functional and sustainable at the local levels.

2.1. Slow pace in adopting urban wastewater reuse programs

Nationally, wastewater reuse in cities increased with the increasing of wastewater discharge, but the amount of use was still low. Based on China Urban Construction Statistical Yearbook, the total use amount of reclaimed water in 2012 was 3.5 billion m^3, and it only increased 5% compared with the use amount in 2010. In 2012, the ability of reclaimed water production in China was 17.4 million m^3 per day, and only about half the amount of reclaimed water was used. China Urban Construction Statistical Yearbook stated that only 154 of 657 surveyed cities had augmented urban wastewater reclamation and reuse practices (Fig. 3b). The wastewater reuse ratio in 6 cities was greater than 60%, and it in 99 cities which mainly distributed in southern China was less than 20%. The amount of water recovered was disappointing as the figures included the unintended and unplanned environmental uses. So far, only 23 cities formally adopted policies delineating objectives and strategic plans of wastewater reuse.

2.2. Establishment of integrated water resources management framework and guidelines for wastewater reuse programs

In many regions of China, integrated water resources management involved reclaimed water is still at its infancy. Some related laws and regulations such as Water Pollution Control Action Plan are issued for guiding integrated water resources management, but they are still short of detailed methods in China. In Europe, European Union and its member states have successively implemented European Union wide and national measures over the last three decades to ensure a sustainable integrated water resources management process, and their important outcome is the Water Framework Directive (WFD). WFD promotes the implement of integrated water resources management, and favors municipal wastewater reclamation and reuse to be implemented on a larger scale, with the advantages of both augmenting water supply and decreasing the impact of human activities on the environment. For promoting the development of integrated water resources management involved reclaimed water, the appropriate methods should be established based on the local conditions. The United States Environmental Protection Agency provided Guidelines for Water Reuse as a comprehensive technical reference to facilitate wastewater reuse programs throughout the United States. The guideline was first published in 1980 and was updated in 1992, 2004 and 2012. With assistance of the guideline, successful reuse programs have been developed in many states, particularly in Arizona, California, Florida, and Texas.

China issued a draft Technical Guideline for Municipal Wastewater Reclamation and Reuse in late 2012. The 41-page document contained general discussions rather than technical instructions in planning, designing and implementing the reclamation and reuse operations. Compared with the policies and regulations in the European Union and United States, these in China are shortage of flexibility. The States in the European Union and United States can issue the policies and regulation of wastewater reuse under the national wastewater reuse framework based on their own actual situations. The current wastewater treatment professionals in China were lack of the engineering knowhow and experiences to initiate wastewater reuse projects especially in dealing with public opinions, market-based financing and marketing, advanced treatment technologies, and water quality control and assurance issues (Yi et al., 2011).

2.3. Incoherent water quality requirements

Reclaimed water is required to meet separate quality standards for uses in environmental enhancement, urban sanitation and fire protections, industrial processing, crop irrigation, and greenbelt landscape irrigation that are established by separate governmental authorities. There is little agreement in terms of requirement in treatment technologies, parameters and numerical limits, and monitoring protocols (Chang and Ma, 2012). So far, although series water quality standards for different reclaimed water uses have been issued (Table 4), they are shortage of consistencies including the water quality index and value, and monitoring method since these standards were put forth by different researchers at different years.

In practices, it is questionable as reclaimed water from one agency is often distributed to different end users. Furthermore, there is no link between the reclaimed water quality standard and the sewage discharge standard. The reclaimed water producer sometime has the difficulty to meet the water quality requirements due to the uncontrolled water source from wastewater treatment plants. There are no specified minimum treatment requirements and corresponding regulations, and thus the produced reclaimed water quality is not guaranteed. In addition, the regulatory authority is not clearly delineated. While the MOHURD is mandated to implement wastewater reuse policies in China, others like the Ministries of Environmental Protection, Agriculture, and GAQSIQ also hold jurisdictions on reclaimed water used in environmental enhancement, irrigation and others. The regulatory maze is difficult to negotiate.

2.4. The limited commercial development of reclaimed water

Wastewater reclamation and reuse is driven by policy factors other than water scarcity or economic factors. Stepwise regression analysis between the influencing factors and wastewater reclamation and reuse levels of 23 cites showed that reclaimed water use rate was mainly related with penalty for policy violations ($R^2 = 0.6101$), and the impacts of local water scarcity (represented by per capita water resource) and local economic level (represented by per capita GDP) were limited. The results suggested that the enlargement of reclaimed water use in China was not a natural development following the market ruling and local natural resources requirement, but to the result of strong government intervention. In Beijing, the wastewater reclamation and reuse policy framework stipulated binding responsibilities for producers and designated users to meet the targets. Violators are legally punishable with fines, prison terms, and/or administrative disciplines. This provision is critical in expending the wastewater reuse.

Wastewater reuse requires large upfront capital investments and the recognized long-term economy. Meantime, reclaimed water price is kept low at 1 CNY per 1 m^3 roughly which is 17% that of the city's public water, and is far from inadequate to recuperate capital investments and operation costs of the wastewater reuse system (Chen et al., 2013a). The reclaimed water producers do not have the incentive to commit capital investments and expand the user markets. Public institutions have limited ability to invest in or even maintain wastewater reclamation and reuse programs because of the high initial cost. Thus, governments should invest the allowance which is generally aimed at allowing the project to operate on a commercial basis for wastewater reuse. However, the benefits of water supply cannot still cover all project costs because of the distortions of the water supply market. In the market mechanism, the cost-benefit calculation of wastewater reuse should include total cost for integrated water resources management alternatives, rather than consider simply for cost before and after the project. In addition, the shares of benefit and cost among the stakeholders with reclaimed water use are also very different than that with the conventional water use. Thus, there is a need for definite and reasonable institutional arrangements, when the cost and benefit of a project are shared among different groups. It is not ethically and economically possible that reclaimed water use consumers have to bear all the costs.

2.5. The strengthening of public awareness and cooperation among stakeholders

Public involvement is critical to the successful implementation of reclaimed water use programs. Little information is available on public perception on reclaimed water use in China. A 714 questionnaires survey in Beijing (Table 5) which may represent the best situation in China showed that while the overall acceptance of public was high, the willingness to three major reuse types of river water supplement, park water supplement and agriculture irrigation were not high, shedding by the water quality problems (Chen et al., 2015b). The public's knowledge on reclaimed water use appears superficially. Survey from 54 wastewater reclamation and reuse stakeholder professionals (Table 5) showed that while they strongly supported the advancement of reclaimed water reuse, the acceptance of producers and researchers for potentially potable and body contact reuses were low because of being worried about technology cost and the potential environmental risks from wastewater reuse. The gap might be closed, only by demonstrating the success of current programs.

At present, the attitude of policy makers for wastewater reuse is positively encouraging with lower concerns of reclaimed water quality in China. The concerns of researchers for wastewater reuse are focus on the sustainable development of environment. The researchers are positive for wastewater reuse since reclaimed water as an alternative water resource is very important for ameliorating the issues of water scarcity and pollution, and at the same time they are very worried about the potential environmental risks because of reclaimed water quality. The producers mainly consider the question about policies, investment, water price and pipeline networks of water supply with fewer concerns of environmental risks. However, some stakeholders have a limited knowledge of wastewater reuse, and they recognize unclearly the related contents such as water quality demand and what can be gained under the current policies and regulations with wastewater reuse. Thus, it is necessary to increase the related knowledge on wastewater reuse of stakeholders and strengthen cooperation among stakeholders, and then the functions realizing of stakeholders can be maximum during the management of wastewater reuse.

3. Conclusions

China as a country facing serious water resource scarcity and unbalanced distribution is undergoing rapid urban developments. The increasings of water demand and wastewater discharge motivated by urbanization enhance the development of wastewater reuse. The development of wastewater reclamation and reuse can result in many environmental and economic benefits such as relieving the water scarcity, decreasing the pollution emission, improving soil quality and saving the production cost. In addition, the development of wastewater reclamation technologies and policies and regulations issued by governments are also the driving factors of expanding wastewater reuse.

However, China is still in a primary stage of wastewater reclamation and reuse. At national level, the speed in adopting urban wastewater reuse programs is still slow. For sustainable wastewater reuse at China, the establishments of integrated water resources management framework, guidelines for wastewater reuse programs and justifiable water quality standards are essential. The limited commercial development of reclaimed water, public awareness and cooperation among stakeholders are also important challenges faced by China at current for wastewater reuse.

Table 5 – Public's acceptance of wastewater reuse options [a].

Reuse category	Managers	Producers	Researchers	Public
Potentially potable reuses	3.50	2.27	2.32	2.87
Body contact	3.90	3.32	2.64	–
Non-body contact and non-potable reuses	4.60	4.95	4.86	3.37
Average	4.00	3.51	3.27	3.12

[a] Data are based on Chen et al. (2015b), and greater values mean greater acceptance.

Some recommendations may be considered when planning and undertaking wastewater reclamation and reuse in China: (1) forming an integrated water resources management framework including the managements of water supply, storm water, wastewater, non-point source pollution and water reuse; (2) revising the guidelines, regulations and standards of wastewater reuse by the local departments according to the local situations under the national framework; (3) improving the market mechanism of wastewater reuse; (4) training stakeholders on the financial, environmental, legal, institutional and economic knowledge related to wastewater reuse, and allowing public to take part in developing standards, regulations and policies concerning wastewater reuse; (5) enhancing the scientific researches on the reuse of material and energy during the process of reclaimed water production and the effects of reclaimed water end use on soil and water ecosystem.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 41271501).

REFERENCES

Al-Sahali, M., Ettouney, H., 2007. Developments in thermal desalination processes: design, energy, and costing aspects. Desalination 214 (1–3), 227–240.

Asano, T., Bahri, A., 2011. Global challenges to wastewater reclamation and reuse. Water Front 2, 64–72.

Asano, T., Levine, A.D., 1996. Wastewater reclamation, recycling and reuse: past, present, and future. Water Sci. Technol. 33 (10–11), 1–14.

Asano, T., Burton, F.L., Leverenz, H.L., Tsuchihashi, R., Tchobanoglous, G., 2007. Water Reuse: Issues, Technologies, and Applications. McGraw-Hill, New York, USA.

Bao, C., 2014. Spatio-temporal coupling relationships among urbanization, economic growth and water use change in China. Acta Geograph. Sin. 69 (12), 1799–1809 (in Chinese).

Battilani, A., Steiner, M., Andersen, M., Back, S.N., Lorenzen, J., Schweitzer, A., et al., 2010. Decentralised water and wastewater treatment technologies to produce functional water for irrigation. Agric. Water Manag. 98 (3), 385–402.

Beijing Water Authority, 2013. Beijing water resources bulletin. Avaliable at: http://www.bjwater.gov.cn/pub/bjwater/zfgk/tjxx/ (2015-7-26).

Bergmann, M.E.H., Rollin, J., Iourtchouk, T., 2009. The occurrence of perchlorate during drinking water electrolysis using BDD anodes. Electrochim. Acta 54 (7), 2102–2107.

Bernabeu, A., Vercher, R.F., Santos-Juanes, L., Simon, P.J., Lardin, C., Martinez, M.A., et al., 2011. Solar photocatalysis as a tertiary treatment to remove emerging pollutants from wastewater treatment plant effluents. Catal. Today 161 (1), 235–240.

Bixio, D., Wintgens, T., 2006. Water Reuse System Management — Manual AQUAREC. Directorate-General for Research, European Commission Brussels, Belgium.

Bixio, D., Thoeye, C., De Koning, J., Joksimovic, D., Savic, D., Wintgens, T., et al., 2006. Wastewater reuse in Europe. Desalination 187 (1–3), 89–101.

Brissaud, F., 2007. Low technology systems for wastewater treatment: perspectives. Water Sci. Technol. 55 (7), 1–9.

Cano, A., Cañizares, P., Barrera, C., Sáez, C., Rodrigo, M.A., 2011. Use of low current densities in electrolyses with conductive-diamond electrochemical e oxidation to disinfect treated wastewaters for reuse. Electrochem. Commun. 13 (11), 1268–1270.

Chang, D.H., Ma, Z., 2012. Wastewater reclamation and reuse in Beijing: influence factors and policy implications. Desalination 297, 72–78.

Chang, I.S., Lee, E.W., Oh, S., Kim, Y., 2005. Comparison of SAR (sodium adsorption ratio) between RO and NF processes for the reclamation of secondary effluent. Water Sci. Technol. 51 (6–7), 313–318.

Chang, D.H., Ma, Z., Wang, X., 2013. Framework of wastewater reclamation and reuse policies (WRRPs) in China: comparative analysis across levels and areas. Environ. Sci. Pol. 33, 41–52.

Chen, A., 2002. Urbanization and disparities in China: challenges of growth and development. China Econ. Rev. 13 (4), 407–411.

Chen, W.P., Lu, S.D., Jiao, W.T., Wang, M.E., 2013a. Reclaimed water: a safe irrigation water source? Environ. Dev. 8, 74–83.

Chen, Z., Ngo, H.H., Guo, W.S., 2013b. A critical review on the end uses of recycled water. Crit. Rev. Environ. Sci. Technol. 43, 1446–1516.

Chen, W.P., Lu, S.D., Zhang, W.L., Yi, L.L., Jiao, W.T., 2014. Ecological risks and sustainable utilization of reclaimed water and wastewater irrigation. Acta Ecol. Sin. 34 (1), 163–172.

Chen, W.P., Lu, S.D., Pan, N., Wang, Y.C., Wu, L.S., 2015a. Impact of reclaimed water irrigation on soil health in urban green areas. Chemosphere 119, 654–661.

Chen, W.P., Bai, Y.Y., Zhang, W.L., Lyu, S.D., Jiao, W.T., 2015b. Perceptions of different stakeholders on reclaimed water reuse: the case of Beijing, China. Sustainability 7, 9696–9710.

Drogui, P., Elmaleh, S., Rumeau, M., Bernard, C., Rambaud, A., 2001. Oxidising and disinfecting by hydrogen peroxide produced in a two-electrode cell. Water Res. 35 (13), 3235–3241.

Duncan, R.R., Carrow, R.N., Huck, M.T., 2009. Turfgrass and Landscape Irrigation Water Quality: Assessment and Management. CRC Press, Boca Raton, FL.

Fan, Y.P., Chen, W.P., Jiao, W.T., Chang, A.C., 2013. Cost-benefit analysis of reclaimed wastewater reuses in Beijing. Desalin. Water Treat. 53 (5), 1224–1233.

Feigin, A., Ravina, I., Shalhevet, J., 1991. Irrigation with Treated Sewage Effluent. first ed. Springer-Verlag, Berlin.

Fitzhugh, T.W., Richter, B.D., 2004. Quenching urban thirst: growing cities and their impacts on freshwater ecosystems. Bioscience 54 (8), 741–754.

Ghermandi, A., Bixio, D., Traverso, P., Cersosimo, I., Thoeye, C., 2007. The removal of pathogens in surface-flow constructed wetlands and its implications for water reuse. Water Sci. Technol. 56 (3), 207–216.

Gomila, M., Solis, J.J., David, Z., Ramon, C., Lalucat, J., 2008. Comparative reductions of bacterial indicators, bacteriophage-infecting enteric bacteria and enteroviruses in wastewater tertiary treatments by lagooning and UV-radiation. Water Sci. Technol. 58 (11), 2223–2233.

Huber, M.M., Gobel, A., Joss, A., Hermann, N., Loffler, D., McArdell, C.S., et al., 2005. Oxidation of pharmaceuticals during ozonation of municipal wastewater effluents: a pilot study. Environ. Sci. Technol. 39 (11), 4290–4299.

Hyun, K.S., Lee, S.J., 2009. Biofilm/membrane filtration for reclamation and reuse of rural wastewaters. Water Sci. Technol. 59 (11), 2145–2152.

Jenerette, G.D., Larsen, L., 2006. A global perspective on changing sustainable urban water supplies. Global Planet. Change 50 (3–4), 202–211.

Jeong, H., Jang, T., Seong, C., Park, S., 2014. Assessing nitrogen fertilizer rates and split applications using the DSSAT model for rice irrigated with urban wastewater. Agric. Water Manag. 141, 1–9.

Jimenez, B., Asano, T., 2008. Water Reuse: An International Survey of Current Practice, Issues and Needs. International Water Association, London, England.

Lazarova, V., Savoye, P., Janex, M.L., Blatchley, E.R., Pommepuy, M., 1999. Advanced wastewater disinfection technologies: state of the art and perspectives. Water Sci. Technol. 40 (4–5), 203–213.

Levine, A.D., Asano, T., 2004. Recovering sustainable water from wastewater. Environ. Sci. Technol. 38 (11), 201A–208A.

Lydakis-Simantiris, N., Riga, D., Katsivela, E., Mantzavinos, D., Xekoukoulotakis, N.P., 2010. Disinfection of spring water and secondary treated municipal wastewater by TiO_2 photocatalysis. Desalination 250 (1), 351–355.

Ma, H.L., Xu, J., Wang, P.C., 2014. Water resource utilization and China's urbanization. Resour. Sci. 36 (2), 0334–0341 (in Chinese).

Madera, C.A., Pena, M.R., Mara, D.D., 2002. Microbiological quality of a waste stabilization pond effluent used for restricted irrigation in Valle del Cauca, Colombia. Water Sci. Technol. 45 (1), 139–143.

Melidis, P., Athanasoulia, E., Parisis, A., Koppmann, M., 2009. Microbiological effluent control by UV-disinfection of a small-scale SBR system. Desalination 248 (1–3), 915–922.

Nakada, N., Shinohara, H., Murata, A., Kiri, K., Managaki, S., Sato, N., Takada, H., 2007. Removal of selected pharmaceuticals and personal care products (PPCPs) and endocrine disrupting chemicals (EDCs) during sand filtration and ozonation at a municipal sewage treatment plant. Water Res. 41 (19), 4373–4382.

Norton-Brandao, D., Scherrenberg, S.M., van Lier, J.B., 2013. Reclamation of used urban waters for irrigation purposes — a review of treatment technologies. J. Environ. Manag. 122, 85–98.

Oron, G., Gillerman, L., Buriakovsky, N., Bick, A., Gargir, M., Dolan, Y., Manor, Y., Katz, L., Hagin, J., 2008. Membrane technology for advanced wastewater reclamation for sustainable agriculture production. Desalination 218 (1–3), 170–180.

Pedrero, F., Albuquerque, A., Amado, L., Marecos do Monte, H., Alarcón, J., 2011. Analysis of the reclamation treatment capability of a constructed wetland for reuse. Water Pract. Technol. 6 (3).

Reungoat, J., Escher, B.I., Macova, M., Keller, J., 2011. Biofiltration of wastewater treatment plant effluent: effective removal of pharmaceuticals and personal care products and reduction of toxicity. Water Res. 45 (9), 2751–2762.

Rojas-Higuera, N., Sánchez-Garibello, A., Matiz-Villamil, A., Salcedo-Reyes, J.C., Carrascal-Camacho, A.K., Pedroza-Rodríguez, A.M., 2010. Evaluation of three methods for the inactivation of coliforms and *Escherichia coli* present in domestic wastewaters used in irrigation. Univ. Sci. 15 (2), 139–149.

Sevostianova, E., Leinauer, B., 2014. Subsurface-applied tailored water: combining nutrient benefits with efficient turfgrass irrigation. Crop Sci. 54 (5), 1926–1938.

Tong, L., Liu, X., Liu, X.W., Yuan, Z.W., Zhang, Q., 2013. Life cycle assessment of water reuse systems in an industrial park. J. Environ. Manag. 129, 471–478.

United Nations Environment Programme, 2015. Good practices for regulating wastewater treatment: legislation, policies and standards. Avaliable at: http://unep.org/gpa/documents/publications/GoodPracticesforRegulatingWastewater.pdf (2015–11-10).

Wei, X.Z., Gu, P., Zhang, G.H., 2014. Research progress in the new model of pollutants in water and their removing methods. Ind. Water Treat. 34 (5), 8–12.

Xu, P., Drewes, J.E., Bellona, C., Amy, G., Kim, T.U., Adam, M., et al., 2005. Rejection of emerging organic micropollutants in nanofiltration-reverse osmosis membrane applications. Water Environ. Res. 77 (1), 40–48.

Yi, L., Jiao, W., Chen, X., Chen, W., 2011. An overview of reclaimed water reuse in China. J. Environ. Sci. 23 (10), 1585–1593.

Yim, S.K., Ahn, W.Y., Kim, G.T., Koh, G.W., Cho, J.W., Kim, S.H., 2007. Pilot-scale evaluation of an integrated membrane system for domestic wastewater reuse on islands. Desalination 208 (1–3), 113–124.