



An Innovative Triple Water Supply System and a Novel SANI[®] Process to Alleviate Water Shortage and Pollution Problem for Water-scarce Coastal Areas in China

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ABSTRACT

Water scarcity has been a long standing problem in China, especially in North China. To tackle water scarcity, we have developed a low-cost Triple Water Supply (TWS) system consisting of fresh water supply, seawater for toilet flushing, and grey water reuse and recycling. This innovative system maximizes the water resource saving in coastal cities up to 23%. Moreover, this novel system opens the door for adopting an innovative sewage treatment technology, namely the SANI[®] process which effectively avoids sewage sludge production. If the TWS system and the SANI[®] system were to be jointly applied to the 16 major water-stressed coastal cities of China, this could possibly reduce 3,600 million m³/year of freshwater demand. As compared with wastewater reuse and desalination, the reduction of annual electricity and greenhouse gas emission by seawater toilet flushing can amount to 630 – 22,000 GWh and 0.4 – 15 million tonnes of CO₂, respectively. Moreover, the SANI process can avoid the production of 10 million tonnes of sludge, reducing 35% energy consumption and 36% greenhouse gas emission as compared to conventional sewage treatment processes. This is equals to 1,400 GWh/year energy saving and 1.2 million tonnes of CO₂/year emission reduction, respectively.

Keywords: Seawater toilet flushing; Water reuse; Sewage treatment; SANI process

1. INTRODUCTION

Water scarcity has been a long standing problem in China. About 400 of China's 660 cities were short of water; of those, 108 cities, including Beijing and Tianjin were facing serious water shortages (World Bank (WB), 2009). In 2008, the average rainfall in China was 655 mm, ranging from 323 mm in North

China and 1244 mm in South China. The renewable water resource was 2,743 billion m³/year, equal to 44% of the total precipitation (WRB, 2010). The amount of water resource is the sixth largest in the world; however the per capita available renewable water resource was 2,100 m³/year, or only one-fourth of the world's average. To tackle the water scarcity problem, apart from relying

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on surface waters, China had abstracted 108 billion m³/year of groundwater for freshwater supply and 41 billion m³/year of seawater for cooling in the fossil fuel and nuclear power stations (WRB, 2010).

Global warming is worsening the world's water scarcity problem. Without any further policy actions, global emissions of greenhouse gases are projected to grow by 37% by 2030 and 52% by 2050 (OECD, 2008). Climate change with possible consequences of higher evaporation rate, snow disappearing on the highlands, and intensive but uneven precipitations resulting in flooding and drought, will accentuate the uncertainty of water resources and challenges of water collection and storage capacity. Such problem has actually been experienced in China in recent years. Over the past 20 years, main stream water flows have declined by 41% in the Hai River basin and 15% in the Yellow River and Huai River basins (WB, 2009).

The scarcity of water in China was also aggravated by pollution. In 2009, around 43% of the river sections and 77% of the major lakes were classified at or below Grade IV (SEPA, 2010), i.e. not suitable for human consumption even after treatment. To improve its water quality, China has been constructing a large number of sewage treatment plants. In 2008, there were 1,692 municipal sewage treatment plants treating 57.4% of the sewage generated in all cities in Mainland China (SEPA, 2009). The operation of sewage treatment plants is generating a large amount of sludge requiring proper treatment and disposal. However, current sludge minimization, treatment and disposal technologies are not sustainable, more economic and environmentally friendly solutions are urgently needed.

In this respect, the Hong Kong Special Administrative Region (HKSAR)'s 50 years of experience in using seawater for toilet flushing and the newly developed novel Sulfate reduction Autotrophic denitrification and

Nitrification Integrated (**SANI**[®]) process by the Hong Kong University of Science & Technology in partnership with the Delft University of Technology to minimize sludge production in saline sewage treatment (Lau et al., 2006, Wang et al., 2009; Lu et al., 2009, Tsang et al., 2009, Lu et al., 2011b) appeared to be a good option. The integration of seawater toilet flushing and the SANI[®] process can help to save a substantial amount of freshwater resources as well as energy and resources for sludge handling and disposal. This paper reports our recent studies on the possibility of developing a Triple Water Supply (TWS) system with seawater as a key element (Leung et al., 2011) and the use of the SANI[®] process for the coastal cities of China (Lu et al., 2011b), as well as the environmental and financial benefits in applying this system in China.

2. Is Seawater a Better Alternative Water Resource than Wastewater Reuse and Desalination?

HKSAR is one of the most severe water-scarce areas in the world. The annual per capita renewable water resource is only 150 m³, which is far below the "scarcity" of 1,000 m³. To alleviate this grand challenge, HKSAR has adopted a seawater-and-freshwater dual water supply system since 1950s (Lee and Wu, 1997). In 2008/09, HKSAR supplied an average of 750,000 m³/day of seawater for toilet flushing covering 80% of its 7 million inhabitants (WSD, 2010). It is one of the largest alternative water supply systems in the world (Table 1). Although the use of seawater for toilet flushing has contributed to a saving of 22% of HKSAR's freshwater consumption, the saline sewage appears to have limited some important water reuse options, such as irrigation which accounts for around 1% of total water demand in highly urbanized cities like Hong Kong to 62% in Mainland China

(WRB, 2010).

Although wastewater reuse appears to be an attractive option for applications that do not require high quality water, such as gardening and landscape irrigation, highly treated reclaimed water is usually required for toilet flushing, as shown in Table 1, in order to reduce the health risk associated with possible cross-connections between the freshwater and reclaimed water systems (Asano et al., 2007; Ogoshi et al., 2001). To investigate the suitability of a dual water supply system supplying both potable freshwater and non-potable partially treated surface water for domestic uses, the Dutch Government conducted a pilot trial at six new housing estates in 1999 (Oesterholt et al., 2007). During the trial, a number of cross-connections were discovered, among which a serious incident occurred in 2001 resulting in about 200 residents infected. In light of the difficulty in detecting cross-connections and the health risk associated with reclaimed water, many authorities, such as the Dutch and California (California, 2001) governments, have prohibited such a dual water supply system to residential developments. As a result, the use of high quality potable freshwater for toilet flushing is still the vast majority in sanitation practices worldwide. For example, although Irvine Range Water District has a very sophisticated dual water supply system and that an ordinance has been passed requiring all new buildings over 17 m high to install a dual distribution system for toilet flushing in areas where reclaimed water is available (USEPA, 2004), such provision of reclaimed water for toilet flushing is only limited to high rise office buildings. As a result, less than 10,000 m³/day reclaimed water was supplied for toilet flushing in Irvine (California, 2002). Similarly, the amount of reclaimed water used for toilet flushing in Florida only amount to 2,000 m³/day, or 0.1% of all reclaimed water supplied (Florida, 2010). This is clearly not

sufficient for many water-scarce cities in the world.

While seawater desalination appears to be a universally applicable option, it should be used as the last option due to its high operational cost, high energy consumption and high greenhouse gas emission (Table 1). A more cost-effective water resource management system is therefore required.

3. Integration of Seawater, Reclaimed Grey Water and Freshwater Forms an Innovative Triple Water Supply (TWS) System

Our recent analysis indicated that by constructing separate supply pipes of freshwater, seawater and reclaimed grey water, an innovative triple water supply (TWS) system can be developed, as shown in Figure 1. This system not only minimizes the risk of cross-connection between freshwater and seawater supply as seawater can be easily detected through its taste, but also saves a significant amount of energy and greenhouse gas emission as compared to a water supply system supplying solely potable freshwater. The application of this TWS system has been applied in the Hong Kong International Airport with up to 52% of freshwater saved (Leung et al., 2010). Taking HKSAR as a whole, seawater toilet flushing has saved 22% of freshwater demand and saved a total amount of about HK\$208 million based on the difference between the average cost of treatment, operation and maintenance of freshwater and seawater system in 2008/09. With TWS, we can further reduce our freshwater demand by providing reclaimed water for irrigation, which amounted to only 1% of the total water consumption in HKSAR, as well as other possible applications such as street cleansing, car washing and industrial uses.

4. The Role of the SANI® Process Promotes the TWS System

Since the introduction of the Biological Nitrogen Removal (BNR) process in 1960s (Ludzack and Ettinger, 1962), the key biological processes in municipal sewage treatment works has been relying on the electron flow from organic carbon to oxygen through an integrated carbon and nitrogen cycle, namely autotrophic nitrification and heterotrophic denitrification (Figure 2). Depending on the sludge age, about 50 – 60% of the organic carbon in the sewage will be converted to CO₂ and the remaining 40 – 50% converted to sewage sludge.

Making use of the sulphate ion available in the saline sewage resulting from seawater toilet flushing, we have invented the SANI® process in 2006 (Lau et al., 2006, Wang et al., 2009), which eliminates the need for sludge disposal. In the SANI® process, we introduced a sulphur cycle into the carbon and ni-

trogen cycle (the S-C-N three cycles) (Figure 2). Sulphate originating from the saline sewage acts as the electron carrier to oxidize organic carbon to CO₂ by anaerobic sulphate reduction in the first reactor. Most of the electrons flow to sulphide while the alkalinity of the sewage will increase, which keeps the sulphide completely dissolved. As only a minority of the electrons will be used for assimilative metabolism, the observed sludge yield is 0.04 kg VSS/kg COD. The new electron carrier, i.e. dissolved sulphide, will flow to the next anoxic reactor to provide the electrons for autotrophic denitrification. On the other hand, the ammonia nitrogen present in the sewage will be oxidized by oxygen to nitrate in the third reactor by autotrophic nitrifiers. The nitrate will then be recycled to the second reactor to react with the sulphide ion and convert into nitrogen gas by autotrophic denitrifiers while sulphide will be converted back to sulphate. This completes the entire biological nitrogen removal process.

Table 1 Comparison of the energy consumption of alternative water sources

	Seawater for Toilet Flushing ¹	Freshwater Supply ²	Reclaimed Water ³	Seawater Desalination ⁴
Energy Consumption (kWh/m ³)	0.013 – 0.025	0.05	0.2 – 1	2.5 – 6.0

Note: ¹Screening + electro-chlorination; estimated in this study; ²Conventional water supply system; cited from AATSE, 2004; ³UV + microfiltration or reverse osmosis; cited from AATSE, 2004; ⁴Reverse osmosis, cited from WB, 2004.

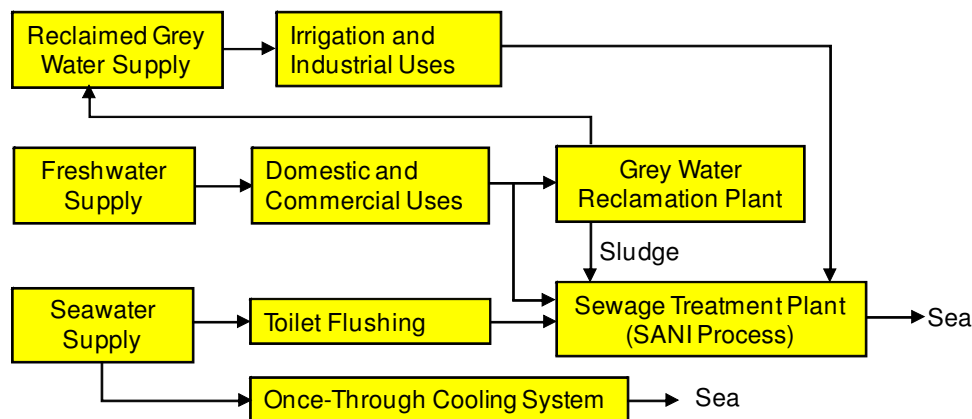


Figure 1 Conceptual diagram of the TWS system

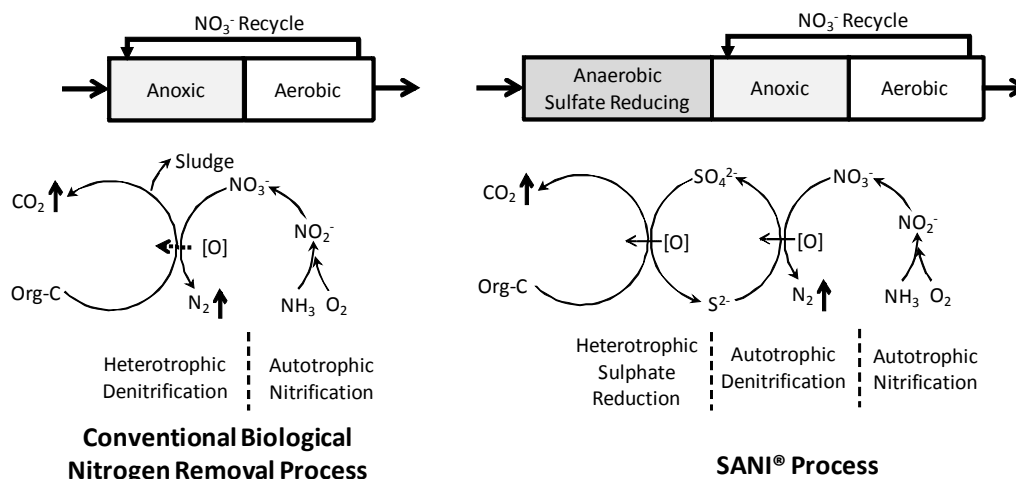
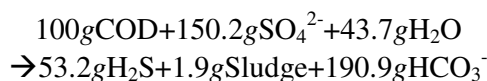


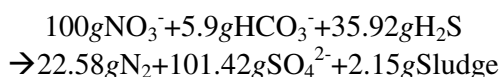
Figure 2 Conventional BNR process, the SANI[®] process and the S-C-N cycle theory

The SANI[®] process not only reduces the oxygen consumption for organic matter removal, but also minimizes biodegradable sludge generation as the three key biochemical reactions, namely Anaerobic Heterotrophic Sulphate Reduction, Anoxic Autotrophic Sulphide Oxidation and Denitrification, Aerobic Autotrophic Nitrification. All produce minimal sludge as shown below for the daily conversion in the pilot plant (Lu et al., 2011a):

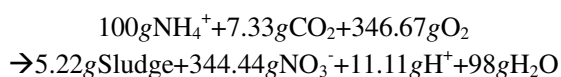
- (1) Anaerobic Heterotrophic Sulphate Reduction:



- (2) Anoxic Autotrophic Sulphide Oxidation and Denitrification:



- (3) Aerobic Autotrophic Nitrification:



We have completed a 225-day 10 m³/day on-site pilot-scale trial of the SANI[®] process (Lu et al., 2011b) treating raw saline sewage from Hong Kong (Figure 3). Without passing

through primary sedimentation, the pilot plant treated 6 mm screened saline sewage with average quality of 280 mgSS/L and 431 mgCOD/L, and produced an effluent with average quality of 36 mgSS/L, 56 mgCOD/L, and 3.4 mgNH₄-N/L. Throughout the entire trial, the pilot plant operated satisfactorily without the need for withdrawing any excess sludge.

Sludge thickening, digestion, dewatering and disposal facilities usually represent 40 – 60% of the construction cost of sewage treatment plants, and accounts for 50% of the operating cost (Peavy et al., 1986). Moreover, as sludge dewatering and incineration are energy consuming, by eliminating the sludge handling and incineration process through the SANI[®] process, an overall cost reduction of 50%, energy saving of 35% (or 0.163 kWh/m³), and greenhouse gas reduction of 36% (or 0.143 kgCO₂/m³) can be achieved, as compared with conventional BNR process plus sludge incineration, even when the latter is incorporated with energy recovery from biogas production from anaerobic sludge digestion (Lu et al., 2011b).

5. Water Resource and Energy Saving Perspectives of the TWS and SANI Process in China

The uneven precipitation and population distribution has resulted in water scarcity in many parts of China, in particular, the North China, where only 16.8 % of the country's renewable water resources are supporting 44.4% of the water demand (WRB, 2010). In a few important basins, water scarcity is even more serious. In the Huang-Huai-Hai River basins where Beijing and Tianjin are located, around 35% of the country's population is relying on less than 10% of the country's water resource, with annual per capita renewable water resource ranges from 360 m³ in the Hai basin to 750 m³ in the Huang (Yellow River) Basin (WB, 2009). This was far below the "scarcity" level of 1,000 m³. To meet its enormous water demand, some 95 billion m³/year of groundwater were abstracted in 2008 to provide 36.2% of the water supplied in North China (WRB, 2010). Such excessive overexploitation of groundwater resource has resulted in lowering of water tables and rapid depletion of groundwater reservoirs (WB, 2009). To tackle the ever increasing water scarcity problem in the Huang Basin, China has implemented a multi-billion South-to-North Water Diversion Project to bring water from the Yangtze River to Yellow River to provide water for water stress cities including Tianjin and Beijing.

Noting the water scarcity problem of China, we believe that the TWS system can help to alleviate the water scarcity problem of her water-stressed islands and coastal cities.

Based on the population of 16 highly water stressed densely populated coastal cities in China (Figure 4 and Table 2), and using the water usage model of HKSAR, we estimated that around 3,600 million m³/year of freshwater demand can be saved by using the TWS system. This is equal to about 60% of the first stage of the Middle and Eastern Line of the South-to-North Water Diversion Project. The potential energy saving from water production is also tremendous, as shown in Table 3.

Based on the assumption that the sewage generation rate per person is about 250 L/day, and that the dry sludge production rate for activated sludge process is about 235 g/m³ of sewage treated (Tchobanoglous and Burton, 1991), the amount of sludge produced by conventional biological treatment process is estimated to be about 2 million tonnes of dry solids (or 10 million tonnes of wet solids assuming a solid content of 20 %) per year. With the SANI® process, the production of this excess sludge handling and disposal requirement can be avoided, which saves 1,400 GWh/year energy and reduces 1.2 million tonne CO₂/year emission, respectively. Overall, the combined TWS and SANI® process can achieve a reduction of roughly 2,100 - 5,000 GWh/year energy and 1.7 - 3.7 million tonne CO₂/year emission as compared with convention biological sewage treatment plus reclaimed sewage effluent to achieve the same amount of alternative water resources.

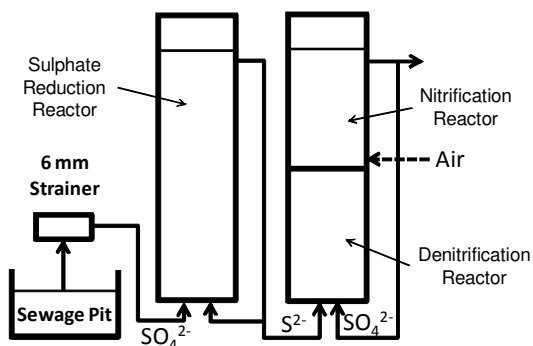


Figure 3 The pilot plant of the SANI® process in Hong Kong

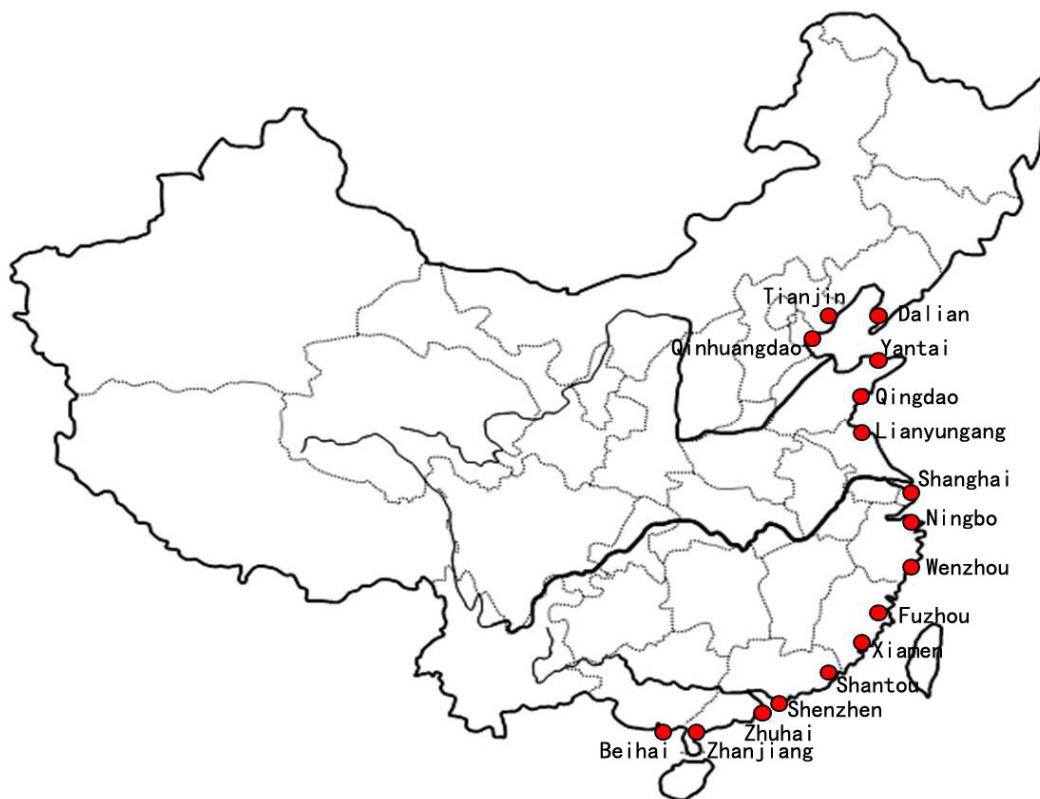


Figure 4 Water stressed coastal cities in mainland

Table 2 Population of the water-stressed coastal cities (China, 2005)

City	Population (million)	City	Population (million)	City	Population (million)
Fuzhou	6.6	Dalian	5.8	Lianyungang	4.8
Xia'men	3.0	Shanghai	13.4	Ningbo	5.6
Qingdao	7.6	Shenzhen	8.3	Wenzhou	7.8
Yantai	1.8	Zhuhai	1.4	Zhanjiang	6.7
Tianjin	10.0	Shantou	4.9		
Qinhuangdao	2.8	Beihai	1.5		
Total					92.0

Table 3 Comparison of energy and CO₂ emission from alternative water sources

	Seawater for Toilet Flushing	Freshwater Supply	Reclaimed Water	Seawater Desalination
Energy Consumption (kWh/m ³)	0.013 – 0.025	0.05	0.2 – 1	2.5 – 6.0
Comparison based on a total flushing water flow of 3,600 million m ³ /year from 16 coastal cities:				
Energy Consumption (GWh/year)	47 – 90	180	720 – 3,600	9,000 – 22,000
CO ₂ Emission (10 ³ tonne/year)	33 – 63	130	500 – 2,500	6,300 – 15,000

Note: Based on the greenhouse gas emission factor of 0.7 kgCO₂/kWh (EPD and EMSD, 2010)

CONCLUSIONS

Through providing separate freshwater, seawater and reclaimed grey water supply systems and separate grey water and black water sewerage, we have developed an innovative triple water supply (TWS) system which can help to maximize the water resources in coastal cities at a low cost. With the novel SANI[®] process, we can further achieve a reduction of 50% of the overall cost, 35% of the energy consumption, and 36% of the greenhouse gas emission from sewage treatment. If these two systems were used in the 16 coastal cities in China, it could save 3,600 million m³/year of freshwater, avoid 10 million tonnes of wet sludge, and achieve a reduction of roughly 2,100 – 5,000 GWh/year energy and 1.7 – 3.7 million tonne CO₂/year emission as compared with convention biological sewage treatment plus reclaimed sewage effluent.

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