Sustainable and Safe Use of Non-conventional Waters
-Reclaimed Water and Desalinated Water

Shuang Liu


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Fresh water scarcity, pollution and an uneven distribution have caused an increasingly serious global water crisis. One of the most widely adopted response strategies is the exploitation and use of non-conventional water sources. Water reuse and desalination were in focus in the study which was aimed to develop the strategies to promote the sustainable and safe use of reclaimed water and desalinated water from the perspective of key factors affecting the development. China and Sweden are used for case studies. With the help of literature reviews, water quality analysis, microbial risk assessment models and statistic evaluation methods the suggested strategies were evaluated and improvements to the strategies suggested.

If sustainable development of non-conventional waters should be promoted, improvements and clarifications must be made in the aspects of legislation, management, water security and policy. Key factors for desalination were identified and analysed. The most important are technology promotion, energy efficiency, feed water treatment, full cost coverage in the price. Strategy and technology for lowering cost and developing intelligent pricing system are critical to desalination market. A sound management system, qualified water and supported policy and transparency to the public are key factors for water reuse. The relevant strategy for further sound development were suggested not only for China but also available for the countries with similar situations.

For improving the security of using non-conventional waters especially reclaimed water, the study was carried out from two perspectives: developing water reuse guidelines assessing microbial risk for using treated wastewater for different applications. The approaches for setting guidelines and how they should be formulated were discussed. A combination of epidemiology study and risk assessment was recommended for developing microbial indicators standard. Guidelines must include regulations of treatment processes and instructions on how to protect users and the public. Statistic methods imply that water quality monitoring can be simplified. Quantitative microbial risk assessment is an effective supplementary tool to guidelines and was applied for judging the possibility of reuse the studied water for different applications. The protective guidelines could be developed based on the process and results of risk assessment by controlling exposure pathway and dose.

Besides the strategy developed by water managers, other stakeholders, especially public and users, play an important role. The key stakeholders were identified and their interaction and influence for water reuse industry were analysed. Their participation is crucial for enhanced water reuse. Strategies for clear legal basis and guarantee, establish communication platforms, formulate incentive mechanisms and improve education of public, for promoting stakeholders’, especially public, acceptance and participation were discussed.

As a summary, the potential market of non-conventional waters is huge and will be greatly promoted by the strategies and means discussed in the thesis for sustainable development, improvement of water security and the stakeholders’ cooperation and participation. For China, the wastewater discharge is about 80 billion m$^3$ per year, which means if intelligent strategy adopted, the potential reclaimed water could not only meet the 40.4 billion m$^3$ of annual water shortage, but also save the water from long-distance water diversion, as well as reduce the pollution burden of natural waters. Seawater desalination is here more marginal, but could supply 803 million m$^3$/a by 2015 as planned.

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Doctoral Thesis

Sustainable and Safe Use of Non-conventional Waters - Reclaimed Water and Desalinated Water

By

Shuang Liu

LUND UNIVERSITY

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Shuang Liu
ABSTRACT

Fresh water scarcity, pollution and an uneven distribution have caused an increasingly serious global water crisis. One of the most widely adopted response strategies is the exploitation and use of non-conventional water sources. Water reuse and desalination were in focus in the study which was aimed to develop the strategies to promote the sustainable and safe use of reclaimed water and desalinated water from the perspective of key factors affecting the development. China and Sweden are used for case studies. With the help of literature reviews, water quality analysis, microbial risk assessment models and statistic evaluation methods the suggested strategies were evaluated and improvements to the strategies suggested.

If sustainable development of non-conventional waters should be promoted, improvements and clarifications must be made in the aspects of legislation, management, water security and policy. Key factors for desalination were identified and analysed. The most important are technology promotion, energy efficiency, feed water treatment, full cost coverage in the price. Strategy and technology for lowering cost and developing intelligent pricing system are critical to desalination market. A sound management system, qualified water and supported policy and transparency to the public are key factors for water reuse. The relevant strategy for further sound development were suggested not only for China but also available for the countries with similar situations.

For improving the security of using non-conventional waters especially reclaimed water, the study was carried out from two perspectives: developing water reuse guidelines assessing microbial risk for using treated wastewater for different applications. The approaches for setting guidelines and how they should be formulated were discussed. A combination of epidemiology study and risk assessment was recommended for developing microbial indicators standard. Guidelines must include regulations of treatment processes and instructions on how to protect users and the public. Statistic methods imply that water quality monitoring can be simplified. Quantitative microbial risk assessment is an effective supplementary tool to guidelines and was applied for judging the possibility of reuse the studied water for different applications. The protective guidelines could be developed based on the process and results of risk assessment by controlling exposure pathway and dose.

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As a summary, the potential market of non-conventional waters is huge and will be greatly promoted by the strategies and means discussed in the thesis for sustainable development, improvement of water security and the stakeholders’ co-operation and participation. For
China, the wastewater discharge is about 80 billion m$^3$ per year, which means if intelligent strategy adopted, the potential reclaimed water could not only meet the 40.4 billion m$^3$ of annual water shortage, but also save the water from long-distance water diversion, as well as reduce the pollution burden of natural waters. Seawater desalination is here more marginal, but could supply 803 million m$^3$/a by 2015 as planned.
ABSTRACT (Chinese)

淡水资源的短缺，水环境污染和水资源的不均衡分布已经引起了严重的全球水资源危机。世界各国都采取了一系列策略以应对和缓解水资源危机。其中，非常规水源的开发和利用是一项在很多国家受到认可并广为应用的应对策略。本课题的研究对象为非常规水源中的再生水和淡化水，课题研究了如何从市场发展的影响因素角度制定发展策略以促进再生水和淡化水的安全及可持续利用。本课题以中国和瑞典作为研究案例，并且综合运用文献综述，水质分析，微生物风险评价模型及多元统计分析方法为发展策略的制定和改进提供依据。

课题研究表明为了促进非常规水源的可持续利用，相关的立法、管理体系、水质安全和政策等方面需要进行加强和完善。本课题识别并分析了中国脱盐产业发展的关键影响因素，主要包括脱盐技术的进步，能源的种类及利用效率，原水及其预处理，成本的回收和价格体系的合理性。降低成本的策略和技术的应用以及合理价格体系的形成是脱盐市场进一步发展的关键。此外，对于再生水回用，完善的管理制度，合理的水价体系，政策的支持，公众的支持和参与对其可持续发展起到重要作用。同时，课题对脱盐产业和再生水回用发展所面临的挑战与问题进行分析和讨论，并对相关的发展策略的制定和改进提出建议。

为了提高非常规水源特别是再生水利用的安全性，课题从两方面展开研究：制定再生水回用准则和针对再生水不同回用用途进行微生物风险量化评价。课题讨论了再生水回用准则的制定方法和所应该包含的内容。研究指出对于微生物指标标准的制定，应该将流行病学研究和风险评价方法相结合以提高指标的可靠性。除了指标限值，准则还应对处理工艺和处理程度、储存和输配过程，对用户和公众的保护条例做出明确规定。统计学方法和模型可以用于水质指标的相关性分析和准则中指标体系的简化。此外，对于保障再生水回用的安全性，风险评价是再生水回用准则的有效的补充手段并且可以应用于判断再生水回用于不同用途的可行性。同时，通过风险暴露途径的识别和暴露计量的计算，风险评价的过程和结果可以为制定用户和公众的保护条例提供依据。

除了管理者，其他利益相关者，特别是用户和公众，对非常规水源的安全及可持续利用同样起到至关重要的作用。课题对再生水回用的利益相关者进行识别并对其相互作用和对再生水产业发展的影响进行分析。利益相关者的认同和参与是促进再生水市场发展的关键。课题对如何提高利益相关者的认同并促进其参与的策略进行讨论，主要包括明确有效的法律依据和保障，建立沟通平台，制定激励机制和加强公众的教育等方面。
非常规水源潜在的发展空间是巨大的，并且本研究中所讨论的相关策略将会对其发展产生极大的促进作用。以中国为例，污水排放量大约为每年 800 亿立方米。如果策略实施得当，潜在的再生水产量不仅可以弥补每年 404 亿立方米的缺水量，并且可以减少长距离引水工程，同时大大降低自然水体的污染负荷。同样，相关政策和策略的有效实施将会保证海水淡化实现‘十二五’规划目标，2015 年达到每年至少 8.03 亿立方米的产量。
POPULÄRVETENSKAPLIG SAMMANFATTNING


För att lindra vattenbrist, särskilt i de snabbväxande städerna, behöver återanvändning av vatten och bättre hushållning med vattenresursen öka. Sådana vattenresurser kan hämtas från renat avloppsvatten (återvunnet vatten), avsaltat vatten, uppsamling av regnvatten och eventuellt långväga import av vatten från vattenrikare områden. I denna avhandling diskuteras återvinning av avloppsvatten och avsaltning av saltvatten, eftersom de är stabila och rikliga vattenresurser som påverkas mindre av naturliga faktorer som geologi, klimat och årstider.


Återanvändning har flera fördelar ur miljömässiga och ekonomiska perspektiv. Återvunnet vatten kan användas för att minska efterfrågan på färskvatten och kontrollera överexploatering. Rätt återanvänt vatten är också en metod som minskar kostnaderna för kväve- och fosforrenning, om närsalterna i avloppsvattnet används för växtodling. Behovet av konstgödning minskar också, vilket kan lindra utsläpp av näringsämnen till miljön.
minska övergödningsproblem. Vid utveckling av industriområden kan återanvänt vatten öka värdet på mark, öka möjligheten att anlägga våtmarker och skydda mot torka och värmeböljor. För att allt detta goda skall kunna ske behöver regler för hur vatten återanvänds tas fram och efterlevas. Vidare måste tydliga kvalitetskrav på återanvänt vatten fastställas som leder till att risker för användare och allmänhet minimeras. Återanvändningen måste granskas och kvaliteten på det återvunna vattnet garanteras. Många aktörer har en intuitiv rädsla mot återanvändning av avloppsvatten, vilket gör att kontrollen och införandet av återanvändningsmetoder måste ske transparant och i nära samverkan med alla intressenter som kan tänkas påverkas av återanvändningen.


Med utgångspunkt i kinesiska och svenska förhållanden har denna avhandling ägnats åt att undersöka hur strategier bör utvecklas för att främja en hållbar användning av av icke-konventionella vatten och hur säkerheten vid återanvändning av vatten kan garanteras för användare och allmänhet. En delstudie har ägnats åt hur de olika intressenterna kan involveras för att förbättra deras delaktighet vid återanvändning av vatten i samhället. En annan delstudie har ägnats åt att diskutera vilka krav som måste ställas på regelverket vid återanvändning av avloppsvatten i Sverige. Sverige saknar för närvarande helt ett regelverk för kvalitetskrav på medveten återanvändning av avloppsvatten. En tredje delstudie analyserar hur det kinesiska samhället kan främja en ökad utveckling av avsaltningsverkan för att minska överuttaget av färskvatten i kustnära områden i östra Kina. En fjärde studie fokuserar på villkoren för hur återanvändning av avloppsvatten kan garanteras i Kina. En femte studie granskar olika mikrobiella riskvärderingsmetoder för att bedöma säkerhet och uthållighet i återanvändning av avloppsvatten för tillämpningar utanför dricksvattensektorn.

Av arbetet framgår tydligt att åtgärder mot vattenbrist och för ökad vattensäkerhet måste genomföras på alla plan i samhället. Det räcker inte med bara tekniska lösningar. Därtöver måste en konkret nationell strategi tas fram där ett tydligt regelverk fastställs och en struktur för att granska efterlevnaden av regelverket utvecklas. Statistiska metoder kan användas för att förfina kontrollprogram för övervakning av vattenkvalitet och

APPENDED PAPERS

This thesis is submitted with the following appended papers, which will be referred to by their Roman numerals in the body text.


AUTHOR’S CONTRIBUTIONS TO THE APPENDED PAPERS

**Paper I.** The author planned the work, outlined the practical part and wrote most of the text. The co-author participated with supervision and contribution to the text.

**Paper II.** The author planned the work, outlined the practical part and written most of the text. The co-author supervised the work and participated with suggestions, advices and contributed in the text development.

**Paper III.** The author planned the work, outlined the practical part, elaborated the calculation model and wrote most of the text. The co-author supervised the work and participated with suggestions, advices and contributed in the text development.

**Paper IV.** The author planned the work, outlined the practical part, collected all water samples, made the entire chemical analysis, elaborated the statistical part and wrote most of the text. The co-authors participated with suggestions and advices and contributed in the text development.

**Paper V.** The author planned the work, outlined the practical part and wrote most of the text. The co-author participated with suggestions and advices and contributed in the text development.
RELATED PUBLICATIONS

Conference papers

Shuang Liu, Raed Alshaaer, Kenneth M Persson. Prospects for desalination as a water supply method. 9th conference in the series membranes in the production of drinking and industrial water (MDIW 2010), June 2010, NTNU-Trondheim, Norway.


Shuang Liu, Kenneth M Persson, Lena Flyborg. Study and discussion on reclaimed water quality guidelines. 26th annual water reuse symposium, September 11-14, 2011, Phoenix, US.

Shuang Liu, Kenneth M Persson, Cintia Bertacchi Uvo. A study of treated wastewater as feed-water for different reuse applications. IDA world congress 2013 on desalination and water reuse. October 21-25, 2013, Tianjin, China.
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Symbol/Description</th>
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<tr>
<td>As</td>
<td>Arsenic</td>
</tr>
<tr>
<td>BOD&lt;sub&gt;5&lt;/sub&gt;</td>
<td>5 days biological oxygen demand</td>
</tr>
<tr>
<td>BOD&lt;sub&gt;7&lt;/sub&gt;</td>
<td>7 days biological oxygen demand</td>
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<tr>
<td>BRA</td>
<td>Baseline Risk Analysis</td>
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<tr>
<td>CDA</td>
<td>China Desalination Association</td>
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<tr>
<td>Cd</td>
<td>Cadmium</td>
</tr>
<tr>
<td>CFU/100ml</td>
<td>Colony-forming unit per 100 milliliter</td>
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<tr>
<td>COD&lt;sub&gt;Cr&lt;/sub&gt;</td>
<td>Chemical oxygen demand (by potassium dichromate method)</td>
</tr>
<tr>
<td>Cr&lt;sup&gt;6+&lt;/sup&gt;</td>
<td>Hexavalent Chromium</td>
</tr>
<tr>
<td>°C</td>
<td>Degrees Celsius</td>
</tr>
<tr>
<td>DO</td>
<td>Dissolved oxygen</td>
</tr>
<tr>
<td>DPD</td>
<td>N, N diethyl-p-phenylenediamine</td>
</tr>
<tr>
<td>DACEHTA</td>
<td>Danish Centre of Health Technology Assessment</td>
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<td>e.g.</td>
<td>For example</td>
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<td>ED</td>
<td>Electrodialysis</td>
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<tr>
<td>E. coli (EC)</td>
<td>Escherichia coli</td>
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<td>Eff.</td>
<td>Effluent</td>
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<td>EHEC</td>
<td>Enterohaemorrhagic E. coli</td>
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<td>ETEC</td>
<td>Enterotoxigenic E. coli</td>
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<td>EPEC</td>
<td>Enteropathogenic E. coli</td>
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<td>EIEC</td>
<td>Enteroinvasive E. coli</td>
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<td>EPHC</td>
<td>Environment Protection and Heritage Council</td>
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<td>FC</td>
<td>Fecal coliform</td>
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<tr>
<td>Fe</td>
<td>Iron</td>
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<tr>
<td>GB</td>
<td>Chinese mandatory national standards</td>
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<td>GB/T</td>
<td>Chinese recommended national standard</td>
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<td>GWI</td>
<td>Global Water Intelligence</td>
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<tr>
<td>Hg</td>
<td>Mercury</td>
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<tr>
<td>HI</td>
<td>Instruments’ serial number from HannaNorden Company</td>
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<tr>
<td>ICP</td>
<td>Inductively Coupled Plasma</td>
</tr>
<tr>
<td>ICP-MS</td>
<td>Inductively Coupled Plasma Mass Spectrometry</td>
</tr>
<tr>
<td>IPCS</td>
<td>International Programme on Chemical Safety</td>
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<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
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Km  Kilometer
km²  Square kilometer
LAS  Anionic surfactant (Linear alkylbenzene sulfonate)
L/s  Liter per second
MSF  Multi-stage flash evaporation
Mn  Manganese
m  Meter
m³  Cubic meter
m³/a  Cubic meter per year
m³/d  Cubic meter per day
mg/L  Milligrams per liter
N  Number of exposure events per year (day)
N  Nitrogen
NAS  United States National Academy of Sciences
NGO  Non-governmental organization
NH₄-N  Ammonia nitrogen
NO₃-N  Nitrate nitrogen
NO₂-N  Nitrite nitrogen
NRC  United States National Research Council
NTU  Nephelometric Turbidity Units
NRMMC  Natural Resource Management Ministerial Council
N₅₀  Median infectious dose (mass)
P  Phosphorus
p  p-value in statistical significance testing
Pb  Lead
PCA  Principal Component Analysis
PCs  Principal components
PCU  Platinum-cobalt units
P₁ (A)  Annual probability of infection
P₁ (λ)  Daily probability of infection from viruses
POPs  Persistent Organic Pollutants
PPCPs  Pharmaceuticals and Personal Care Products
ppm  Parts per million (out of a million), equivalent to milligram per liter
QMRA  Quantitative Microbial Risk Assessment Model
RMB  Chinese currency Renminbi

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RO  Reverse Osmosis
SCB  Sweden Statistics Central Bureau
st/100ml  Most probable number of colony per 100 milliliter
SWWA  Swedish Water & Wastewater Association
TC  Total coliform
TDS  Total dissolved solids
TP  Total Phosphorus
TSS  Total suspended solids
VAT  Value-added tax
WHO  World Health Organization
WWTP  Wastewater Treatment Plant
US EPA  United States Environmental Protection Agency
US AID  United States Agency for International Development
US$/m³  US dollar per cubic meter
UV  Ultraviolet
#/L  Number per liter
% of sat.  Percentage of saturation
α  Slope parameter in dose-response modelling
λ  Exposure dose per person per day (mass) in dose-response modelling
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1. INTRODUCTION

1.1 Background

Water is not only an indispensable resource on which all life depends, but also an important and fundamental economic resource for social development. The available fresh water, which is closely related to human society and ecological environment protection, only accounts for 0.34% of the total water on the globe (The Earth Sciences, 2006). Over 780 million people are still without access to improved sources of drinking water and 2.5 billion lack improved sanitation (United Nations Children's Fund (UNICEF) and World Health Organization (WHO), 2012). Fresh water is unevenly distributed among the world’s population. Just 10 countries share sixty percent of the world’s natural, renewable water resources, while 80 countries are facing fresh water shortage (Growing Blue, 2013; Alois, 2007). Besides, the pollution and deterioration of water environment make fresh water shortage increasingly serious with the development of industry. Fresh water scarcity and water pollution, as well as an uneven distribution of water on the earth have caused a global water crisis.

Much effort has been made to deal with the water crisis, and one of the most widely adopted strategies is the development and use of non-conventional water sources which can be used to supplement intensively exploited conventional sources. The non-conventional water includes treated wastewater (reclaimed water), desalinated water, rain harvesting, and imported water (Jaber & Mohsen, 2001). Reclaimed water and desalinated water are discussed in the thesis since they have the characteristics of stable water quality and quantity and large volume, and are less affected by natural factors such as geology, climate and seasons. Also, the use of reclaimed water and desalinated water has been increasingly given attention and wildly carried out in many countries and regions, such as US, Middle East, EU, Singapore and China, and are being promoted as an important means of dealing with water shortage caused by quantity and quality.

1.1.1 Water reuse

Reclaimed water, which is defined as ‘municipal wastewater that has gone through various treatment processes to meet specific water quality criteria’ (Asano, et al., 2007), is one of alternative water sources for many countries, because water reuse, which is the use of reclaimed water/treated wastewater for beneficial purposes, is considered to be a cost-effective solution to deal with the water shortage (Asano, et al., 2007; United States Environmental Protection Agency (US EPA), 2013). Generally, water reuse can be divided into two types: direct and indirect reuse, both of which include potable and non-potable applications. According to Asano et al. (2007), the applications of water reuse include agriculture irrigation; industrial uses, such as manufacturing (both process water and cooling water) and construction industries; landscape irrigation, such as irrigation for gardens, golf courses, sport and recreational lands; urban non-irrigation uses, such as toilet flushing, car washing, fire-fighting, street washing, dust suppression and snowmaking; environmental and recreational uses, such as water for the restoration and re-creation of existing or creating new aquatic ecosystems, recreational water bodies and fish ponds;
groundwater recharge, such as aquifer recharge through infiltration basins and injection wells for water storage and saline intrusion control; and potable reuse (both direct and indirect) which is not discussed in the thesis since it is not as widely applied as non-potable reuse.

Water reuse has many benefits from environmental, ecological and economic perspectives. For the non-potable applications, water quality does not necessarily meet the drinking water quality standards. Reclaimed water can be used in those applications to lower the demand for fresh water and avoid over-abstraction. In addition, intelligent water reuse can be a method to reduce the costs of nitrogen and phosphors removal in wastewater treatment plant when the effluent is applied for irrigation, since plants use nutrients from the water. Hence, if applied correctly, it is a method to reduce nutrient discharge to the environment and the loss of fresh water to the sea, which are both beneficial for water environment protection and saving fresh water. Further on, when developing brownfield sites, water reuse can increase the value of land and offer drought-proof irrigation or be used to increase local ecological benefits and tourism. Also, reused water can be applied to create and restore wetlands or be used in urban irrigation to develop greener cities. In the long-term, the need for and cost of long sea outfalls could be minimized to some extent when water is reused instead of discharged to the sea. And from energy and ecological costs aspects, the costs of water reuse are normally lower when compared to other methods such as deep groundwater extraction or pumping, importation, impoundment, long-distance water diversion and desalination.

Although much progress has been achieved, the challenges and problems in the fields of management, reclaimed water quality, guidelines, policy, acceptance and participation by stakeholders, fund raising, market development and so on, still exist and hinder the sustainable development of water reuse, which is a growth model focusing on sustainability and long-term sound development, to a certain extent. Of all challenges the security of reuse is subjected to the most attention and studied. Different from fresh water, wastewater contains high concentration of pollutants. Although the concentration significantly lowers after treatment, many kinds of pollutants, especially the pathogenic microorganisms, still can be detected in reclaimed water and pose a potential threat to human health (Zhao et al., 2010; Toze, 2006). Also, the use of reclaimed water maybe increase the risk of the groundwater contamination and water eutrophication associated with residual unregulated chemicals in the reclaimed water (Lee, and Jones-Lee, 1995; Yin et al., 2012.). The safety of use of reclaimed water is still an important research subject and a political issue, and strongly affects the public perception and acceptance.

1.1.2 Desalination

Desalination can be defined as water treatment processes that remove salt and other minerals from saline water such as ocean and brackish water and make it safe for human consumption and use (Buros, 2000). Desalination is an important method for producing potable water and is a rapidly growing technology worldwide since it can increase the total amount of fresh water on earth (Ruiz et al., 2007). Historically, desalination has been a fresh water supply opportunity for a long time, especially at remote locations and on naval
ships off shore. The rapid growth of desalination technology with the social and economic development in the recent decades allowed it to continue and grow also in arid and semi-arid areas. The installed desalination capacity has increased rapidly worldwide, from 8,000 m$^3$/d in 1980 to about 80.2 million m$^3$/d installed or contracted production capacity with over 16,000 industrial-scale desalination units by 2012 (Global Water Intelligence (GWI), 2013). A variety of desalting technologies has been developed over the years, primarily thermal and membrane processes. According to International Desalination Association Year Book 2012–2013 (GWI, 2013), so far, reverse osmosis (RO) and multi-stage flash evaporation (MSF) dominate the market of desalination and take up 63% and 23% of installed capacity, respectively; seawater and brackish water is the main raw water for desalination since they account for 59% and 21% of installed capacity, respectively; and the desalted water is mainly used for municipal (62%) and industry (26%) purpose, while other applications include power station, irrigation, tourism, military and others with small proportion. Energy input, which is divided into two categories 1) conventional fossil based energy (gas, oil, coal) and 2) renewable energy sources (wind, solar, etc.), is an important factor to the development of desalination since it is associated with the cost of desalination and the impact on the environment. Until now, desalination relies heavily on conventional energy, because the cost of fresh water produced from desalination using conventional energy is much lower at present (Karagiannis and Soldatos, 2008). Although the investment and operational costs of desalination plants depend on a variety of factors, such as capacity, water source, energy input and technology, total production costs have significantly decreased with time (Wangnick, 2002). The market is also driven by the falling costs of desalination, which are due to the technological advances in the desalination process (Tsiourtis, 2001).

The challenge in desalination industry mainly comes from the higher price compared to other methods of water supply, especially in developing countries. Desalination costs are either at a similar or often at a higher level than average municipal water tariffs in most developing countries (Schiffler, 2004), which lowers the competitiveness of desalination for customers and influences the attitude of decision makers when they develop policy, strategy and planning. Thus, further reducing the cost of producing water is crucial to the sustainable development of desalination market. Besides, similar with water reuse, supported policy and the market operation mechanism such as pricing, financing and selling, greatly affect the development of desalination industry.

1.2 Objective and scope

As mentioned in Section 1.1, the objects of the study were reclaimed water (non-potable applications) and desalination. Other non-conventional waters such as rainwater harvesting and water diversion were not included in the study. The structure of thesis work is shown in Figure 1. The objective of the study described in this thesis was to developed strategy to promote sustainable development and safe use of non-conventional waters, including (a) develop the strategy from policy, management, guidelines, market operation mechanism, price and technology to promote the sustainable development of water reuse and desalination industry, (b) develop the strategy from the perspective of health-based guidelines and risk assessment to improve the security of water reuse; and (c) promote
sustainable and safe use of non-conventional waters (reclaimed water for example in the thesis) from the analysis of stakeholders and the improvement of stakeholders’ participation perspective.

The scope of the study on promoting development focused on strategy and policy. The processing technology of reclaimed water and desalination was not focal point. Also, for the study of improving security of water reuse, the scope was to focus on providing a reference of approach and principal to water managers to formulate health-based protective guidelines and reuse policy, but did not involve the quantitative of limits for water quality parameters in the guidelines and complex pathogens detection, which should be based on more studies and experiments.

The situations vary in different countries mainly depending on status of water resources and economy. Case studies were needed for detailed analysis. In the thesis, China and Sweden were in focus since they were representatives of countries with different situations. Literature review, water quality analysis, microbial risk assessment and multivariate data analysis were employed and the following sub-questions were addressed to achieve the main objective.

- What is the situation of desalination in China? How to reduce the cost and promote the development of desalination industry from technology, energy, feed water, financing and policy perspective?

- What are the situations and challenges of water reuse in China? How to solve the problems and improve e.g. management systems, guidelines, water security, policy, price system and market operation mechanism, to realize the sustainable use of reclaimed water?

- Can the water in the studied site be reused for different applications from microbial perspective? What should be suggested to water manager to improve the security of reuse treated wastewater according to the process and results of microbial risk assessment?

- What should be suggested for developing the water reuse guideline in Sweden from the scope of the approaches and contents?

- Who are the stakeholders of water reuse? How to improve the stakeholders’ acceptance and participation to promote the sustainable development of water reuse?
1.3 Thesis structure and appended papers

This thesis is based on the research work presented in the five appended papers numbered I to V. After introduction in Chapter 1, the theoretical background of the appended papers including the situations of studied areas and literature review of recent research are presented in Chapter 2. In Chapter 3, an overview of methods and material used as well as data collected are presented. In Chapter 4, the main results from the appended papers are summarized and discussed. Finally, conclusions, limitations and unresolved questions as well as further studies are presented in Chapter 5.

The main methods used and results arrived at are summarized in this thesis but more details can be found in the appended papers which are shortly described as following.

Paper I presented an overview of the desalination status in China as a case study from the perspectives of driving force, investment, cost, policy, safety and energy. The analysis of problems made the recommendations how to develop desalination market and make desalination as a sustainable water supply. In addition, the paper compared desalination with wastewater reuse in water quality, cost, management, public acceptance and so on and
discusses the proposal for integrated utilization of different non-conventional water sources.

In Paper II, the driving forces, the situations of applications, the social institutions and cultural backgrounds related to the water reuse in China were reviewed and presented by a literature review and survey. The obstacles and challenges were discussed from management system, safety of reclaimed water quality, economy and policy perspectives. The representative cities such as Beijing and Tianjin were selected for examples in some aspects. Through review and analysis, it could be concluded that the management system, price system, security of reclaimed water and supported policy are the main factors affecting the development of water reuse in China. The paper also identified strategies for further sustainable and safe water reuse.

Paper III estimated the microbial risk of E. coli and rotavirus in reclaimed water for different applications of irrigation, landscape, industry, unban non-potable water. A Quantitative Microbial Risk Assessment model was used and the samples were collected from the pond system of Källby wastewater treatment plant in Lund, Sweden during one full year. The results were used to evaluate if the treated wastewater after tertiary treatment process combined with pond system can be reused for different applications from a microbial point of view. And the recommendation how to lower the risk and make water reuse for different applications safer was discussed. The objective and scope of the paper focused on providing reference to water manager to formulate health-based protective guidelines and reusing policy according to the process and results of risk assessment.

In Paper IV, recommendations for development of water reuse guidelines in Sweden were discussed and concluded based on the quality of treated wastewater from Källby wastewater treatment plant, learning from existing guidelines and Principal Component Analysis (PCA). The results from monitoring of water quality and learning from other water reuse guidelines gave the suggestions for the selection of water quality parameters, the approach to set microbial parameters and regulations of wastewater treatment. PCA was applied for identification of the significant factors affecting the water quality, which should be considered when formulating the guidelines, and simplification of routine monitoring parameters regulated in guidelines by obtaining the correlation between parameters. Protective measures which should also be included in the guidelines were suggested.

Paper V identified the key stakeholders of reclaimed water which were named policymakers, administrators, supplier, investors, customers, public, researchers, land users and other waters sectors, and analysed their interest and impact on water reuse and interaction, as well as how to improve the stakeholders’ acceptance to promote the sustainable development of water reuse. The paper also analysed the challenges and strategy for sustainable water reuse in China from stakeholder’s communication and participation perspective.
2. THEORETICAL BACKGROUND

This chapter provides the background and a literature review about situations of desalination and water reuse in studied area and relevant theoretical concept as a basis for discussion in the following chapters. It is not intended to present a full account of state of the art, but rather the necessary facts to familiarize the reader with the context.

2.1 The use of non-conventional waters in China

2.1.1 Water crisis in China

Listed on the thirteen countries of the most water-poor in the world, China, which is a populous developing country is facing severe water crisis. The total annually renewed fresh water is about 2800 billion m³, equivalent to about 2000 m³ per capita per year, as compared to a global average of about 6200 m³ (World Bank, 2012; UN Food and Agriculture Organization, 2012). Moreover, there is much variation of distribution within the country, from less than 500 m³/year per inhabitant in the Huai and Hai-Luan river basins in the north, to over 25 000 m³/year per inhabitant in river basins in the southwest (UN Food and Agriculture Organization, 2012). By the end of 20th century, among 661 cities in the country, more than 400 cities had problems of inadequate water supply. 110 cities are facing serious water shortage. Besides, water quality deterioration aggravates the difficulty of water supply (Yu, 2004), which is mainly caused by human activities such as illegal discharge from industry, agriculture and domestic sewage without proper treatment and uncontrolled disposal of municipal solid waste, as well as lagging water pollution control. The situations of fresh water shortage and pollution are well documented in the literature and bulletins (Hong, 2003; Yang, 2004; Yan, 2004; Yu, 2004; Ministry of Environmental Protection of China, 2011). Also, the overexploitation of groundwater takes place in almost all large- and middle-sized cities, which leads to ground subsidence, seawater intrusion for coastal locations, salinization of land, drained wetlands, dried watercourses and lakes and other ecological damages. Besides the over-exploitation, groundwater in 76 cities is seriously polluted to a level where the water is unsuitable for water supply. Due to fresh water scarcity, severe pollution and temporally and spatially uneven distribution, more and more obstacles and problems for the water supply in China are identified. It is predicted that the water resources per capita would decrease to 1,760m³ by 2030, which was calculated according to the population increasing to 1.6 billion (Liu and Chen, 2001). The value would be closed to 1,700m³ per capita, which is the internationally recognized water stressed standard. By 2050, the shortage of water would increase to $3.71 \times 10^{11}$ m³/a, and the output value impacted by urban water shortage would be up to more than $2.0 \times 10^{11}$ Yuan RMB /a, with about 40 million of the population affected (Wan, 1999). Moreover, both water consumption per capita and total water consumption per year increase for recent years (Ministry of Water Resources of China, 2000-2011). This means that the imbalance between supply and demand is expanding. The complicated and severe situation makes China a representative case for the research presented in this thesis.
Much effort has been made taking both supply and demand parties into account, such as water saving policy, the development of water-saving technology in agriculture and low-water consumption industry, the adoption of economic and legal means to prevent the waste of water and illegal discharge and carrying out the South-to-North Water Diversion Project to distribute the imbalance in the area of water resources. Besides the methods above, in the case of mediating shortage and pollution of conventional water resources, non-conventional water resources, especially reclaimed water and desalinated water which can provide stable and large water, have been developed and used to ease the water crisis and guarantee sustainable water supply in China.

2.1.2 History and situations of desalination in China

In China, the littoral resides 40% of the total population and contribute to 70% GDP of China in the 13 provinces with coast. China’s population and economy are concentrated in the coastal zone, which makes desalination a viable alternative source of water, as many coastal cities face serious fresh water shortage (Zhou and Tol, 2005). Of the main modes of access to fresh water besides local surface water source, desalination is an important way to provide fresh water to these water-shortage areas instead of over-exploitation of groundwater or transferring water from long way, since China has 32,000 km of coastline and 3,000,000km² of marine areas which contain abundant seawater resources (Zhang et al., 2005) and desalination has less impact on surrounding residents and ecological environment and normally lower cost than South-to-North Water Diversion in China.

Research on technology of water desalination in China started with ED in 1958, in a cooperation between the navy and the Chinese Academy of Sciences; the research on RO started in 1965; the research on large- and medium-sized distillation started in 1975. In 1981, the first ED desalination station with capacity 200m³/day was officially put into operation in Yongxing Island of Xisha (Paracel) Islands (Ruan et al., 2006). After more than 40 years of development, desalination in China has made considerable progress and achievements, gradually forming a comprehensive technology subject and water treatment technology industry (Peng, 2006), which has accelerated in recent years for increasingly serious water crisis. Data from the Ministry of Science and Technology showed that as of September 2011, the total capacity of seawater desalination in China had reached 660,000m³/day, which was more than 13 times of the level in 2005 (50,000 m³/day) (Anonymous, 2012). Up to 2007, 41% of the desalinated water was used for municipal, 38% for industrial and 21% for power production purposes; RO has the largest share of the Chinese desalination market with 75% proportion; the main feed water is seawater, accounting for 53% (GWI, 2007-2009). The average seawater desalination cost in China, which is 5–7 Yuan RMB/m³ (Baidu Encyclopedia, 2013), is higher than the average in the world (0.5 US$/m³) (Bashitialshaer and Persson, 2010), because of multi reasons such as shortage of large plants, lack of core technology and intellectual property rights, and bad raw water quality due to serious pollution of ocean, which are discussed in the thesis.

Nevertheless, compared with the Middle Eastern countries, desalination in China is still not as much applied as might be expected. The total installed capacity is only ranked sixth in the world and daily output is only about 1% of the global production (GWI, 2012).
Besides comparatively high price there are also other problems existing, such as inadequate policy and management, which delay the pace of development. In 2012, the issue of ‘The views on accelerating the development of the desalination industry’ (Document No. 13, 2012) by the office of State Council identifies the desalination industry to the national strategic level (State Council Office, 2012). Information from China Desalination Association (CDA) shows that during ‘12th Five-Year’ period, investment for desalination is expected to reach 200 billion Yuan RMB (Anonymous, 2012). Desalination in China is facing unprecedented opportunities for development yet many challenges remain.

2.1.3 Non-potable water reuse in China

Water reuse has the advantages as already described in the Section 1.1.1, such as saving fresh water and reducing pollution discharge, and more importantly being cost-effective, which is appropriate method for developing countries such as China. In China, the use of reclaimed water can be traced back to the 1950s when China adopted the method of sewage irrigation to reuse treated wastewater. In the late 1980s, thanks to the reform and opening policies and consequent economic development and improvement of the living standard, water demand in Chinese cities sharply increased. At the same time, water pollution was increasingly serious because many enterprises illegally discharged untreated wastewater into natural water. In addition, the waste of water resources was widespread, mainly due to the inaccurate low pricing of the water resource. The growth of mega-cities also started during this period. The research and practice of water reuse developed rapidly in this period, and aimed to address the increasing water shortage and pollution (Li, et al., 2007). In 1989, China’s first water reuse demonstration project was designed and constructed in the Dalian Chunliu wastewater treatment plant, and was officially put into operation in 1992 (Yao, 2006). Reclamation of sewage was included in succession in the key science and technology research of ‘the seventh, eighth and ninth five-year plans’. Up to the period of “the tenth five-year plan” (2001–2005), reclaimed water for the security of water resources was officially written into this planning framework and the scientific and technological research was subsequently carried out (Wei, et al., 2006). To make reclaimed water the second water source for urban areas, China began to initiate water reuse on a nationwide scale. By 2009, in total, 243 reclaimed water plants had been built, with a total production capacity of 18.54 million m³/d. Reclaimed water pipelines were built to a length of 4344 km (Zhong et al. 2012).

Non-potable uses, which are named by the regulation of the national standard of The Reuse of Urban Recycling Water—classified standard (GB/T 18919-2002) as agriculture and forestry irrigation, industrial use, scenic environment use, urban non-potable water and supplementary of water source, are the main application modes of reclaimed water in China. To encourage and streamline use of reclaimed water, the improvement of reclamation and use of treated wastewater have been written in the Water Law (Presidential Decree No. 74 of the People's Republic of China, 2002, 29th August), and relevant regulations are developed on local level which however is on the lowest force level of the Chinese multi-level decision structure.
For safe use of reclaimed water, authorities promulgated a series of water quality national standards and design specifications for urban water reuse for different applications. The national standards include six parts: Classification of Municipal Wastewater Reuse (GB/T 18919–2002) and reclaimed water quality standards for five applications (shown in Table 1).

Table 1: National Reclaimed Water Quality Standards

<table>
<thead>
<tr>
<th>Classification</th>
<th>Purpose</th>
<th>Reclaimed Water Quality Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industry uses</td>
<td>Cooling water, Washing water, Boiler water, Process and Products water</td>
<td>“The reuse of urban recycling water - Water quality standard for industrial uses” (GB/T 19923-2005)</td>
</tr>
<tr>
<td>Scenic environment use</td>
<td>Entertainment landscape environment water</td>
<td>“The reuse of urban recycling water - Water quality standard for scenic environment use” (GB/T 18921-2002)</td>
</tr>
<tr>
<td></td>
<td>Aesthetic landscape environment water</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wetlands environmental water</td>
<td></td>
</tr>
<tr>
<td>Agriculture, forestry, husbandry and fishery</td>
<td>Agriculture irrigation, Forestation, Farm and pasture, Aquaculture</td>
<td>“The reuse of urban recycling water — Quality of farmland irrigation water” (GB 20922-2007)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“Water Quality Standards for Fisheries”(GB 11607-89)</td>
</tr>
<tr>
<td>Water resources supplement</td>
<td>Groundwater recharge</td>
<td>“The reuse of urban recycling water - Water quality standard for groundwater recharge”</td>
</tr>
<tr>
<td></td>
<td>(surface and injection recharge)</td>
<td>(GB/T 19772-2005)</td>
</tr>
</tbody>
</table>

Source: The series standards for the reuse of urban recycling water. (China's State Administration of Quality Supervision, Inspection and Quarantine, China National Management Committee for Standardization, 2002-2007)

GB: National standards

Water pricing is important. At the present stage, the cost of producing reclaimed water is about 0.5–3 Yuan/m³ (Baidu Encyclopedia, 2013), varying with different technologies, capacity and so on. For promoting the development of water reuse market, some supporting policy about investment, use and operation have been implemented. For example, to encourage the use and operation, the relevant incentives policies have been
made at both the government and the local level. ‘The notice on the value-added tax (VAT) policy of comprehensive utilization of resources and other product’ (Finance and Taxation [2008] No.156) developed by the Ministry of Finance and State Administration of Taxation and ‘The identification and management methods on the comprehensive utilization of resources encouraged by the state’ ([2006] No.1864) developed by the National Development and Reform Commission, Ministry of Finance and State Administration of Taxation, stipulated a free VAT policy on the sale of reclaimed water; the Beijing government set the policy that the reclaimed water users could be exempted from the water resources fee and the sewage treatment fee; the Tianjin government formulated a lower price and free water resources fee and city utility surcharges for reclaimed water users (Wu et al., 2010).

Although much progress has been made, for several reasons wastewater treatment and reuse of treated wastewater are still developing slowly. According to the data from Ministry of Environmental Protection of China (2011) and Ministry of Water Resources of China (2011), the secondary treatment rate of wastewater was about 49.9% in 2011. Besides, Wastewater treatment is unevenly developed with the rates of some cities are 70–90%, even up to 100%, while many places have no wastewater treatment at all. In 2011, the amount of reclaimed water produced was only 1.29 × 10⁹ m³, 9.6 × 10⁸ m³ of which was actually used (Ministry of Environmental Protection of China, 2013). The reclaimed water was only 0.5% of the total water supply in 2011 according to the data of China's Environment Bulletin (2011). The rate of water reuse (the amount of water reused / the amount of wastewater treatment) was rather low and varies a lot for different cities from zero to 60%. The study on the challenges and appropriate strategy are significant for the sustainable reuse of treated wastewater in China and is a key focus area in the thesis.

2.2 Water reuse in Sweden

In general, Sweden is a country with rich fresh water resources. In most parts of Sweden, there is no incentive for using treated wastewater directly because abundant resources can meet all needs (Swedish Water & Wastewater Association (SWWA), 2000). Indirectly water reuse is however common and is the main way in Sweden, which means that treated wastewater is discharged to receiving water and becomes water sources again through the natural hydrological cycle. Nevertheless, direct reuse of treated water still makes sense in Sweden for some reasons. Firstly, parts of Sweden, such as the south eastern of the country and Skåne county, experienced dry and hot summer expressed as low precipitation and high evaporation in some year e.g. 2008, 2010 and 2013, which caused restrictions on irrigation and resulted in a bad harvest (Stockholm News, 2008; Radio Sweden, 2010; The Local, 2010; Johansson, 2013). In these cases, reclaimed water can provide a stable alternative water source and reduce the harvest loss caused by water shortage in dry summers. In addition, water reuse is an ecological solution to reduce the discharging of treated sewage water to the receiving water. From economical perspective, reuse of treated wastewater can minimize infrastructure costs and chemicals, and thus be profitable both for water utility authority and users. From rational and sustainable use of water resources perspective, the practice of reuse contributes to prevention of excessive diversion of water from alternative uses, such as conserve groundwater for other uses (Vigneswaran and
Sundaravadivel, 2004; Raso, 2013). Also, water reuse can be developed for sanitation or environmental protection purposes in response to increasingly stringent environmental regulations (Angelakis, 2013).

There have been some projects to use the treated effluents directly in Sweden, mostly for irrigation and industry. For example, in the south eastern region of Sweden there is an interest in reusing the tertiary treated effluents of WWTP for irrigation (United States Environmental Protection Agency (EPA), 2004). The effluent reuse contributes to ease the water shortage and preserves surface and groundwater for other uses. In south east Sweden, over 40 reuse projects are implemented. They consist mainly of treated effluent storage up to 9 months in large reservoirs before being used for irrigation. In some cases the effluent is blended with surface water (Marcos do Monte, 2007). In Sweden, industry is the main part of water consumption (64% of total water withdrawals, Sweden Statistics Central Bureau (SCB), 2010). Water recovery is an important way to reduce water consumption and started early in Sweden. The industrial wastewater, after proper treatment, is used for cooling, district heating and so on (Salter, 2006). The reclaimed water not only reduces fresh water consumption, but also saves energy. Besides, there are also some demonstrations in eco-villages, such as Toarp (Fittschen & Niemczynowicz, 1997), which reuse treated wastewater for non-potable application, such as irrigation for agriculture and garden. Water reuse makes the water in eco-villages to form closed loop, which means virtually zero pollution discharge to outside water body.

Yet these projects have minor contribution to the water balance of Sweden. The amount of reused water is limited compared to the wastewater discharged to the receiving water, and so far, there are no Swedish guidelines/standards for water reuse developed, which are important steps for safe water reuse (Raso, 2013) and few studies of how to reuse the treated wastewater safely in Sweden can be found.

2.3 Pollutants in reclaimed water

Reclaimed water is a special water resource since it originates from wastewater which contains lots of chemical and microbial pollutants. With the development of society and industry, more and more types and amounts of chemicals which pose a serious threat to human health and ecological environment due to their refractory, bioaccumulation, chronic toxicity, can be found in domestic, industrial and pharmaceutical wastewater which are maybe feed water for reuse. Many kinds of pollutants, such as chemicals (e.g. Persistent Organic Pollutants (POPs), Pharmaceuticals and Personal Care Products (PPCPs)) and pathogenic microorganisms (enteric viruses, Escherichia coli (E.coli), Giardia lamblia, Cryptosporidium parvum, and helminth), can be detected in reclaimed water (Zhao, et al., 2010; Toze, 2006). Despite low concentration, the remaining pollutants, the concentration of which is closely related to the quality of feed water and treatment process, in the reclaimed water pose a potential threat to human health and environment if experienced long-term exposure. For example, chemicals and pathogens maybe contaminates surface and ground water; high salinity causes salinization or soil compaction; pathogens and chemicals may be a threat to public health through respiratory or direct contact; toxic
chemical pollutants and heavy metals may be toxic to irrigated plants or accumulated in plants and soil (Xu and Wei, 2009).

Conventional treatment process can effectively remove most organic or inorganic matters, but generally they have low efficiency for pathogens and special pollutants (Hela et al., 2005) such as POPs, environmental endocrine disrupter and PPCPs, on which advanced treatments such as activated carbon, coagulation and precipitation, membrane technology, especially RO, have better removal effect. Besides, the requirements of removal of pollutants and the selection of technology depend mainly on the reuse applications. For example, nitrogen and phosphors do not need to be removed when reclaimed water is used for irrigation since they are essential for plant growth, but they are the main substances causing eutrophication when used for landscape. Pathogens, which can cause acute or chronic diseases and even be lethal, are the main source of health risk when reclaimed water is used, thus, the efficient and sufficient removal is necessary process for all the applications. To guarantee the safe reclaimed water quality and supply to customers and environment, relevant guidelines and risk assessments are significant measures and adopted by most countries.

2.4 Reclaimed water guidelines

The reclaimed water should meet sufficient requirements of human health and environmental safety. One of the critical steps for the safe use of reclaimed water is the establishment of reasonable reclaimed water quality standards and utilization guidelines, which have been formulated in many countries such as US, Australia, Canada, Israel, Japan, China, Germany, Spain. For example, US EPA formulated guidelines for water reuse in 2004, and some states in US have local regulations due to different local conditions, which are more stringent than national guidelines. Most state guidelines include requirements on reclaimed water quality, treatment, monitoring, storage, treatment facility reliability and the types of application. For irrigation, some states have special regulations for loading rates, groundwater monitoring and setback distances (US EPA, 2004). The regulations, which are formulated after cautious discussion and study, have high operability for implementation. Also Australia has an elaborated national water reuse guidelines, and detailed state guidelines have been developed in e.g. Queensland, Victoria, and South Australian.

It is impractical to detect and include all pollutants in guidelines due to the technique and economic constraints. Depending on the difference in types of application and local situations, mainly the level of economy and technology, the emphasis of guidelines and the selection of water quality parameters vary from counties to countries. For example, Chinese national reclaimed water quality standards (China's State Administration of Quality Supervision, Inspection and Quarantine, China National Management Committee for Standardization, 2002-2007) have detailed classifications for applications with different requirements of physical, chemical and microbial parameters and clearly provide measuring methods and frequency for testing. But there are no stringent requirements of treatment, distribution and storage. Compared to Chinese standards, most guidelines in other countries or regions don't include as many parameters as Chinese standards. But the
strict requirements on treatment and management suggest that the quality of reclaimed water can be guaranteed even if the monitoring of some parameters is omitted. Many guidelines mainly focus on pathogens, which is the most serious threat from reclaimed water (Toze, 2006). Therefore, parameters related to pathogen density are suggested for monitoring in these countries, such as TSS, turbidity and fecal coliform. A summary of select guidelines and mandatory criteria for reclaimed water use in a variety of U.S. states and other countries is presented in Figure 2.

<table>
<thead>
<tr>
<th>Country/Region</th>
<th>Fecal Coliforms (CFU/100 ml)</th>
<th>Total coliforms (cftu/100 ml)</th>
<th>Helminth eggs (PRL)</th>
<th>BOD5 (ppm)</th>
<th>Turbidity (NTU)</th>
<th>TSS (ppm)</th>
<th>DO (% of Sat.)</th>
<th>pH</th>
<th>Chlorine residual (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia (New South Wales)</td>
<td>&lt;1</td>
<td>&lt;250</td>
<td>--</td>
<td>&gt;20</td>
<td>&lt;2</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Australia</td>
<td>&lt;1</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1</td>
<td>--</td>
<td>--</td>
<td>4.5-9</td>
<td>--</td>
</tr>
<tr>
<td>California</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>2</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Cyprus</td>
<td>50</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>10</td>
<td>--</td>
<td>10</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>EC bathing water</td>
<td>100 (g)</td>
<td>500 (g)</td>
<td>2,000 (m)</td>
<td>10,000 (m)</td>
<td>2 (g)</td>
<td>1 (m)</td>
<td>80-120</td>
<td>6-9</td>
<td>--</td>
</tr>
<tr>
<td>France</td>
<td>&lt;1000</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Florida (m)</td>
<td>25 for any sample for 75%</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>20</td>
<td>--</td>
<td>5</td>
<td>--</td>
<td>1</td>
</tr>
<tr>
<td>Germany (g)</td>
<td>100 (g)</td>
<td>500 (g)</td>
<td>20 (g)</td>
<td>1-2 (m)</td>
<td>10</td>
<td>--</td>
<td>60-120</td>
<td>6-9</td>
<td>--</td>
</tr>
<tr>
<td>Japan (m)</td>
<td>10</td>
<td>10</td>
<td>--</td>
<td>--</td>
<td>10</td>
<td>5</td>
<td>--</td>
<td>6.9</td>
<td>--</td>
</tr>
<tr>
<td>Israel</td>
<td>--</td>
<td>2.2 (50%)</td>
<td>12 (60%)</td>
<td>--</td>
<td>15</td>
<td>--</td>
<td>15</td>
<td>6.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Italy</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Kuwait</td>
<td>--</td>
<td>10,000</td>
<td>--</td>
<td>--</td>
<td>10</td>
<td>--</td>
<td>--</td>
<td>6.9</td>
<td>1</td>
</tr>
<tr>
<td>Kuwait</td>
<td>--</td>
<td>100</td>
<td>--</td>
<td>--</td>
<td>10</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1</td>
</tr>
<tr>
<td>Oman 1</td>
<td>&lt;200</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>15</td>
<td>--</td>
<td>15</td>
<td>6.9</td>
<td>--</td>
</tr>
<tr>
<td>Oman 1</td>
<td>&lt;1000</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>20</td>
<td>--</td>
<td>30</td>
<td>6.9</td>
<td>--</td>
</tr>
<tr>
<td>South Africa</td>
<td>0 (g)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Spain (Canary islands)</td>
<td>--</td>
<td>2.2</td>
<td>--</td>
<td>10</td>
<td>2</td>
<td>3</td>
<td>--</td>
<td>6.5-6.4</td>
<td>1</td>
</tr>
<tr>
<td>Texas (m)</td>
<td>75 (m)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>5</td>
<td>3</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Tunisia</td>
<td>--</td>
<td>--</td>
<td>&lt;1</td>
<td>30</td>
<td>30</td>
<td>7</td>
<td>6.5-8.5</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>UAE</td>
<td>--</td>
<td>&lt;1000</td>
<td>--</td>
<td>&lt;10</td>
<td>--</td>
<td>--</td>
<td>&lt;10</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>United Kingdom Bathing Water Criteria</td>
<td>100 (g)</td>
<td>500 (g)</td>
<td>2000 (m)</td>
<td>10,000 (m)</td>
<td>2 (g)</td>
<td>1 (m)</td>
<td>60-120</td>
<td>6-9</td>
<td>--</td>
</tr>
<tr>
<td>US EPA (g)</td>
<td>14 for any sample, 6 for 90%</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>10</td>
<td>2</td>
<td>--</td>
<td>6-9</td>
<td>1</td>
</tr>
<tr>
<td>WHO (irrigation)</td>
<td>200 (g)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Figure 2: Summary of Water Recycling Guidelines and Mandatory Standards

(g = guidelines, m = Mandatory Standards)
From Figure 2 (US EPA, 2004), it can be seen that Fecal coliform (FC) or total coliform (TC) are the indicators of microbiology, of which the limits vary considerably. The large difference comes from different principles of formulation. Currently, there are three different approaches to setting microbiological guidelines: 1) The absence of fecal indicator organisms in the wastewater, 2) No measurable excess cases in the exposed population, and 3) A model-generated risk which is below a defined acceptable risk (Blumenthal, et al., 2000). Some countries, such as US, adopt approach 1), which enact the FC indicator based on “zero risk” concept. That means fecal contamination should be absent and no potential infection risk should be present (Havelaar et al., 2001). This requirement is not immediately available for most developing countries due to economy and technology. For the safe use of treated wastewater in agriculture and taking realistic condition in developing countries into account, World Health Organization (WHO) revised its guidelines based on approach 2) epidemiological perspective in 1989 (Blumenthal, et al., 2000), which aims at making the health risk lower than certain value. Most countries, especially developing countries such as China adopt the WHO guidelines or use it as a basis for setting national guidelines, as it is cost-effective.

However, although the WHO guideline takes into account all available epidemiological evidence and information, the controversy still exists. The critics argue the guideline to be too lenient and offering insufficiently health protection, especially in developed countries (Havelaar, et al. 2001). In addition, due to the limitation of technology and economy, most guidelines only have the requirements for conventional parameters such as BOD, suspended solid, colour and pH, and indicative indexes for microbiology, mainly fecal coliform or total coliform, while the non-conventional and emerging species such as POPs, PPCP, pharmaceutically active agents and endocrine disruptors, which are difficult to be removed in conventional treatment, and specific pathogen strains are not include. Thus, besides meeting the requirements of water quality standards, the evaluation potential risk targeted special pollutants and adoption of risk control measures are auxiliary steps to guidelines for the safe use of reclaimed water in practical projects.

2.5 Risk assessment

Risk refers to ‘possibility of damage, loss, or other adverse outcomes or an unwelcome event’ (Kaplan and Garrick, 1981). It can be described as ‘probability of the accident occurring multiplied by expected loss in case of the accident’ in mathematical formula (Jager et al., 2001). Risk assessment is a process to describe and quantify the probability of the adverse outcomes or unwelcome events. For water reuse, risk assessment is a systematic process that quantitative description of the probability of the occurrence and the extent, timing and character of the adverse effects to human and environment caused by exposed to chemicals and pathogenic microorganisms in reclaimed water through various exposure routes (Qiu and Wang, 2003). Health risk assessment which is one part of the environmental risk assessment and a focus area in the thesis is defined by US National Academy of Sciences (NAS) as ‘the characterisation of the potential adverse health effects of human exposures to environmental hazards’ (NAS, 1983). It is considered as the most appropriate approach to protect the public from harm and to provide an important scientific basis of risk management by NAS and US National Research Council (NRC). Also, NAS
developed basic steps which are widely used for quantified risk assessment includes hazard identification, exposure assessment, dose–response analysis and risk characterisation. The method is recommended by US EPA and used as the basic framework of international standardization by International Programme on Chemical Safety (IPCS).

The steps for risk assessment are interpreted as follows (Zhao et al., 2010; NAS, 1983; US EPA, 1992; Wang, 2010; Haas and Eisenberg, 2001; Burmaster and Anderson 1994; Finkel 1990). The hazard identification, which is the first step of risk assessment, is to identify potential hazards pollutants, including the properties, intensity and potential hazards of risk source and the selection of risk factors to be evaluated through collection and analysis of relevant data. Exposure assessment, which is a critical and difficult step, is to identify exposure groups, exposure route and determine the intensity of hazard factors in exposure environment, exposure time and frequency, as well as estimating the exposure dose to hazard factors. Situation assessment method, which establishes exposure scenarios including exposure environment, time, routes and group, by combination of substance concentration and characteristics of human activity, is used in the thesis to determine the exposure dose. Dose–response analysis is quantitative calculation of the relationship of exposure dose of hazard and the resulting adverse effects of exposure groups. The quantitative relationship is generally obtained from extrapolation of appropriate mathematical models using epidemiological and animal toxicological experimental data. Risk characterisation is the calculation of probability of occurrence of adverse health effects to exposed population at different exposure conditions, and analysis of their reliability or uncertainty on the basis of integrated information of the first three steps. According to Haas and Eisenberg (2001), this may be done in two basic ways. One way is that a single point estimation of exposure combined with a single point estimation of the dose–response parameters to compute a point estimation of risk. This may be done using a ‘best’ estimate to obtain a measure of central tendency, or using an extreme estimate to obtain a measure of consequence in the most adversely affected circumstance, which is named Baseline Risk Analysis (BRA). The main problem for this way is the uncertainty, which is the factor of imprecision and inaccuracy that limit the ability to exactly quantify risk. For example, the estimation of exposure time and frequency is based on the worst situations which maybe not happen, as well as the uncertainty of the dose-response model. The uncertainty maybe causes the failure of the assessment results. Another approach is to combine the full distribution of exposure and dose–response relationships to obtain a distribution of risk. This approach which conveys important information on the relative imprecision of the risk estimate, as well as measures of central tendency and extreme values, can evaluate the relative contribution of uncertainty and variability to a risk estimate (Haas and Eisenberg, 2001; Burmaster and Anderson 1994; Finkel 1990).

In the thesis, the microbial risk is evaluated since pathogens is the main source of potential risk to human by using reclaimed water and the limits vary a lot in guidelines. The chemical risk assessments are planned for in future studies. The details of risk assessment steps are described in Section 3 Methodology.
2.6 Stakeholder

Stakeholder, described by Freeman (1984), is ‘any group or individual who can affect or is affected by the achievement of the organisation’s objectives’. In other words, stakeholders are the actors (persons or organizations) who manage, working with, directly or indirectly contribute to, have vested interest in or affected in positive or negative manner by the program of work or its outcomes (Schmeer, 1999; WRMS, 2000; Llewellyn, 2009). Stakeholder analysis and management are important to the successful development and implementation of projects. And the stakeholder theory has been increasingly used by policy-makers, regulators, governmental and non-governmental organizations, businesses and the media (Friedman and Miles, 2006) in many different fields for different purpose, such as corporation, management and decision.

Stakeholders’ participation is considered to be an important part in integrated water resources management, as well as important for non-conventional waters, especially for water reuse. The stakeholders’ acceptability and contribution are significant for use of reclaimed water, since their behaviours directly or indirectly influence the factors such as management, investment, quality, policy, laws and regulations, which affect the development of water reuse. There are some case studies for communication with stakeholders in the water reuse projects, such as the study on stakeholders’ attitudes towards reuse of treated wastewater conducted by Ogilvie, Ogilvie & Company (2010), the survey of public perception regarding water reuse in Arizona by Rock et al. (2012), the participation of stakeholders in the project of recycled water study in city of San Diego (Brown and Caldwell, 2012), the participation of stakeholders in the recycled water program for the city of Los Angeles, and so on.

As a non-conventional water resource, reclaimed water is an emerging concept compared to conventional water. Additionally, the source of reclaimed water is probably wastewater which contains chemical and microbial pollutant to some extent. The prejudices and misconceptions easily happen, which makes some obstructs for acceptance by stakeholders and the participation not as positive and effective as expected. The failure of communication and participation of stakeholders probably causes a number of problems during the implementation of water reuse projects. Thus, how to improve the stakeholders’ acceptance and promote a truly sustainable and safe reuse from stakeholders’ participation and contribution perspective is one of the crucial problems for the development of water reuse.
3. METHODOLOGY

The approach and material used in the study are described in detail in this section.

3.1 Literature review and investigations

In Paper I, Paper II and Paper V, the main approach for collecting data and information were literature and documents review and different kinds of investigation such as interviews and field visits. In Paper I, the challenges of desalination developed in China were analysed based on articles, reports and documents review; in Paper II, besides literature review, the situations of water reuse in China, especially the data and information related to management system, price and investment, were investigated by personal interview and the visiting of the water recycling plant in China; in Paper V, the analysis of stakeholders and the strategy of promoting stakeholders’ acceptance and participation are based on the information obtained from literature review.

3.2 Laboratory testing

In Paper III and Paper IV, water quality monitoring testing was carried out for the collection of data to evaluate the probability and potential risk of treated wastewater reuse.

3.2.1 Studied site

The water samples were collected in Källby Wastewater Treatment Plant (WWTP) in the south of Lund, which is a city in the province of Scania, southern Sweden. The WWTP treats an average of about 350 L/s (28,000 m³/day) wastewater from 80,000 residents in central Lund and the boroughs Värpinge, Vallkärra and Stångby. The wastewater is treated by tertiary treatment process, which includes physical (screens, grit removal basins, primary and secondary clarifiers), biological (activated sludge in anoxic and aerobic conditions) and chemical treatment (ferric chloride is added to precipitate residual phosphorus), followed by chemical clarifiers and a sedimentation system using ponds for final polishing. After passing through six ponds by gravity, the effluent is discharged into the receiving water-stream Höjeå (VASYD, 2010). The values of some water quality parameters of influent to the plant, effluent after tertiary treatment and the last pond are tested by the lab of WWTP. There is no regular monitoring for other ponds except last one, neither any data of microbial indicators collected which is required and important for assessing a safe directly reuse.

3.2.2 Sampling and monitoring experiments

The water samples were collected from January to December 2012. The sampling frequency is different for different parameters and influenced by the weather. The monitoring parameters, including physical, chemical and microbial aspects, were selected according to requirements in Chinese reclaimed water quality standards (China’s State Administration of Quality Supervision and Inspection and Quarantine & China National
Management Committee for Standardization, 2002-2007). The samples were generally collected weekly for physical and chemical parameters, biweekly for microbial parameters and monthly for metals. The sampling was influenced by weather, such as snow, freezing and rain. Seven different samples were collected as grab samples each time at around 0.5-1m depth at the outlet of each pond and the effluent from WWTP before discharged into pond system (expressed as Eff. following). Quality parameters (except microbial parameters) were analysed with standard methods in laboratory. The testing methods and instruments used are shown in Table 2. The description of detailed parameters of instruments HI-98128, HI-83099, HI-98703, HI-98312, HI-96769, HI-3815, HI-3864 and the matching reagents can be found in the web of HANNA instruments (HannaNorden Company, 2013).

The samples for microbial parameters (20 samples in total) were sent to the laboratory of VASYD Company, Malmö, Sweden. Fecal coliform and E. coli which were tested by the method of IDEXX Colilert quanti-Tray® which is the standard method of ISO (ISO 9308-2:2012) and approved by US EPA, are incubated in 37 °C and 44 °C for 48 hours, respectively.

Table 2: Testing methods and instruments

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Abbreviation</th>
<th>Methods</th>
<th>Instruments or laboratory*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td></td>
<td>Glass electrode method</td>
<td>HI-98312</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>Glass electrode method</td>
<td>HI-98128</td>
</tr>
<tr>
<td>Colour (PCU)</td>
<td></td>
<td>Colourimetric platinum cobalt (ISO)</td>
<td>HI-83099</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td></td>
<td>Spectrophotometry (ISO)</td>
<td>HI-98703</td>
</tr>
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<td>Suspended solids (mg/L)</td>
<td>SS</td>
<td>Weight</td>
<td>Filter membrane 0.45μm</td>
</tr>
<tr>
<td>Total dissolved solids (mg/L)</td>
<td>TDS</td>
<td>Glass electrode method</td>
<td>HI-98312</td>
</tr>
<tr>
<td>Anionic surfactant (Linear alkylbenzene sulfonate) (mg/L)</td>
<td>LAS</td>
<td>Adaptation of the USEPA methods 425.1</td>
<td>HI-96769</td>
</tr>
<tr>
<td>Alkalinity(mg/L)</td>
<td></td>
<td>Bromocresol green</td>
<td>HI-83099</td>
</tr>
<tr>
<td>Dissolved oxygen (mg/L)</td>
<td>DO</td>
<td>Iodometric method (ISO)</td>
<td>HI-83099</td>
</tr>
<tr>
<td>Nitrate nitrogen (mg/L)</td>
<td>NO₂⁻N</td>
<td>Alkaline potassium persulfate digestion UV spectrophotometry</td>
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</tr>
<tr>
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<td>NH₄-N</td>
<td>Nessler</td>
<td>HI-83099</td>
</tr>
<tr>
<td>Nitrite nitrogen (mg/L)</td>
<td>NO₂⁻N</td>
<td>Diazotization</td>
<td>HI-83099</td>
</tr>
<tr>
<td>Total Phosphorus (mg/L)</td>
<td>TP</td>
<td>Amino acid</td>
<td>HI-83099</td>
</tr>
<tr>
<td>Biological oxygen demand 7 days (mg/L)</td>
<td>BOD₅</td>
<td>SS-EN 1899-1</td>
<td>VASYD lab</td>
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<td>Potassium dichromate method (ISO)</td>
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<tr>
<td>Chlorine residual total (mg/L)</td>
<td>DPD</td>
<td></td>
<td>HI-83099</td>
</tr>
</tbody>
</table>
Chloride (mg/L)  Titration  HI-3815
Phenol (mg/L)  4 – Amino antipyrine (ISO)  HI-3864
Hardness  (mg/L CaCO₃)  Inductively Coupled Plasma (ICP)  Accr.lab at Lund University, optical ICP instrument from PerkinElmer, model ELAN 6000
Metals  (Mercury, Arsenic, Cadmium, Lead)  Hg, As, Cd, Pb  Inductively Coupled Plasma Mass Spectrometry (ICP-MS)  Accr.lab at Lund University, ICP-MS instrument from PerkinElmer, model Optima 8300
Iron, Manganese  Fe, Mn  Inductively Coupled Plasma (ICP)  Accr.lab at Lund University, optical ICP instrument from PerkinElmer, model ELAN 6000
Hexavalent Chromium (mg/L)  Cr⁶⁺  Diphenylcarbohydrazide  HI-83099
Fecal coliform (st/100ml)  FC  IDEXX Colilert quanti-Tray® (ISO 9308-2:2012)  VASYD lab
E. coli (st/100ml)  EC  IDEXX Colilert quanti-Tray® (ISO 9308-2:2012)  VASYD lab

*) HI- instruments from HannaNorden Company

### 3.3 Quantitative microbiological risk assessment (QMRA)

The Quantitative Microbial Risk Assessment model (QMRA), which is a common tool for quantifying the microbial risk, was used in Paper III for estimating the microbial risk of water reuse for different application. The model has been widely studied and applied in many conditions to estimate the microbial risk from reclaimed water. For example, the QMRA model has been used as methodology to revise the reclaimed water quality standards for WHO guidelines; Zhao et al. in Tsinghua University applied the QMRA model to determine the concentration limits of Cryptosporidium parvum and Giardia lamblia for using the reclaimed water to irrigate the urban green land (Zhao et al., 2010); some studies applied the QMRA for assess the microbial risk for agricultural irrigation with reclaimed water (Hamilton et al., 2006; Muñoz et al., 2010; An et al., 2007). For micro-organisms, hazard assessment (i.e. the identification of a pathogen as an agent of potential significance) is generally a straightforward task, thus, QMRA model mainly includes three steps: exposure assessment, dose-response analysis and risk characterisation (NAS, 1983; Haas and Eisenberg, 2001). The estimation is based on extreme adverse conditions to obtain the maximum risk.
3.3.1 Selection of Microorganisms and data input

E. coli and rotavirus are selected for risk assessment in the study. Most stains of E. coli cause no harm when they are in the normal intestinal flora of humans and animals. However, in other parts of the body, E. coli can cause serious disease, such as urinary tract infections, bacteremia and meningitis (WHO, 2008). In addition, a limited number of enteropathogenic strains such as enterohaemorrhagic E. coli (EHEC), enterotoxigenic E. coli (ETEC), enteropathogenic E. coli (EPEC) and enteroinvasive E. coli (EIEC), can cause acute diarrhea (WHO, 2008). The testing of pathogenic E. coli, which is more complicated and costly than total E. coli, is typically not available for daily monitoring. Besides, in actual work, it is impractical and uneconomic to test and assess the risk of all pathogens. Total E. coli could be used as an indicator for the assessment of a general microbial risk since it is recommended by US EPA as the best indicator of health risk from water contact (US EPA 2010) and its presence indicates the potential for the co-existence of pathogenic organisms (An et al. 2002). Since dose-response models have not been developed for total E. coli, the best-fit dose-response parameters for the ingestion of non-enterohaemorrhagic strains (except O111) of E. coli defined by Haas et al. (1999) are used in QMRA, which was adopted by An et al. (2002). The actual risk of pathogenicity is expanded for this replacement but it could be safer for users if any protective guidelines or measures are formulated according to assessment results of expanded risk.

Rotavirus is a representative of the enteric viruses group which can survive longer in water than most intestinal bacteria and are very important and commonly used in microbial risk assessment since they can cause most waterborne infections in developed countries and are highly infective (Hamilton et al. 2006; Muñoz et al. 2010; CDW 2010). Rotavirus could cause gastroenteritis and are highly infectious (Hamilton et al. 2006; Muñoz et al. 2010), and it is the most important single cause of death in children in the world (WHO 2008). In addition, rotavirus has a higher resistance to disinfection than E. coli. Thus, E. coli is not a reliable indicator of its presence/absence and infectious risk (WHO 2008). Additionally, Sweden does not have a vaccination program yet although it is being considered (National Board of Health and DACEHTA, 2012). The detection of viruses is a rather time consuming, complex and expensive procedure due to pathogen variability, especially when large volumes of water must be tested (Shuval and Katzenelson, 1972; Ferguson et al., 2012). For the preliminary study, it is better to find a straightforward way to obtain the data since the study focuses on the risk evaluation process and the development of protection guidelines based on QMRA rather than detection method and procedure. The data of rotavirus used in the study was obtained based on the rough ratio between rotavirus and fecal coliform of $1:10^5$, which was presented by Oragui et al. (1987) who studied on the removal of excreted bacteria and viruses in waste stabilization ponds which are similar to the situation in this study. The ratio was adopted by Muñoz, et al. (2010) for assessment of microbial risk from using treated wastewater for agriculture. More discussion could be found in Paper III.

The monitoring data of E. coli and Fecal coliform is shown in Table 3 and Figure 3 (a) and (b). Deterministic modeling (single point estimation or BRA), which is promulgated as a practical approach in several major national and international guidelines (US EPA and US
AID, 2004; WHO, 2004; NRMMC and EPHC, 2005), is used in this study since it has the pragmatic advantage of simplicity in analysis and results and are more readily embraced by water resource managers (Benke and Hamilton, 2008) which is consistent with the scope of the study. The extreme values (including outliers) of density in different periods are used as input in QMRA to calculate the maximum and minimum potential risk for different scenarios. The reason of the outliers included in input data is that most outliers of FC and EC were concentrated in February, while others appeared in the samples at the beginning of March, which means the unusual values are in certain regularity, and maybe not outliers in the data of longer-period (several years) sampling. They were probably caused by weather conditions in that period, such as extremely low temperatures of the year, snow and freezing on the surface, and the physicochemical conditions influenced by the weather. As there is a short data collection period (only one year) and limited data, it cannot conclude that the outliers are occasional samples or errors. The objective of the study is to estimate the maximum risk that may occur. Thus, all the data including outliers which actually occur should be considered for the worse case.

Table 3: The density of fecal coliform and E. coli in samples from January to December 2012

<table>
<thead>
<tr>
<th>Unit: st/100ml</th>
<th>Eff.</th>
<th>Outlet of pond 1</th>
<th>Outlet of pond 2</th>
<th>Outlet of pond 3</th>
<th>Outlet of pond 4</th>
<th>Outlet of pond 5</th>
<th>Outlet of pond 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fecal coliform</td>
<td>2.40x10^4</td>
<td>2.25x10^5</td>
<td>9.68x10^5</td>
<td>7.15x10^5</td>
<td>6.11x10^5</td>
<td>4.11x10^5</td>
<td>2.8x10^5</td>
</tr>
<tr>
<td></td>
<td>&gt;2.42x10^3</td>
<td>&gt;2.42x10^3</td>
<td>1.73x10^5</td>
<td>1.3x10^5</td>
<td>7.27x10^4</td>
<td>5.48x10^4</td>
<td>5.17x10^4</td>
</tr>
<tr>
<td>E. coli</td>
<td>7.55x10^3</td>
<td>4.50x10^2</td>
<td>1.06x10^3</td>
<td>3.60x10^2</td>
<td>2.60x10^2</td>
<td>80-</td>
<td>30-</td>
</tr>
<tr>
<td></td>
<td>1.20x10^3</td>
<td>2.42x10^5</td>
<td>6.13x10^4</td>
<td>5.79x10^4</td>
<td>2.76x10^4</td>
<td>2.14x10^4</td>
<td>1.96x10^4</td>
</tr>
</tbody>
</table>

Figure 3 (a): Boxplot of fecal coli form density
3.3.2 Exposure assessment

In the study, QMRA is applied for four exposure scenarios of planned wastewater reuse for non-potable applications as follows:

- **Scenario 1**: Reclaimed water is applied for irrigation for the potato which is the most common crop with the largest irrigated area in Sweden and irrigated during July and August when a shortage of water sometimes occurs. The potential risks, both for farmers and neighbor children, though the route of inhalation is assessed in scenario 1 using the monitoring data from July to August.

- **Scenario 2**: Reclaimed water is applied for industrial cooling tower. The exposure way is mainly breathing in aerosols from cooling tower drift, where recycled water contains all the minerals, chemicals and bacteria present in the tower (Workplace Health and Safety Queensland, 2007).

- **Scenario 3**: Reclaimed water is applied for recreational impoundment which needs large amounts of water and is easy for persons, especially children, to have access to the reclaimed water and be exposed to the pathogens. The route of exposure is mainly body (such as hand) contamination and resultant transfer to mouth or open wounds. Considering the climate in south of Sweden, the data from May to September is used for the assessment.

- **Scenario 4**: Reclaimed water is applied for irrigation of golf courses, which needs large amounts of water. The exposure ways are mainly inhalation for occupational group due to spray irrigation and direct contact for public. The data from May to September is used for the assessment.
The details of calculation of exposure dose, determination of parameters and assumptions are described in **Paper III**.

### 3.3.3 Dose-response modelling

The Beta-Poisson model is used for the dose-response analysis of E. coli and rotavirus and the equations (Haas et al., 1993) are the following:

\[
P_I(\lambda) = 1 - \left(1 + \frac{\lambda}{N_{50}} \left(2^{1/\alpha} - 1\right)\right)^{-\alpha}
\]  

(3.1)

Where \(P_I(\lambda)\) is the daily probability of infection from viruses; \(N_{50}\) is the median infectious dose (mass); \(\alpha\) is the slope parameter; \(\lambda\) is the exposure dose per person per day (mass).

The annual probability of infection \(P_I(A)\) can be calculated by equation (3.2):

\[
P_I(A) = 1 - (1 - P_I(\lambda))^N
\]  

(3.2)

Where \(N\) is the number of exposure events per year (day)

Equation (3.1) is described by two parameters: \(N_{50}\) and \(\alpha\). According to Haas et al. (1993) and Haas et al. (1999), \(N_{50}\) is 6.17 and \(\alpha\) is 0.2531 for rotavirus, while \(N_{50}\) is \(8.60 \times 10^7\) and \(\alpha\) is 0.1778 for E. coli, respectively. The model was calculated straight-forwardly using Excel 2007.

### 3.3.4 Risk characterisation

According to Haas et al., (1993), the range of \(10^{-4}\) to \(10^{-6}\) which is used by US EPA as a target reference risk for carcinogens in drinking water was considered a reasonable level of risk for communicable disease transmission, and annual risk values of above \(10^{-4}\) were considered high for infection. The value of \(10^{-4}\) (1 per 10,000 people infected per year) developed by US EPA (1989) was used for the preliminary study in **Paper III** as the benchmark of annual acceptable risk used to examine whether or not the studied water is acceptable for different applications. It is the most commonly applied benchmark in risk assessment (Regli et al., 1991), and adopted in many studies of assessment of microbial risk from using treated wastewater, such as Muñoz et al (2010), An et al. (2007), Zhao et al. (2010) and Ryu et al. (2007). The discussion of the benchmark of acceptable risk could be found in **Paper III**.

### 3.4 Reclaimed water guidelines

Guidelines or standards have been developed in many countries with the practice of reuse, but not in Sweden yet. In **Paper IV**, the reclaimed water guidelines/ standards developed by World Health Organization (WHO) and some countries such as US, China, Portugal, Spain, Cyprus, and Italy, were used as a reference for e.g. parameters, treatment and
approach in the work of formulating guidelines in Swedish situation. The WHO guidelines (1989) (focusing on microbial pollutants), which takes both developing and developed countries’ conditions into account, is the basic requirements for safe reuse and is used as a reference by many countries when they develop national guidelines (Blumenthal, 2000); guidelines developed by US EPA and US AID (2004) are more strict for risk control, especially for microbial risk than WHO guidelines; Chinese reclaimed water quality standards (GB/T 189919-2002; GB 20922-2007; GB/T 19923-2005; GB/T 18920-2002; GB/T 18921-2002 GB/T; 19772-2005) are used as baseline for treated water quality and as reference for selection of monitoring parameters in laboratory testing. The reason for that is that Chinese standards, although not as strict as US guidelines, have specific requirements for more parameters’ limits (chemical, physical and metals parameters) for different applications than the other two. And at present, no Swedish guidelines for water reuse exists. It could be wise to start with a draft guideline from those countries that focus on low-cost solutions for water reuse. It is maybe better to approach the development in steps and start with simple, straight-forward guidelines such as Chinese ones, rather than go from nothing to the most complicated and regulated standards, such as US ones, in one step. It probably technically and economically reduces the interest of reuse treated wastewater if heavy and very strict guidelines are introduced in Sweden at an initial phase. Besides, guidelines in some European countries summarized in Angelakis et al. (2013) where water reuse is practiced earlier and refined can also be a reference for Sweden.

### 3.5 Principle component analysis (PCA)

In Paper IV, Principal Component Analysis (PCA), which is a powerful method to reduce the noise and simplify data analysis for large data sets, was used as a tool to provide reference for developing water reuse guidelines through analysing the relationships of parameters and impact factors for water quality in studied site. PCA is a multivariate statistical technique that finds the least possible orthogonal vectors to characterize data characteristics. Through a linear transformation, PCA reduces the dimensionality of a data set consisting of a large number of inter-related variables, while retaining as much as possible the variability present in data set, and provides information on the most meaningful parameters (Kebede & Kebedee, 2012; Ma et al., 2010; Singh, 2004). In addition, PCA can also show the association between variables (Kebede & Kebedee, 2012; Vega, 1998). PCA has been widely used for analysis and assessment of water quality data for different water bodies (Kebede & Kebedee, 2012; Mazlum et al., 1999; Ying, 2005; Mishra, 2010).

In Paper IV, PCA was compiled in Matlab. Since the results of PCA on raw data showed that the variance of water quality parameters was distributed among several components, the rotation of PCA, which reduces the number of principal components (PCs) by eliminating some relatively unimportant components (Mazlum et al., 1999), was applied for the data. Varimax rotation, which is the most widely used rotation in PCA, was used here to make the interpretation easier (Mazlum et al., 1999). The PCs for rotation were selected according to Chateld and Collins (1980), which stated that the components with an eigenvalue of less than 1 should be eliminated. Thus, the components with an eigenvalue of more than 1 were rotated by varimax methods.
In PCA, the explained variance represents how much percentage of the variance is explained by components which are the important patterns that appear in the field. In Paper IV, bi-plots of loadings show the relationships in different parameters for each sampling point and overall situation. The loadings represent how much of the parameters explained by the information in that component. In general, component loadings which are larger than 0.6, should be taken into consideration in the interpretation (Mahloch, 1974). The parameters with high loadings in the same component and closed to each other are in the same group, which indicates that they have strong co-variance and are probably affected by the same factors. The parameters which are close to origin are not well explained by that component.

3.6 Stakeholder map

A stakeholder map, which can identify all interested parties both inside and outside the project, is helpful for identifying the stakeholders (Llewellyn, 2009). There are several commonly used techniques for stakeholder mapping, such as the Power/Influence vs. Interest Grid, the Power/Dynamism Matrix, the Power/Legitimacy and Urgency Model, the Problem-Frame Stakeholder Map and the Participation Planning Matrix (Ham, 2011). The Power-Impact Grid developed by the Office of Government Commerce, UK (2003) and the Influence-Interest Grid developed by Imperial College, London (2007) are in combination used in Paper V, since the techniques can determine the communication needs by the stakeholders’ interests and power/influence, which are important characteristic of stakeholders and necessary for stakeholders’ management. The Influence-interest grid is shown in Figure 4. The stakeholders with both high influence and interest should be fully engaged; high influence but low interested stakeholders should be provided sufficient information to ensure that they are up to date but not too much; low influence but interested stakeholders should be adequately informed to ensure that no major issues arise; and low influence and low interested people should be minimally communicated to prevent boredom (Office of Government Commerce, UK 2003, Imperial College, 2013).

Figure 4: Influence - Interest Grid (Imperial College London, 2007)
4. RESULTS AND DISCUSSION

4.1 The strategy for promoting sustainable development of non-conventional waters

4.1.1 Study on sustainable development of desalination in China

Existing problems in the development of desalination

Although there is some progress after more than 40 years of development, desalination in China is still in the initial stage with the features of unsophisticated technology and is not as widely used as it could be for water supply. The problems are listed as follows (from Paper I).

- Small-scale plants. Most of the desalination plants of China are still small- or medium-scale plants. As of 2009, large capacity plants only account for 4.7% of the production (GWI, 2009). Desalination has not reached the economic scale in China, which is one of the reasons causing higher price. In a market economy, the demands decide markets. The small-scale means the users do not have enough awareness and wide acceptance for desalinated water as a water supply. Besides, the insufficient investment because there are not enough benefits to attract investors to be involved in the desalination industry and the lack of support from government are also the reasons for small-scale and slow development.

- Technology. China is in lack of independent intellectual property rights of core technology and key equipment. About 80% of installed capacity use introduced technology from foreign countries, and key equipment, such as 90% of RO membrane (RO shares 75% of the installed capacities), 50% of the thermal material and energy recovery technology, are mainly dependent on imports since the performance of domestic equipment is not as good as import ones, such as the shorter service life span of membrane, which is one of main reasons for elevated investment and operational costs. Besides, domestic desalination industry in China performs worse than international industry in terms of retention, energy efficiency and expected lifetimes of the plants. This is the main reason why Chinese enterprises have a small proportion in the market in spite of lower prices. In the 16 completed desalination projects over 10,000 m$^3$/d, only 25% are self-constructed, and less than 13% if calculated in capacity (Anonymous, 2012).

- Energy consumption. Although conventional energy sources are limited and has a significant environmental impact, in China as same as global situation, most desalination plants use conventional sources of energy (gas, oil and electricity), which is cheaper at present. The application of alternative energy sources are still in the research or initial development stage.
• Investment system. At present, the investment for desalination mainly comes from two sources: corporate (desalinated water needed) self-financing or public investments. The former is still the main case. The investment ways are still impacted by habits and customs from the former planned economic system. The investment institution based on market-oriented operation which is only tested in some cases has not been formed. Furthermore, for the plants invested by company, there are not enough incentives or subsidies granted from government. Because of the higher cost than regular water sources, the investors cannot get benefit from desalination, which decrease their investment interests. Large-scale desalination projects need substantial investments, which generally cannot be provided for by local government or small corporate on one’s own. The lack of funding is one of important reasons for the rare large capacity desalination projects that have been launched in China. There is still not rational financing institution established.

• Price system. Due to multiple impact factors, such as technology, device, scale and pollution in water source, the average Chinese seawater desalination cost, which is 5–7 Yuan RMB/m³, is higher than the average in the world (0.5 US$/m³) (Baidu Encyclopedia, 2009; Bashitialshaaer and Persson, 2010). Together with distribution fee, tax and profit for enterprise, the price is higher than tap water for resident and industry in most regions. That is the main reason that most desalination capacity is used for islands with fresh water shortage and industry with limited water supplies and higher cost than desalination if tap water is used to make process water.

• Policy issues. The bottlenecks in the development, such as technology, device, investment and price, have not been fundamentally solved due to lack of supporting policy. Most desalination projects are individual schemes and the desalination industry has not formed the proper functioning system, since there are no laws or detailed executable guidelines to follow.

Recommendations for the development of desalination in China

For the problems described above, some proposals for the strategy of sustainable development of desalination market are discussed and summarized (from Paper I).

• Take effective methods to reduce the cost, especially accelerate the development of key technology and equipment with independent intellectual property rights.

• Government should increase the attention and investment, and strongly support the development of domestic relevant industries, such as research on the technology and manufacture of material and equipment to get rid of the high dependence on imported technology and device which can effectively reduce the cost and attract the investors and users.

• Develop rational investment institution and price system to promote market-oriented operations and expand the scale for water supply. Broaden the investment channels and comprehensive consider the pricing of different water sources.
• Management systems such as laws and regulations, guidelines, regulations and management sectors should be established or improved, not only programmatic objectives without any detailed procedure and action.

• Relevant supporting policy should be developed, which can learn from the policy for water reuse, and there should be regulations to guarantee the enforcement.

• According to local conditions, optimal allocation and rational overall planning of different water sources, both in terms of quantity and quality, should be implemented to generate benefits for both society and environment.

• Intensify the integrated use of desalinated water with other water sources, especially reclaimed water.

• Develop the application of alternative energy to operate the plants, such as wind, solar, nuclear, and biological energy. Pay more attention to the impact of desalination projects on ecological environment and make clear regulations for minimize the impact.

• Use of various means of media to increase the publicity of non-conventional water sources. Make the public to be aware of the background knowledge, such as the pros and cons, why and how to use it, which can make non-conventional water sources more accepted by public.

4.1.2 Discussion on the sustainable development of water reuse in China

Problems existing in the reuse of treated wastewater in China (from Paper II)

• Legal basis and guarantee. Although water reuse has been written in Water Law and mentioned in some relevant laws and regulations, there has not been any national comprehensive law for water reuse developed. The management is mainly based on rules and regulations enacted by water sectors and local government (city or province level), which are representing the lowest force level of the multi-level Chinese decision structure. The lack of legislation as a guarantee causes many problems in management. But so far, there has not been any proposal about legislation for water reuse submitted to the National People’s Congress (NPC, the highest authority of state power in China), which probably reflect that the degree of attention that treated wastewater is an important resource for dealing with water crisis is far from enough.

• The governing bodies. Insufficient enforcement and unclear responsibilities of enforcement agencies are common problems in the management of reclaimed water. There is no clear definition of duties for each administration department, which leads to some confusion in the management process. The lack of effective communication and cooperation between the departments and vacancy of co-ordination and supervision mechanism aggravate the situations. The management is overlapping and concentrated
where there is interest or benefits, while there is less or no management where there are problems or high costs (Zhang, et al., 2007). Besides, another problem is that the sectors which use reclaimed water do not have the rights for any management, which leads to a contradiction between the supplier and the users and reduces the users’ enthusiasm in using reclaimed water.

- Public participation. The lack of public participation and supervision is another issue regarding reclaimed water management. The process of planning, production and allocation of reclaimed water is mainly decided by water managers (e.g. government and reclaimed water company), with little public participation and observation (Zhang, et al., 2007). As reclaimed water is a non-conventional water resource and administrative departments do not provide enough information and education, there is a lack of public understanding of relevant information and knowledge. Most public do not have enough ability to participate in management. In addition, there has been no effective communication platform established for public participation in management. Excessive administration and confusion of responsibility cause difficulty in dealing with public feedback. Normally, people do not always accept or use something new which they do not know well or cannot manage. The lack of participation in the management is one of the reasons that reduce the public enthusiasm for using reclaimed water.

- The safety of water reuse. Although the reclaimed water quality standards have been developed, the safety of using reclaimed water is still a hot topic under discussion and study and of highest concern for users. Some unqualified reclaimed water use, although happening occasionally, cause the users’ distrust and resistance to use. The main problems reflect in three aspects: a) whether the standards are strict enough for protecting users is discussed and studied a lot; b) in some cases the standards cannot be strictly enforced because of ineffective management and supervision with absence of effective punitive measures, especially in agriculture irrigation; c) the risk management mechanism has not been developed for water reuse and most of the public and users do not have the knowledge of how to control the risk and protect themselves from using reclaimed water due to the lack of relevant protective guidelines.

- Price system. From the economic perspective, the main problem is an intelligent price system that has not been developed for different water resources. At present, the cost recovery for production and distribution of reclaimed water comes from two supplies: the sale of reclaimed water and government subsidies. In the market economy, the price of reclaimed water as a commodity should be adequate to meet the cost requirements and maintain the normal operation of reclaimed water plants. However, price superiority to other water resources, especially tap water, is one of main driving force for market. Due to the implementation of the planned economy in the past, the price of tap water has long been on the low side with the average price at 1–1.5 Yuan RMB / m³, which is still applied in some regions now. The low tap water price gives users a lack of awareness of the water resources shortage and water saving. Furthermore, it causes that users and investors cannot get more benefit, which hinders the widespread use of reclaimed water.
• Supporting policy. To achieve the target and keep the sustainable development of the water reuse industry, related supporting policies have been made in different levels by government, but not enough, which causes that the development is not as fast as planned. There should be more management initiatives and possibly policies added to solve the problems.

Strategy for sustainable use of reclaimed water

Due to the problems as described above, water reuse is still developed slowly although some progress has been made. In the thesis, some strategies for sustainable development of water reuse are summarized as following (from Paper II):

• Improve the legal system, both on national and local levels, which should include not only general but also detailed regulations for planning, production, use, investment, charges of reclaimed water and the responsibility of governing bodies and so on.

• Establish an effective supervisory and monitoring system, for example, supervised by a third party without any interest involved. Formulate clear penalty ordinance for improving the laws and supervision enforcement.

• Promote and deepen integrated management of waterworks and specified a competent department to co-ordinate all the agencies related to reclaimed water and enhance communication and co-operation between different departments with clear responsibilities.

• Multiple ways, such as survey, building platform and exhibition should be adopted for improving public participation, education and information for more acceptable of reclaimed water by users.

• For improving the safety for using reclaimed water, strict regulations for e.g. treatment requirements, distribution, storage and protective measures should be added in the water reuse guidelines. Risk-assessment methods, both for chemical and microbial pollutants, are recommended for evaluating and improving the reclaimed water standards and for evaluating the risk for individual cases before the water reuse projects are carried out to reduce and control the potential risk. Risk management system should be established for e.g. planning, design, operation (production) and application.

• The investment channels should be more broadened to solve the financial problems and market-oriented operation mechanism should be strengthened. Water price reform should be deepened. It is essential to establish the intelligent pricing system, which integrated considering different water resources such as tap water, natural water, reclaimed water, desalination and long-distance water diversion to promote the rational utilization of different water resources, especially the development of non-conventional water market. Some economic measures, such as anti-ladder-type price which means
the more used the less charged for the unit price, could be used to encourage the use of reclaimed water.

- For promoting the sustainable development of water reuse, more policies both in central and local levels should be formulated. For instance, fund raising, pricing, attracting investment, encouraging the users’ and public participation, intensify construction of facilities, and establishing more effective management including risk management and supervision system from the third party.

4.2 Study on improving the safety of water reuse

In the thesis, the strategy for improving the safety of water reuse is discussed from guidelines and risk assessment perspectives. Sweden is used as a case study.

4.2.1 Suggestions for developing water reuse guidelines in Sweden (from Paper IV)

A guideline or a standard, which is one of the important measures to guarantee the sound and safe water reuse and protect users, have been developed in many countries with the practice of reuse, but not in Sweden yet, which may cause health risk and environmental pollution from unconscious use of unqualified reclaimed water. The development of water reuse guideline should be based on local situations combined with learning from existing guidelines by other countries. In this part, the recommendations for the approaches and contents should be considered to set guideline are discussed, but the quantitative of limits for water quality parameters is not included, since this should be based on more studies and experiments.

Formulation of water quality parameters in guideline

Monitoring results of studied water quality

The monitoring results of physical, chemical, metals and microbial parameters are shown in Paper IV. As an open system, the water quality and treatment effect in ponds is affected not only by the process in WWTP, but also by external environment factors such as temperature, precipitation and UV-radiation from the sun. The variation of colour, turbidity and SS is consistent with the changes in temperature. There is an increasing trend in the three parameters from Eff. to pond 6, especially in summer time. The pH of all sampling points is moderate and close to ambient. TDS is generally stable through the time, and a certain degree of reduction takes place when the water runs through the set of ponds. For chemical parameters, in most cases, the concentration of NH$_4$-N decreases pond by pond; LAS, COD$_{Cr}$, NO$_3$-N and TP are also reduced, but not so significantly; Chloride and hardness keep stable and low value all the time except few individual samples; there is no significant reduction by ponds for other parameters. The reduction of metals depends probably on chemical precipitation, thus, the results keep low values and are stable in most time. There is a slight reduction of Mn, As, Hg and Cd, and a certain reduction of Fe from pond 1 to 6. The concentration of FC and EC in ponds are lower in the summer time (from
May to August) than other seasons probably due to UV effect from much stronger sunshine, but the removal efficiency by pond system is not so high (maximum 3.3 log for EC, 1.1 log for FC from pond 1 to pond 6).

Selection of water quality parameters

It is impractical to monitor all pollutants in reclaimed water. The selection of parameters to be included, which could be based on local water quality, wastewater treatment technology, economic constraints, and reference from WHO and other countries’ guidelines, is a necessary and important step to set up guideline. The parameters could vary for different applications which have different requirements for water quality. For physical parameters, turbidity and SS which are mostly common parameters in different guidelines, should be regulated, since some chemical and microbial pollutants attach to the solid particles which could be indictors related to those pollutants. pH is also an important parameter due to its influence of components and reactions. For irrigation, salinity should be controlled by limits for soil protection in form of TDS or conductivity. In terms of the water at Källby, pH and TDS are stable and can meet the requirements in other guidelines. For these two parameters, the occasional monitoring is sufficient if regular testing would be too costly. For chemical parameters, BOD and COD or TOC should be formulated for organic pollution for all applications. Nutrition (N, P) is not necessarily formulated for irrigation but required for other applications especially landscape to avoid eutrophication. In terms of the water in studied site, the monitoring data shows that the current treatment process can guarantee some parameters such as LAS, phenol and hardness which meet the requirements for safe reuse. If this is true also for the other wastewater treatment plants, these parameters could be excluded in Swedish guidelines when the proper treatment required. Similarly, the concentration of heave metals such as As, Cd, Cr and Hg, which are include in some guidelines by e.g. Portugal, Italy and China, are rather low after tertiary treatment. Nevertheless, considering the recalcitrance, bioaccumulation and chronic toxicity of heavy metals, it is recommended that heavy metals could be regulated as optional monitoring indicators or monitored occasionally according to local situations. FC, EC and helminth egg are normally used for microbial pathogens indicators, but the limits vary a lot. The approaches for microbial parameters are discussed in the following section. Besides, Persistent Bio-accumulative Toxins such as Methyl mercury, PCBs, DDT and dioxins, and emerging components such as PPCPs, antibiotics and endocrine disruptors, which are not widely included in the existing guidelines at present, should be considered to be listed in Swedish guidelines for protection of users and environment.

Discussion on the approaches to set microbial parameters

The approaches for setting the limits of microbial parameters are introduced in Section 2.4. Sweden, as a developed country, could afford strict guidelines of no potential infection risk as US. For the water reuse applications where people likely may be in direct contact with or in exposure to the water, the strict guidelines should be formulated for avoid potential risk of fecal contamination, although this reduces the economic advantage of water reuse. However, the guideline should take both safety and economy into account and find a balance between the two to make the maximum benefit from water reuse in the
premise of no actual health risk. Considering this, for the applications with less possibility of direct contact, such as irrigation and industry, Sweden could possibly adopt the approach used by WHO guidelines which has amounts of evidence supporting. For improving safety, it is better to combine the risk assessment approach with the epidemiological studies. After setting the limits based on epidemiological studies, the potential risk of using the water with limits of microbial pollutants could be evaluated to check if the maximum risk is acceptable. Also, the acceptable risk could be set firstly, and a limit can be regulated based on acceptable risk (Zhao et al., 2010). The limit should be compared with the one which is set based on epidemiological studies and the lower one of the two limits should be regulated in the guidelines.

Same as other pollutants, the selection of microbial parameters to be evaluated risk and included in the guidelines is the first and a critical step to set criteria. WHO (2008) points out that fecal coliform and E. coli are not reliable index to all pathogens of their presence/absence since several pathogens have higher resistance to conventional treatment processes involving disinfection or stronger ability to adapt to unfavorable environment than indicator organisms have. When the water reclamation plant consider adopting the national guidelines, the special pathogens should be selected for complement based on the testing and analysis the composition of pathogens in reclaimed water locally and then the ones with high possibility of infection and pathogenicity should be chosen to evaluate the potential risk and included in local regulations for regular monitoring.

**Regulation of wastewater treatment in guideline**

The treatment process, which is one of important barriers to remove pollutants, should be regulated in guideline to guarantee the qualified water as many countries e.g. US, Portugal and Cyprus (only for irrigation purposes) do. Compared with the treatment required in other guidelines, the biggest flaw of treatment process in studied site is a lack of disinfection step, which is rarely done for treating wastewater in Sweden. Monitoring data shows that probably some kind of disinfection should be added for both improving water security and getting acceptance from the public for water reuse. The treatment process suggested as following:

- For agriculture irrigation which is the application with most development potential in Sweden because its requirements of large amount and lower quality of water than others, secondary treatment include various types of activated sludge process, biological filters and natural system is necessary and disinfection should be stressed since the monitoring data of microbial parameters exceed most of requirements in other guidelines. Membrane methods have better retention of chemical and microbial pollutants than the conventional activated sludge process but also with higher cost. Feasibility studies are needed to identify which treatment methods are needed for treating wastewater to meet water reuse requirements.

- For industry uses, urban non-potable water and scenic environment use, tertiary treatment as well as disinfection should be required. The monitoring data of studied water shows that advanced process such as enhanced coagulation and sedimentation or
filtration is needed to remove colour, turbidity, SS, organic matter and algae, especially in summer.

- For disinfection which is main process for pathogens removal, ultraviolet (UV) is recommended previous to chlorination and ozone since it does not produce harmful by-products and dissolved solids, and no chemical involved in the process and is ecological and environmental friendly. Besides, the investment and operational cost of UV is lower than ozone and operation and management is easier (Liu, 2004). UV can be also used for algae removal in summer. The flaw of UV is no follow-up effect on pathogens regrowth during long-time distribution and storage. The combination with chlorination or secondary disinfection by users should be required in that case.

- If chlorination is used for keeping long-time disinfection, the impact factors for producing by-products, such as the dose, the components e.g. organic precursors and pH in reclaimed water should be controlled and regulated in guidelines.

- Monitoring data shows the variation of water quality with time. In addition to disinfection, a prolonged storage time is suggested both for degradation of pollutants and stabilizing and balancing the water quality. The storage time should be studied based on local situations.

**Regulation of protection measures in water reuse guidelines**

Guideline should not only regulate wastewater treatment process and the limits of water quality parameters, as measures for improving the safety from water supply-side. Also health protection measures for risk control from user’ perspective should be included. The guideline should provide instruction that in what conditions that reclaimed water should/shouldn’t be applied, which is not only for safe reuse but also can be guideline for planning and design, and what should be done to avoid risk and protect the users and environment when reclaimed water applied. The protection guidelines could be based on risk assessment process as shown in Section 4.2.2. In addition, distribution should be included, e.g. pipes with reclaimed water should be marked clearly to distinguish from tap water which is drinkable directly in Sweden. For protection of source of drinking water, such as wells which are common water source in Sweden, safe distance should be given. The education of public about the knowledge such as potential risk and relevant protective measures should be stipulated with detail and practical steps. Normally, the guideline is applied for general situations which maybe cannot consider individual cases due to different local conditions. Risk assessment should be formulated in the guidelines as complementary approach to guarantee safe reuse in that case. Also, the effective supervision and monitoring for the implement of protective measures should be clearly regulated in guidelines.

**Applied statistical methods in formulating reclaimed water quality guidelines**

*Identification of the impact factors for reclaimed water quality*
In addition to the limits of water quality parameters, the guideline should also provide instructions how to make the water meet the requirements from controlling impact factors of water quality perspective. The identification of impact factors which is the first step to set the regulations could be realized by PCA which could include the majority of the information after noise reduction and data simplification, and often possible to identify the processes underlying the PCs (Jackson, 1991).

The water samples from Källby WWTP are used for example to explain how to use PCA to identify the key factors. The explained variance of rotated PCA for each sampling point is shown in Table 4. From explained variance and loadings shown in bi-plots, the main factors affecting the variation of water quality could be obtained. For example, analysis from data of all sampling points (shown in Figure 5 (a) to (d)) shows that NH$_4$-N and NO$_2$-N are close to each other and strongly contributed to PC1, as do pH and alkalinity. That indicates that PC1 gives the information of redox state. COD, turbidity and colour are in the same group and mainly explained in PC2 which is probably related to algae. The important contributors to PC3 are FC and EC which represent microbial pollutant. Temperature is explained mostly in PC4, as well as LAS, which indicates the main process behind the component seems to be changes with time. TDS and Fe are both explained mostly in PC5 and have co-variance to some extent, and they both decrease with the water pass though the ponds (spatial variation). Thus, PC5 mainly gives the information about the treatment by pond system. The explained variance of rotated PCA for all data shows that the first five PCs give information of similar importance. Thus, the significant factors affecting the overall water quality are mainly redox state, algae, microbial pollutants, seasonal effect (temporal variation) and position in the pond system (spatial variation). The impact factors are similar for other ponds although the degree of importance varies in different ponds. Besides, for Eff., the treatment process in Källby WWTP is one of the significant factors, which is shown in component 4 of Eff. (not shown in the thesis).

Table 4: Explained variance of rotated PCA (%)

<table>
<thead>
<tr>
<th>PC</th>
<th>Eff.</th>
<th>Pond 1</th>
<th>Pond 2</th>
<th>Pond 3</th>
<th>Pond 4</th>
<th>Pond 5</th>
<th>Pond 6</th>
<th>All data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19.82</td>
<td>21.50</td>
<td>24.15</td>
<td>21.58</td>
<td>19.58</td>
<td>27.26</td>
<td>25.37</td>
<td>18.47</td>
</tr>
<tr>
<td>3</td>
<td>11.38</td>
<td>13.09</td>
<td>14.66</td>
<td>14.05</td>
<td>17.28</td>
<td>14.67</td>
<td>14.32</td>
<td>12.68</td>
</tr>
<tr>
<td>4</td>
<td>10.75</td>
<td>12.38</td>
<td>12.82</td>
<td>13.20</td>
<td>14.10</td>
<td>11.69</td>
<td>14.10</td>
<td>12.67</td>
</tr>
<tr>
<td>5</td>
<td>10.70</td>
<td>10.32</td>
<td>11.63</td>
<td>11.20</td>
<td>13.50</td>
<td>8.73</td>
<td>9.53</td>
<td>10.15</td>
</tr>
<tr>
<td>6</td>
<td>9.07</td>
<td>8.10</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>9.18</td>
<td>-</td>
</tr>
<tr>
<td>Accumulation</td>
<td>77.01</td>
<td>81.60</td>
<td>82.43</td>
<td>81.41</td>
<td>81.90</td>
<td>83.91</td>
<td>87.60</td>
<td>68.83</td>
</tr>
</tbody>
</table>

Note: ‘-’ means elimination
Figure 5(a): Bi-plot of component 1 and 2

Figure 5 (b): Bi-plot of components 2 and 3
Figure 5(c): Bi-plot of component 3 and 4

Figure 5(d): Bi-plot of component 4 and 5
The recognition and regulation of key impact factors in a guideline could be helpful to improve the safety of reuse by controlling those factors in treatment and storage process of reclaimed water. For example, the controlling of algae especially in summer is good for improving water quality; the adjustment of redox state is good for nutrients (N) removal; the controlling of temperature may be used to control E. coli which is correlated to temperature in some ponds, and treatment which have been discussed above, should be regulated in guideline to provide the clear instruction for operating and managing treatment process.

Simplification of reclaimed water quality parameters

Multivariate statistical analysis and models, such as PCA and regression analysis modelling, could be used for the selection of indicative parameters and simplification of parameters system in the guideline by obtaining the correlation between substances to make the guidelines more practical and cost-effective. For example, the correlation between parameters can be obtained in PCA correlation matrix. The parameters of high correlation coefficients with significance (p<0.001) in pond 5 are shown in Table 5. Some parameters, such as FC and EC, turbidity and colour, NH$_4$-N and NO$_2$-N, are strongly correlated and alternative to each other. For the whole pond system, COD$_{cr}$ is always strongly correlated to turbidity. And the quantitative relationship could be defined by statistic model. From statistical analysis and models, it is possible to obtain the correlation between special pathogens and proper predictors such as indicators (FC or EC), temperature, physical and chemical pollutants and environmental factors, which could save amounts of complex testing. Similarly, some toxic and hazardous substances, such as PPCPs, Endocrine Disrupting Chemicals and pathogens, existing in reclaimed water and induce potential health risk to users but normally not include in guidelines due to complicated and costly for daily testing, the correlation between which and conventional water quality parameters could be analyzed and modeled in the process of formulating guidelines to simplify the parameters system and daily monitoring and improve the reliability of reclaimed water quality guidelines.

<table>
<thead>
<tr>
<th>Correlation</th>
<th>COD$_{cr}$</th>
<th>Turbidity</th>
<th>NH$_4$-N</th>
<th>NO$_3$-N</th>
<th>NO$_2$-N</th>
<th>TDS</th>
<th>Colour</th>
<th>FC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbidity</td>
<td>0.73</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO$_2$</td>
<td></td>
<td>0.75</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Colour</td>
<td>0.78</td>
<td>0.82</td>
<td></td>
<td>0.76</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.66</td>
<td></td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>EC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>0.76</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.64</td>
</tr>
</tbody>
</table>

4.2.2 Evaluation of microbial risk from using treated wastewater for different applications (from Paper III)
As discussed above, risk assessment for special pathogens is not only an effective method to complement to the guidelines for evaluating the availability of water to be reused, but could also provide basis to formulate protection measures.

**Results of QMRA for different scenarios**

The annual probability of infection calculated by the dose–response modelling for the different scenarios is shown in Table 6. It should be known that the ponds have rich wildlife, particularly birds, such as ducks, swans, frogs and fish. Fecal material from the animals may in some cases randomly cause an increase in indicator organism content and sometimes increase the microbial risk when reusing the water. From the results of the dose-response model, the availability of water to be reused can be discussed. It can be seen that the annual probability of infection of E. coli and rotavirus for farmers in scenario 1 is lower than $10^{-4}$ in ponds 2, 3, 5 and 6, which suggests that this part of the water is safe for farmers to be used for irrigation from a microbial point of view. However, it is not safe enough for children since the probability of infection of rotavirus is over $10^{-4}$. In addition, the annual probabilities of infection of rotavirus in other scenarios are all over $10^{-4}$, which means the water cannot be accepted for safe reuse although most of the probability of E. coli is low enough. The difference between the risk of E. coli and rotavirus is mainly because of the median infectious dose.

Normally in the same scenario, the potential risk gradually decreases as water passes different sampling points. Nevertheless, there are some abnormal results existing. The risk of rotavirus of pond 4 in scenario 1 is unusually larger than the value of pond 3, which is probably caused by deviation due to limited sampling. Averaging multiple sampling could reduce the deviation.

**Table 6: Annual probability of infection for different scenarios of using reclaimed water**

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>farmer</td>
<td>child</td>
<td>3 m</td>
<td>100 m</td>
</tr>
<tr>
<td><strong>E. coli</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eff. 1</td>
<td>8.0*10^{-7}</td>
<td>1.2*10^{-4}</td>
<td>2.1*10^{-4}</td>
</tr>
<tr>
<td></td>
<td>3.0*10^{-6}</td>
<td>4.4*10^{-1}</td>
<td>1.2*10^{-1}</td>
</tr>
<tr>
<td><strong>Rotavirus</strong></td>
<td>8.1*10^{-5}</td>
<td>3.1*10^{-3}</td>
<td>2.5*10^{-3}</td>
</tr>
<tr>
<td></td>
<td>6.7*10^{-4}</td>
<td>9.9*10^{-1}</td>
<td>9.9*10^{-1}</td>
</tr>
<tr>
<td><strong>E. coli</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pond 1</td>
<td>8.2*10^{-7}</td>
<td>2.2*10^{-3}</td>
<td>8.0*10^{-3}</td>
</tr>
<tr>
<td></td>
<td>5.7*10^{-6}</td>
<td>6.8*10^{-1}</td>
<td>4.3*10^{-1}</td>
</tr>
<tr>
<td><strong>Rotavirus</strong></td>
<td>3.1*10^{-5}</td>
<td>4.7*10^{-1}</td>
<td>2.3*10^{-1}</td>
</tr>
<tr>
<td></td>
<td>6.7*10^{-4}</td>
<td>9.9*10^{-1}</td>
<td>9.9*10^{-1}</td>
</tr>
<tr>
<td><strong>E. coli</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pond 2</td>
<td>5.0*10^{-8}</td>
<td>2.6*10^{-1}</td>
<td>1.1*10^{-1}</td>
</tr>
<tr>
<td></td>
<td>1.8*10^{-7}</td>
<td>1.1*10^{-4}</td>
<td>4.7*10^{-4}</td>
</tr>
<tr>
<td><strong>Rotavirus</strong></td>
<td>2.7*10^{-5}</td>
<td>9.3*10^{-1}</td>
<td>6.4*10^{-1}</td>
</tr>
<tr>
<td></td>
<td>6.6*10^{-5}</td>
<td>9.9*10^{-1}</td>
<td>9.5*10^{-1}</td>
</tr>
</tbody>
</table>

40
The process and results of the QMRA could be used as a basis to develop protection guidelines. The factors affect the risk of infection not only concerning the density of pathogens, but also in the ways of the application, the length of exposure time, the distance from the source, the intensity of use, etc., which should also be included in the protection guideline for different applications. For the studied water in the thesis, the suggestions for developing protection guideline for different scenarios are listed as follows:

- The density of pathogens, which is one of main factors affecting the risk, should be lowered in the water for safe reused. The additional treatment, especially disinfection (see Section 4.2.1) should be required in guidelines. Besides, based on the results of the QMRA, agriculture is recommended to be a preferred application in Sweden since it needs lower quality than other applications and no additional treatment process needed for meeting basic health security requirements from microbial perspective.

- When the treated wastewater is applied for agricultural irrigation as described in scenario 1, there should be regulations for prohibiting children close to the spray source since the annual probability of infection for children is higher than adults and children who have a weaker self-protection awareness. When infected by pathogens, children do not have such a strong resistance as adults and fall ill easier. In addition, the methods and intensity of irrigation are also important factors. When using treated wastewater, the drip irrigation is recommended to reduce the atomization and spread of reclaimed water, and the large intensity of spray should be avoided.

### Recommendations for safe water reuse based on the QMRA

<table>
<thead>
<tr>
<th>Pond</th>
<th>E. coli</th>
<th>Rotavirus</th>
<th>E. coli</th>
<th>Rotavirus</th>
<th>E. coli</th>
<th>Rotavirus</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>$1.7 \times 10^9$</td>
<td>$6.6 \times 10^7$</td>
<td>$1.7 \times 10^7$</td>
<td>$6.4 \times 10^7$</td>
<td>$7.2 \times 10^7$</td>
<td>$2.5 \times 10^6$</td>
</tr>
<tr>
<td></td>
<td>$9.4 \times 10^8$</td>
<td>$3.6 \times 10^6$</td>
<td>$2.4 \times 10^4$</td>
<td>$1.0 \times 10^4$</td>
<td>$3.4 \times 10^3$</td>
<td>$4.0 \times 10^4$</td>
</tr>
<tr>
<td>4</td>
<td>$3.1 \times 10^5$</td>
<td>$1.2 \times 10^3$</td>
<td>$8.7 \times 10^1$</td>
<td>$7.6 \times 10^1$</td>
<td>$5.4 \times 10^1$</td>
<td>$2.9 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>$1.0 \times 10^4$</td>
<td>$4.0 \times 10^3$</td>
<td>$9.9 \times 10^1$</td>
<td>$1.4 \times 10^2$</td>
<td>$9.6 \times 10^1$</td>
<td>$5.1 \times 10^3$</td>
</tr>
<tr>
<td>5</td>
<td>$1.2 \times 10^6$</td>
<td>$4.8 \times 10^3$</td>
<td>$1.3 \times 10^2$</td>
<td>$4.6 \times 10^7$</td>
<td>$5.2 \times 10^1$</td>
<td>$1.8 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>$7.7 \times 10^5$</td>
<td>$3.0 \times 10^6$</td>
<td>$1.3 \times 10^2$</td>
<td>$4.9 \times 10^7$</td>
<td>$5.6 \times 10^1$</td>
<td>$1.5 \times 10^3$</td>
</tr>
<tr>
<td>6</td>
<td>$3.8 \times 10^5$</td>
<td>$1.5 \times 10^7$</td>
<td>$3.9 \times 10^1$</td>
<td>$1.4 \times 10^7$</td>
<td>$1.6 \times 10^1$</td>
<td>$5.5 \times 10^2$</td>
</tr>
<tr>
<td></td>
<td>$2.8 \times 10^5$</td>
<td>$1.1 \times 10^8$</td>
<td>$9.9 \times 10^1$</td>
<td>$3.8 \times 10^5$</td>
<td>$4.9 \times 10^1$</td>
<td>$9.1 \times 10^5$</td>
</tr>
<tr>
<td>7</td>
<td>$1.8 \times 10^6$</td>
<td>$6.9 \times 10^1$</td>
<td>$6.9 \times 10^1$</td>
<td>$4.3 \times 10^1$</td>
<td>$3.9 \times 10^1$</td>
<td>$1.8 \times 10^1$</td>
</tr>
<tr>
<td></td>
<td>$9.6 \times 10^5$</td>
<td>$3.7 \times 10^3$</td>
<td>$9.9 \times 10^1$</td>
<td>$5.8 \times 10^3$</td>
<td>$9.5 \times 10^1$</td>
<td>$1.7 \times 10^2$</td>
</tr>
<tr>
<td>8</td>
<td>$1.4 \times 10^5$</td>
<td>$5.5 \times 10^4$</td>
<td>$1.5 \times 10^4$</td>
<td>$5.3 \times 10^5$</td>
<td>$6.0 \times 10^5$</td>
<td>$8.8 \times 10^4$</td>
</tr>
<tr>
<td></td>
<td>$2.0 \times 10^8$</td>
<td>$7.7 \times 10^7$</td>
<td>$9.1 \times 10^2$</td>
<td>$3.5 \times 10^4$</td>
<td>$3.8 \times 10^1$</td>
<td>$8.2 \times 10^5$</td>
</tr>
<tr>
<td>9</td>
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<td>$5.5 \times 10^4$</td>
<td>$5.5 \times 10^4$</td>
<td>$3.0 \times 10^4$</td>
<td>$2.8 \times 10^1$</td>
<td>$1.1 \times 10^1$</td>
</tr>
<tr>
<td></td>
<td>$7.3 \times 10^5$</td>
<td>$2.8 \times 10^5$</td>
<td>$9.9 \times 10^1$</td>
<td>$5.4 \times 10^3$</td>
<td>$9.1 \times 10^1$</td>
<td>$1.3 \times 10^2$</td>
</tr>
</tbody>
</table>

-Acceptable risks are in bold font
For irrigation, whether agricultural or urban green space (golf courses and parks), by affecting the microbial aerosol diffusion coefficient, the distance from the spray source seriously affects the risk of infection for occupational groups. The person should not stay in a downwind direction near a spray source. The ‘safe distance’ during irrigation should be regulated in guidelines.

When reclaimed water is used for recreational water, the public should not be exposed to it immediately. The time for die-off of pathogens needs to be studied and pond storage without prior disinfections needs to be regulated. Further, the public who has open wounds should avoid contacts with reclaimed water. Instructions for staff handling the reclaimed water must be clear. Washing after contact is necessary in order to avoid ingestion of treated wastewater accidently.

For cooling water of industry application, the results show that the height of the cooling tower affects the probability of infection significantly. As the height increases, the risk of infection decreases although it still cannot be accepted without prior disinfection. Thus, the reclaimed water is better to applied for natural daft cooling tower which always is much higher than mechanical draft one.

Protection equipment and time limits for exposure in risk area for the people who are regularly in contact or exposed to reclaimed water should be regulated to avoid occupational disease.

4.3 Discussion on Stakeholders of Water Reuse

In this section, the key stakeholders of water reuse are identified, and their interaction, interest and impact are analyzed. Also, how to improve the stakeholders’ acceptance and participation to promote the sustainable development of water reuse is discussed. China is used as case study to analyse the challenges and proposal strategy to improve stakeholders’ acceptance and participation (from Paper V).

4.3.1 Identify the key stakeholders of water reuse

Identification of key stakeholders who have significant influence upon or importance within the project of water reuse is the first step and important basis for the further analysis. According to Power-Impact Grid and Influence-Interest Grid, the key stakeholders for water reuse project their impacts and interests are listed in Table 7.

<table>
<thead>
<tr>
<th>Stakeholders</th>
<th>Power/ Influence</th>
<th>Interest</th>
<th>Communication needs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Policymakers (central and local government)</td>
<td>High Impact on multiple aspects, such as the management, investment and market, leading the level and</td>
<td>High Have interest in the outcome of water reuse</td>
<td>Actively Engage</td>
</tr>
<tr>
<td>Group</td>
<td>Impact on production, supply and use, as well as the market development by developing the management and supervision system, including laws, regulations and guidelines</td>
<td>Have interest in the sound operation of the water reuse system and market</td>
<td>Keep Satisfied</td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>Administrators (different levels of administrative departments and reclaimed water companies)</td>
<td>High</td>
<td>Low</td>
<td>Have interest in the sound operation of the water reuse system and market</td>
</tr>
<tr>
<td>Supplier/maintainer (reclaimed water companies and plants)</td>
<td>High Impact on production (facilities, reclaimed water quality) and supply</td>
<td>Medium</td>
<td>Have interest in good service and the resulting benefit</td>
</tr>
<tr>
<td>Investors</td>
<td>High Impact on the investment and price. Provide funding and get profit from the service of reclaimed water supply</td>
<td>High</td>
<td>Have interest in the economic benefit</td>
</tr>
<tr>
<td>Customers (farmers, industries, municipalities, residents, and service sectors, such as hotels, the car wash industry, golf courses, office buildings and schools)</td>
<td>High Impact on the use and the market of reclaimed water, as well as the feedback to policymakers, administrators and investors.</td>
<td>High</td>
<td>Have interest in the reclaimed water service and resulting economic benefit</td>
</tr>
<tr>
<td>Public (communities, NGOs, media)</td>
<td>High Impact on multiple aspects, such as policymaking, investing, research and users’ acceptability. Support or oppose the use of reclaimed water in different ways, such as feedback to policymakers, providing funding and the communication platform for researchers, propaganda in media.</td>
<td>Medium</td>
<td>Have interest in the environmental benefit from water reuse</td>
</tr>
<tr>
<td>Researchers</td>
<td>High Provide advanced technology for the production and distribution to reduce the cost and methods for better management</td>
<td>Medium</td>
<td>Have interest in the practical application of the technology</td>
</tr>
<tr>
<td>Land users</td>
<td>Medium Impact on the collection of wastewater</td>
<td>Low</td>
<td>Occasionally contact</td>
</tr>
<tr>
<td>Other waters sectors (e.g. natural waters,</td>
<td>High The quantity, quality, use status</td>
<td>Medium</td>
<td>Have interest in the</td>
</tr>
<tr>
<td>Customers (farmers, industries, municipalities, residents, and service sectors, such as hotels, the car wash industry, golf courses, office buildings and schools)</td>
<td>High Impact on multiple aspects, such as policymaking, investing, research and users’ acceptability. Support or oppose the use of reclaimed water in different ways, such as feedback to policymakers, providing funding and the communication platform for researchers, propaganda in media.</td>
<td>Medium</td>
<td>Have interest in the environmental benefit from water reuse</td>
</tr>
</tbody>
</table>
4.3.2 Interaction of different stakeholders

The stakeholders are not self-existent. Their complex behaviours are affected by others and can form positively or negatively combined effect to the concept of water reuse. The interaction of key stakeholders is shown in Figure 6. The analysis which is shown in detail in Paper V is summarized as following:

- Policymakers affect almost all other stakeholders for water reuse who are administrator, public, investor, customer, land users and other waters sectors, since policymakers have decision-making power and can decide the level and lead the direction of development by formulating and promulgating relevant policy, planning and strategy. Policy orientation affects other stakeholders’ behaviours by effecting on their concerns and interests. Also, policymakers’ behaviours are affected by other stakeholders since they need to develop the policies in line with the requirements of related stakeholders and check the effect of exist policies and revised them according to the feedback from others. Policymakers can be seen as a ‘hub’ of all stakeholders.

- Customers can directly decide the use of reclaimed water and thus affect the development of the market. Besides policymakers, their attitude also directly affects the investors’ interest in investing. Customers’ attitude and behaviour are affected by multiple factors, including quality of service, the risk and the safety of water reuse, the reclaimed water quality, benefits expressed as price and subsidies and information, which are related to administrators, suppliers, researchers and policymakers.

- For administrators, besides policymakers, they should also be affected by public in terms of inspection and customers by their feedback. At the same time, the administrators’ behaviour directly affects the quality of reclaimed water supply though the management and supervision system, thus, impacting the suppliers’ behaviours and the customers’ satisfaction.

- Suppliers’ behaviour has significant impact on that of the customers’ by reclaimed water quality and service. In addition to administrators, they are also impacted by researchers who can provide advanced technology to improve the service, and the investors who provide funding for production and supply system.

- Besides the analysis above, the public, including communities, NGOs and the media, is mainly affected by the situation of water resources and the studied results from researchers. In addition, it influences the researchers in some ways.

Any poor functioning or mistake in any one link may lead to a vicious circle in the whole system and obstructs the development of water reuse. The definitude of the interaction...
between the stakeholders can greatly contribute to keep the system well-functioning and promote water reuse by improving the different stakeholders’ behaviours.

![figure 6: Interactions of stakeholders of reclaimed water](image)

**4.3.3 Improvement of stakeholders’ acceptance of water reuse**

Acceptability is one of the factors on which the success of a strategy depends (Johnson et al., 2008). The acceptance of reclaimed water by the key stakeholders, which is more difficult to reach but more importantly needed for reclaimed water than other water resources in that reclaimed water is a special and emerging water and controversy always happens, is the premise of the reality of sustainable development of water reuse. Recommendations for improving the acceptance of policymakers, investors and customers’ are summarized as following, since they are in charge of decision making, funding and use, respectively, which are significant factors directly affecting the market of reclaimed water.

- For policymakers, the attitude to reclaimed water depends on two aspects: the situation of water resources and environment, and the feedback from other stakeholders, especially from researchers and customers. Thus, the improvement of acceptance mainly comes from increasingly serious situation of water shortage and deteriorating water environment, the superiority of reclaimed water compared to other waters,
effective technique support from researchers and positive attitude from public and customers.

- The improvement of investors’ acceptance is greatly caused by supporting policy to ensure investors’ benefits and increase the investors’ confidence on water reuse industry, and the customers’ positive perceptions which can increase the sale and promote market of reclaimed water.

- For customers, the way for improvement of acceptance is reducing health risk from using reclaimed water and providing good service of the safe and high quality of reclaimed water supply, which is of highest concerned for them. Besides, to correct the misconception and make the users trust the proof of the safety of reclaimed water is important to improvement the acceptance. Some methods, such as identification of problems, improving education and information and collection of feedback are discussed in Paper V.

4.3.4 Challenges and strategy for stakeholders’ participation in water reuse in China

In China, the research for stakeholders theory started from the middle of the 1990s and is still in the initial stage (Zhang, 2011). As rulers introduced the idea of public participation in mainstream ruling ideas and ideologies for governance, stakeholders theory has been developed in an ongoing way and has been successfully realised in some cases. Nevertheless, stakeholders’ participation is still not universal and there are seldom relevant research and application on the stakeholder analysis in the field of water reuse in China. The reasons for that are mainly: a) lack of mandatory legal guarantees; b) impacted by traditional unilateral governance theory of ‘shareholder primacy theory”; c) impacted by traditional indirect participation in form of ‘representative’ constrained by populous situation; d) constrained by inadequate education, knowledge, personal quality and capacity for direct participation; e) lack of initiative caused by insufficient concerned of water crisis and water reuse; f) lack of participation platforms.

The effective participation by all stakeholders, especially public, is particularly important to promote the sustainable development of water reuse as China is a populous country and reclaimed water supply must be a service for public. To improve the situations, some strategies are recommended as following:

- Improve relevant laws and regulations to provide legal basis and guarantee for stakeholders’, especially customers and public, participation. The mandatory should be strengthened in the expression of the law to make the stakeholders’ participation is a compulsory part of decision-making process.

- Build effective and diversified communication platforms including feedback channels and mechanism to make all stakeholders involved in, which could act as an ‘easy’ start of stakeholder’ participation.
- Establish incentive mechanisms to stimulate public initiative in participation, which can increase the public acceptance of water reuse and help them to establish the concept of their own dominant position of stakeholders with corresponding rights and responsibilities.

- Improve the publicity of information and education of public to guarantee enough capacity in participation. It is better to adopt different education ways for different groups which can make the education more effective and targeted.

- Learn from the experience of domestic and foreign success stories.

4.4 Outlook stimulated by integrated strategy

For sustainable development of non-conventional waters, the strategies discussed above include many fields which involve different stakeholders’ interests and influence their behaviour. Of all strategies, improving and guaranteeing security of water supply and use is the basis to the development of non-conventional waters and most concerned by stakeholders. Also, the stakeholders’ acceptance, participation and collaboration play a crucial role on the performance of strategies including the improving of water security. Thus, the strategy should be comprehensively developed and bidirectionally implemented both from water managers and supported and participated by other stakeholders.

The strategy developed from case study is also appropriate for other countries. For example, in Sweden, where the development of non-conventional waters is needed but still in its infancy without any integrated development planning by water managers, the potential market is considerable if the strategy such as sound management system, effective legal protection, intelligent pricing and guaranteed water security are adopted and all stakeholders collaborate for the promotion. Case of agriculture which is the preferred application recommended, the water withdrawal by agricultural irrigation is about 62 million m$^3$/a, which could be totally provided by treated municipal wastewater that is about 122.5 million m$^3$ for three months (SCB, 2010) and could meet the requirements of water quality, to avoid the dependence on runoff and water shortage in dry summer. Desalination is a limited water supply method in Sweden at present, with capacity about 1000 m$^3$/day, but it could be expanded by proper policy, at least for the water supply in islands and specific industries.

Also, the means to improve the water security studied for Sweden could be applied in China which is facing the crisis of confidence on the security of water supply. For reclaimed water, the controversy for reliability and stringency of standards still exists and becomes one of reasons for the question of reclaimed water quality. The approaches discussed in the study especially for the microbial indicators and developing the protective guidelines could greatly help to improve the Chinese standards. Risk assessment model is also beneficial for China both for developing local guidelines and estimating the potential risk for individual cases since the local situations vary a lot in China.
The potential market of non-conventional waters is huge and will be greatly promoted by the adoption of the relevant strategy and guaranteeing water security to deal with the challenges combined with the stakeholders’ effective participation and co-operation which discussed in the study. Case of Tianjin where the multiple types of water resources contributed to water supply, in 2011, the water supply by non-conventional waters (reclaimed water and seawater desalination) only took up 2.2% of total, while 72.6% was from the surface water including long-distance water transfer (34.5%) and still 25.2% (about 582 million m³) is from groundwater in spite of serious overexploitation (Tianjin Water Authority, 2012). After 2014, groundwater extraction will be banned in Tianjin according to the document by Tianjin municipal government. That part of water should be instead by non-conventional waters, which could be guaranteed by adoption of integrated strategy. For the whole China, wastewater discharge is about 80 billion m³/a, only 1.2% of which is reused at present (Ministry of Water Resources of China, 2011). If intelligent strategy is adopted, the potential production of reclaimed water could not only meet the 40.4 billion m³ of annual water shortage, but also greatly reduce the pollution burden discharging to natural waters. The target that seawater desalination supplies 803 million m³/a by 2015 could be reached by implement of relevant strategy and coordinated by relevant stakeholders. The development of water reuse and desalination could save the projects of long-distance water diversion, which need large investment and probably have long-term influence on geology and ecological environment, and greatly reduce the fresh water withdrawal especially the overexploitation of groundwater. The deficit of water balance will be eliminated and the water environmental will be improved by the expansion of non-conventional waters market.

As the development of water reuse and desalination, the conventional water balance will be gradually changed. The optimized allocation of different water resources is becoming more important and complex. In spite of both belonging to non-conventional waters, reclaimed water (treated wastewater) and desalinated water (e.g. seawater) have much difference in e.g. water quality, cost and public perception, thus, should be used for different applications. The optimisation of the supply from water quantity, water quality, pricing and value of water resources should be considered in overall planning of water resources.
5. CONCLUSION AND FURTHER STUDY

5.1 Conclusion

As the global water crisis grows increasingly serious, desalination and water reuse are given more and more attention and widely carried out at different levels in countries around the world. Although much effort has been put in to stimulate the use of non-conventional waters and there are numerous success stories and cases around the world, the challenges and obstacles still exist. It is important to have a strategy to deal with the challenges and to promote the sustainable development of desalination and water reuse, which is studied in the thesis. Some key points are concluded from sustainable development, safe use and the stakeholders’ perspective.

The strategy, concluded from the analysis and discussion of the case study in China in Paper I and Paper II, for sustainable development of desalination and water reuse involves multiple aspects, such as management, the legal basis and guarantee, supported policy, quality of water and service, investment, pricing, cost and technology. The defect in any link will delay and even hinder further development. Among the aspects, water quality and price are the most concerned by users and thus directly influence the market development. The guarantee of qualified water (especially for reclaimed water) and the establishment of an intelligent pricing system (especially for desalination) are the basic measures to promote market development. Additionally, it is difficult to go further without supporting policy. Especially for attracting investments and encouraging use, the supported policy is one of the most important driving forces to help investors build confidence on the market. A sound management system, an effective and strong legal guarantee, and cost reduction by technological advancement are also important ways to promote sustainable development.

In all impact factors, security is the foundation for the development of the non-conventional waters’ market, especially for reclaimed water because of its particularity; thus, the relevant strategy and methods were focused on in the study. For ensuring the safety and health of users, guidelines and risk assessment are essential as well as effective barriers, which is not only agreed on by water managers and researchers in different couriers and organisations but also can be concluded from the study in the case of Sweden shown in Paper III and Paper IV. The development of guidelines, whether the selection of parameters or the approaches applied, should be based on the local situations. A comprehensive guideline should not only include requirements for water quality but also involve the water treatment required, storage, distribution, application, education for the public and important health protection measures. Statistical methods are useful for the simplification of parameters in guidelines. Risk assessment which could be more targets for individual situations is an important supplementary means to guidelines for judging the
possibility of reuse of the studied water and improving the security of reuse. Also, the process and results of risk assessment could be a reference for the development of protection guidelines in terms of, for example, the water treatment required, the controlling of the exposure pathway and the dose.

Besides the strategy from the water manager’s perspective, other stakeholders also play a significant role in the development. Stakeholders theory could be applied regarding the management of non-conventional water since it is an important part in integrated water resources management and successfully applied for other water resources. The characteristic of non-conventional water, especially reclaimed water, makes stakeholders’ acceptance and contribution indispensable for sustainable development. The identification of stakeholders and their interests and concerns as well as the analysis of their interaction could help to set the strategy to improve their acceptance. Among all stakeholders, the public and customers are easily overlooked; the strategy which is shown in Paper V for encouraging their participation and contribution in, for instance, the management system should be adopted.

The application of non-conventional waters is obstructed by some challenges, but the market with huge potential will be greatly promoted if appropriate strategies are adopted by water managers and accepted and collaborated on by relevant stakeholders. In China, with the improvement in the fields affecting development, the potential production of reclaimed water and desalinated water could greatly reduce the extraction of ground water, the needs for projects of long-distance water diversion and the pollution burden discharging into natural waters. In Sweden, where the development of non-conventional waters is in a primitive stage, consequence is smaller, but still very positive. The intelligent strategy will make the treated wastewater at least be used for agricultural irrigation in order to reduce the dependence on precipitation, which will be a good start, while the seawater desalination will be expanded for industrial use.

5.2 Limitations and further study

There are some limitations for the study, such as limited monitoring data, inadequate investigation of public perceptions, as well as the lack of uncertainty analysis for quantitative microbial risk assessment, which should be added in further study. In addition, for desalination, the study should continue with the impact on health concerning the drinking of desalinated water and the improvement of the security of the water supply. Also, the risk assessment for chemical pollutants should be conducted for safe water reuse, and the combined and optimised use of non-conventional waters in terms of quantity, quality, economy and ecological impact should be studied in the future.
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Paper I

Review and prospects of desalination as a water supply method in China

Shuang Liu, Kenneth M Persson

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Review and prospects of desalination as a water supply method in China

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Review and prospects of desalination as a water supply method in China

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ABSTRACT

With the development of urbanization and deterioration of water environment, the fresh water shortage in eastern coastal cities of China is more and more serious. Desalination, as the only way to increase the amount of fresh water, should be more applied in this region, while the actual development is not as expected for some reasons. The study reviews the desalination status in China from the perspective such as driving force, investment, cost, policy, safety and energy. The analysis of problems makes the recommendations how to develop desalination market and make desalination as a safety water supply. In addition, the study compares desalination with wastewater reuse in water quality, cost, management, public acceptance and so on and discusses the proposal for integrated utilization of different unconventional water sources.

Keywords: Desalination; Cost and investment; Technology; Energy; Management and policy

1. Introduction

China is a serious drought and water shortage country, listed as one of thirteen countries that are most water-poor in the world. The total amount of renewable fresh water supply is $2.8 \times 1.0^{12} \text{m}^3/\text{year}$ in 2008 equivalent to a theoretical per capita freshwater resource of $2,220 \text{m}^3$ [1], accounting for 6% of the average value of the world and ranking fourth in the world. But China is a populous country, so the freshwater resource per capita is one-fourth of the world’s mean value (8,840 m3), ranking 121 in the world. Further, the practically available freshwater resources per capita, excluding flood run-off and groundwater resources in remote areas, are only about 900 m3, with extremely uneven distribution [2]. By the end of twentieth century, among more than 600 cities in the country, more than 400 cities had existed problems of inadequate water supply and some 110 cities faced serious water shortage. The bigger city, the bigger is the challenge. In the 32 megalopolis with population over one million, there are 30 cities long plagued by water shortage [3]. At the same time of being confronted with water shortage, water pollution is increasingly aggravating. With the rapid development of economic construction and the population on the increase, sewage and waste emission increases as well. According to China’s Environment Bulletin, only one-fifth of the municipal and industrial wastewater is

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properly treated. The rest is more or less untreated and directly drained into the waters, causing a large area of water pollution and resulting in deterioration of water environment [1]. Despite large flows, the waters of seven major river systems are moderately polluted, and eutrophication is the prominent problem of lakes (reservoirs) [1].

Even if water treatment plants were developed thoroughly over the country, additional water supplies are needed to meet the growing water demand of the urban areas. Desalination has been proven to be an important method for freshwater supply in the world. The rapid growth of desalination in the recent decades allowed the social and economic development to continue and grow also in arid and semi-arid areas. The installed desalination capacity has increased rapidly worldwide, from 8,000 m$^3$/d in 1970 to about 77.4 million m$^3$/d installed or contracted production capacity with over 16,000 industrial-scale desalination units by 2012 [4]. A variety of desalting technologies has been developed over the years, primarily thermal and membrane processes. The cost of desalination per produced water volume is roughly inversely proportional to the production capacity of the plant. The market is also driven by the falling costs of desalination, which are due to the technological advances in the desalination process [5].

Since China is a water shortage country with huge marine resources, desalination should be an important additional water sources and should have a board space for development in the country. Research on technology of water desalination in China started with ED in 1958, in a co-operation between the navy and the Chinese Academy of Sciences; the research on RO started in 1965; the research on large- and medium-sized distillation started in 1975. In 1981, the first ED desalination station with capacity 200 m$^3$/day was of sized distillation started in 1975. In 1981, the first ED started in 1965; the research on large- and medium-

Nevertheless, compared with the Middle Eastern countries, desalination in China is still not as much applied as might be expected. The total installed capacity since 1945 is only ranked sixth in the world [4] and daily output is only about 1% of the global production. Besides comparatively high price, there are also other problems existing, such as policy and management, which delay the pace of development. In 2012, the issue of ‘The views on accelerating the development of the desalination industry’ (Document No. 13, 2012) by the office of State Council identifies the desalination industry to the national strategic level [13]. Information from China Desalination Association (CDA) shows that during ‘12th Five-Year’ period, investment for desalination is expected to reach 200 billion Yuan RMB [8]. Desalination in China is facing unprecedented opportunities for development yet many challenges remain.

The article reviews the desalination status in China from the perspective of general driving forces, management, investment and price system, policy, safety and energy. Through the analysis of problems, it is possible to make recommendations how to develop the Chinese desalination market and to use desalination for a safety water supply. In addition, the article compares desalination with wastewater reuse in terms of water quality, cost, management, policy and public acceptance and discusses the proposal for comprehensive and optimized utilization of different water sources.

2. Driving force for Chinese desalination market – Why desalination needed in China?

The most fundamental driving force for desalination is a freshwater shortage for all the countries using this method. There is no exception for China as previously described. The total water shortage in urban area is 6 billion m$^3$. The output value impacted by urban water shortage is up to more than 2.0 × 10$^{11}$ RMB Yuan/a, with about 40 million population affected [3]. The prediction is that the water resources per capital will decrease to 1,760 m$^3$ by 2030, which is calculated according to the population increasing to 1.6 billion [14]. The value is closed to 1,700 m$^3$ per capital, which is the internationally recognized water stressed standard.

For China, another reason is the advantage of desalination to other ways of getting fresh water. At present, besides local surface water source, the main modes of access to fresh water are exploitation of groundwater, remote water diversion and desalination, in which the last one is the only method that can increase the total amount of freshwater. In the situation of surface water serious polluted, the exploitation
of groundwater has been a regular way to get fresh water. About 400 out of 657 cities are using groundwater as water source, and the amount is up to 18% of total water supply in 2001 [15]. As there is not enough management and monitoring, the over-exploitation of groundwater takes place in almost all large- and middle-sized cities, which leads to ground subsidence, seawater intrusion for coastal locations, salinization of land, drained wetlands, dried watercourses and lakes and other ecological damages. Besides the over-exploitation, groundwater in 76 cities is seriously polluted to a level where the water is unsuitable for water supply. To alleviate water depletion in the north of China, the Chinese government developed a plan of remote water diversion called ‘South-North water transfer project’ in 2002. However, the fresh water available from the Yangtze River basin is insufficient and the impact of the water transfer project on the ecosystem is hard to estimate [16]. The project will also lead to forced migration for hundreds of thousands of people. In addition, the total investment will reach 486 billion Yuan RMB, suggesting that the cost of remote water diversion is much higher than the cost of desalination.

On the other hand, China has 32,000 km of coastline and 3,000,000 km² of marine areas, which contain abundant seawater resources [16]. The littoral resides 40% of the total population and contribute to 70% GDP of China in the 13 provinces with coast. China’s population and economy are concentrated in the coastal zone, which makes desalination a viable alternative source of water, as many coastal cities face serious fresh water shortage [17]. Furthermore, desalination is less influenced by geology and climate than groundwater abstraction or remote water diversion. Desalination has less impact on surrounding residents. That means that desalination is a safer method for water supply. Whether from cost or from impact on ecology and environment perspective, desalination should be a better way to provide fresh water to these water-shortage areas instead of over-exploitation of groundwater or transferring water from long way.

3. The problems and proposals for development

Desalination is not as widely used as it could be for water supply. Although there is some progress after more than 40 years of development, desalination in China is still in the initial stage and has the features of immature technology, such as small-scale plants, slow development, high costs and difficult promotion [18].

In Fig. 2, the distribution of installed capacity by plant size and the top 10 plants by capacity is presented. Most of the desalination plants of China are still small- or medium-scale plants. Large capacity plants only account for 4.7% of the production. Desalination has not reached the economic scale in China. In a market economy, the demands decide markets. The small-scale means there is little demands for desalination. The users do not have enough awareness and
acceptance for desalinated water, combined with high cost and no enough support from government. At present, there are not enough benefits for investors to be involved in the desalination industry. Technology, price and policy, which have some correlation to each other, are the most important points for the development of desalination in China.

3.1. Technology and energy

There are three main types of desalination methods used throughout the world, named Membrane Systems (such as RO and ED), Thermal Processes (such as MSF, MED and VC), and others (such as MD). Of all methods, RO has the largest share of the Chinese desalination market (Fig. 3). Reverse osmosis technology has the advantages of lower project investment, shorter construction period, smaller footprint, easier operation and maintenance, lower energy consumption and lower cost than other methods [19]. Furthermore, RO is more suitable for small- and medium-scaled plants, which are the most common in China. MSF, which is more suitable for large-scale plants, is an important method, second only to RO in the world with about 30% of installed capacity globally, while a modest 9% in China. Besides the scale, energy is another reason for that RO is much more applied than MSF in China since China is also an energy shortage country. For some cases, MSF even has higher cost than RO in China, since it consumes more energy. However, for thermal electric power plants, petrochemical and other enterprises, which require boiler feed water and process water, and produces low-grade steam or heat, MSF has a certain competitive advantage, while RO has large edge for municipal water supply.

From technology perspective, another problem is China is a lack of independent intellectual property rights of core technology and key equipments. About 80% of installed capacity use introduced technology from foreign countries, and key equipments, such as RO membrane and energy recovery equipment, are mainly dependent on imports, which is one main reason for elevated investment costs. Information from CDA shows that 50% of the thermal material and 90% of the membranes (mainly RO) are imported, which increase the investment costs [20]. In addition, the quality of any domestic equipment, such as RO membranes, is an issue. Domestic desalination industry in China performs worse than international industry in terms of retention, energy efficiency and expected lifetimes of the plants. This is the main reason why Chinese enterprises have a small proportion in the market in spite of lower prices. In the 16 completed desalination projects over 10,000 m³/d, only 25% are self-constructed, and less than 13% if calculated in capacity [8]. For China, independent research and development of technology and domestic equipment with higher performance is a major way to reduce the cost and promote development of desalination and related industry. In Membranes industry “12th
Five-Year Development Plan” by China Membrane Industry Association, the market share of domestic RO membrane should increase to 25–30% in the coming five years. The reform and innovation of technology with own intellectual property right is regarded to be the basis for future development of Chinese desalination market. The Chinese Membrane Industry urges the government to increase the investments in relevant research and to formulate the detailed methods and steps for how to support and promote the industry, not only through general planning.

Energy consumption is the one of the main technical and economic indicators for desalination and has important impact on technology selection and cost. It has special relevance for China, which is an energy shortage country. In 1997, “500 m³/d reverse osmosis desalination demonstration project” used a turbine-type energy recovery device for the first time, which made desalination energy consumption of fresh water decrease to below 5.5 kW h/m³; In 2000, a 1000 m³/d reverse osmosis desalination demonstration project built two plant in Changdao of Shandong Province and in Shengsi of Zhejiang Province, using a pressure switching energy recovery device, which made desalination energy need to decrease to below 4.0 kW h/m³ for produced freshwater [19]. In China, desalination energy consumption indicators have decreased by about 90% for the best-performing plants (from 26.4 to 2.9 kW h/m³) in 40 years [21]. The utilization of energy recovery and frequency conversion control technology significantly reduces energy consumption of desalination project, accordingly leading to a reduction in the operational cost. From data above, we can see that China has a certain progress on energy recovery device, but as same as other equipment, energy recovery technology with Chinese independent intellectual property rights is still in the research or initial development stage, and it has not been a mature industry. Furthermore, in China as globally, most desalination plants use conventional sources of energy (gas, oil and electricity), which is cheaper at present but has negative impact on environment. Desalination powered by alternative energy sources, which includes nuclear energy and renewable energy (wind, solar, geothermal energy, etc.), as opposed to conventional energy sources, should be an attractive solution in terms of induced environment impact due to lower conventional energy consumption and lower gas emissions. Since conventional energy sources are limited and has a significant environmental impact, renewable energy sources for desalination will have a great potential market also in China.

China has some research on solar energy device for desalination. For example, the solar power device for distillation desalination named HM/HD, which is developed by Huangming Solar Energy Group, reduces the amount of heat losses and saves energy and cost. The cost is less than 20 Yuan RMB/m³, and the energy consumption is less than 3 kW h/m³ [22]. There are also some small capacity projects using solar, mainly concentrated in islands which lack other energy sources. Nevertheless, the solar power has still not been able to compete with conventional energy sources due to technology problems, such as low water production and high costs. Similar with solar power, other renewable energy sources only take up small proportions of the production, mainly because of the higher operational costs. According to the study by Tian (2001), nuclear energy, which causes less greenhouse gas emissions, has economic competitiveness compared with fossil energy when it is applied in RO, MSF and MED [23]. The stability and sustainability are regarded as superiority to some renewable energy sources depending on the weather conditions. The issue of this kind of energy is the safety of nuclear reactor and how to control the nuclear waste. Another potential energy is biological energy, which can stimulate a recycling economy. Bio-energy can supply energy and reduce waste pollution. It should be more suitable for China, since solid waste management is also a problem in China. The alternative energy is an important direction for research and development, since the conventional energy is more and more limited and the safe energy supply will be critical and a bottleneck for sustainability of desalination development. The implement of “Renewable Energy Law” [24] clarified the status and importance of renewable energy, and it will bring broad prospects for development and investment.

3.2. Feed water

The data show that higher salinity in the feed water means higher operational costs. The selection of feed water depends on local condition and water Fig. 4. China installed capacity by raw water quality [9–12].
availability. In Fig. 4, the installed capacity by raw water quality is presented. The main water source for desalination in China is seawater, accounting for 53%. The brackish proportion in China is lower than the mean value worldwide (19% in 2009 [12]). Wastewater as feed water is used modestly but is expected to gradually grow in importance as it is a stable water source with significant amounts of water with low salinity and thus a lower operational cost than seawater desalination. Wastewater has generally higher concentrations of pollutants and may even contain toxic and hazardous substances. Thus, the health risk is a potential problem and constrain for wastewater desalination. Rivers and pure water have lower salinity and operational costs compared with other raw water types, but desalination of these waters is more expensive compared with regular water treatment processes.

That is the reason why these two kinds of feed water are used less even if they are cheaper. Thus, the desalted water from rivers and pure water could be only used in some special industries, which require better water quality. Increasing the proportion of feed water with less salinity, through for instance mixing seawater with wastewater, is another way to decrease the operational cost of a desalination plant.

3.3. Investment, cost and price system

At present, the investment for desalination mainly comes from two sources: Corporate (desalinated water needed) self-financing or public investments. The former is still the main case. The investment ways are still impacted by habits and customs from the former planned economic system. There are exemptions such as a 100,000 m³/day RO-project in Dagang district in Tianjin, where the BOO model is tested for the Chinese desalination market, yet this kind of investment model is still applied for few cases. The investment institution based on market-oriented operation has not been formed. Furthermore, the government only provides subsidies to the desalination plants owned by government. For the plants invested by company, no incentives or subsidies are granted from government. Because of the higher cost than regular water sources, the investors cannot get benefit from desalination, which decrease their investment interests. Larger desalination projects need substantial investments, which cannot be provided for by local government or small corporate. That is one important reason for the mostly small and middle capacity desalination projects that launched in China. There are still not enough investment funds for large-scale projects. At the same time, China has no lack of investment capital. Private and international funds can be used for investment in desalination. Thus, for long-term development of the desalination structure in China, it is necessary to establish a market-oriented operation institution and relevant policies, which can attract private capital and foreign investment under the premise that the plants are owned or controlled by government. The enterprises, which get the franchise authorized from government, raise funds for the investment of plant construction and charges as a return on investment to realize the rolling investment. The government should keep the responsibility for investments of the construction of facilities, such as public distribution networks, and provide subsidy or preferentials to the enterprises, such as price subsidy and preferential of electricity price, so that it has enough benefit to maintain normal operation.

On the other hand, only there is demand, there will be market. The price is the one of most important factors to stimulate the demands. Despite of investment institution based on market-oriented operation, a rational price system is another important way to promote desalination market. Due to multifactors impact, such as technology, device, scale and pollution in water source, the average Chinese seawater desalination cost, which is 5–7 Yuan RMB/m³, is higher than the average in the world (0.5 US$/m³) [21], [25]. Together with distribution fee, tax and benefit for enterprise, the price is higher than tap water for resident and industry in most regions. That is the main reason that most desalination capacity is used for islands with fresh water shortage and industry with limited water supplies and higher cost than desalination if tap water is used to make process water. Up to now, independent desalination supply for residents and supporting tap water supply through blending in desalinated water has only taken place in Tianjin and Qingdao. Despite the reason of water quality, price is another key factor for the situation. For example, Tianjin, as a coastal city with serious freshwater shortage, has mixed the desalinated water into municipal water supply pipelines in Hangu district. According to the news report by Xinjing Newspaper in 2011 [30], the price for residents is 4.6 Yuan RMB/m³, as same as tap water before mixture. But the actual cost is about 7.5 Yuan RMB/m³, and the price for the water supply company is 8.15 Yuan RMB/m³, which means there is a 3.55 Yuan RMB deficit per cubic meter of water supplied from the company. For industry supply, the desalination price is decided by users and producer. In Tianjin, the tap water price for industry is 6.6 Yuan RMB/m³, which is lower than the desalination cost. Thus, the producer always have deficit when they sell water. Who should
pay for the price difference? In Tianjin, the view is that the deficit should be covered through governmental funds, before the pricing system has evolved so far that the water prize covers the actual costs. Before this has been reached, the financial support from the government is important to allow for new investments in desalination. In the beginning of a development process, deficits should and can only be paid by government before a system for sustainable development has been established.

Under the background of market economy, benefit is the most important driving force for both investors and users. For investors, they want to reduce the cost, which is mostly depending on the technology innovation as mentioned previously. For users, under the premise of safe water quality and supply, the price is the most impact factor for selection in multi-water sources. To promote desalination and make it more accepted by users, desalination must have price superiority. However, due to the implementation of the planned economy in the past, the price of tap water was on the low side in long term with the average price is 1–1.5 Yuan RMB/m³. The low price make users lack of awareness of water resources shortage and water saving. Furthermore, the low prize on tap water means that the users who use the desalinated water cannot get more benefit, which hinders the widespread use of desalination. After 2000, with the reform of water price and rise in water tariff, the situation is gradually improving. The reform also brings opportunity of the development for irregular water sources, such as desalination and wastewater reuse.

Different from cost, price system can be more controlled by policy. Thus, in the case that the desalination cost cannot greatly decrease in short time, the development of rational price system, which should play a regulation role between investors and users, is particular important to promote the market. At present, similar to investment institution, the rational price system still has not been established in most areas. For the development in long term, the followed price proposal can be tried.

From the perspective of integrated utilization of all water resources, including surface water, groundwater, remote water diversion, desalination and wastewater reuse, the management sectors should make integrated prices for different water sources. Desalinated water, as a kind of water resource, should be a part of the whole system, not be considered separately.

For the regulation of balance between supply and demand for different water sources, the price gradient should be formed with the comprehensive consideration of the scarcity of different types of water source, cost, demand, quality, acceptance by users, policy guidance and supports. At the premise of safe supply and water quality, the principle can be the higher consumption, the higher prices for different types of water sources. Scarce water resources, such as groundwater, could be priced higher.

Deepen the reform of tap water price and gradually improve the present situation when the water price is much lower than the supply cost, to make the price more close to value. The increase in tap water price is an inevitable trend. Since water is a necessity of life, the adjustment of water price will influence on the daily life. For municipal water supply, the government should increase the investment to pay for price difference between desalinated water and tap water and guarantee the residents' life quality not to be decreased due to use of desalinated water at higher price. For industries and special high water consumption industry, an increase in tap water price to allow for investments in desalination should have the priority. The profit from water source with higher price but lower cost, such as tap water for industry and special high water consumption industry and from industry with special requirements for water quality, can be subsidies to desalination. Here, pilot areas to test whether the water price system can be accepted by both users and supplier could be established.

Encourage the development of by-products' industries of desalination, such as salt production, or the direct use of seawater and use the profit to subsidize desalination.

Make overall planning for all types of water supply in individual regions to see whether desalination can replace some higher cost water supply ways, such as remote water diversion in some areas. And use the saving money to subsidize desalination.

Since the water resource situations in different regions are quite different, the price systems should also be diversification according to actual water, social and economic situation.

3.4. Management systems and policy

The management system includes soft parts, such as laws, guidelines, planning, regulation and management sectors, which execute the related provision. At present, except planning, there is almost blank in the other aspects of government management for desalination. In the “Special planning for seawater desalination” jointly issued by National Development and Reform Commission, the State Oceanic Administration and the Ministry of Finance in 2005, the programmatic objective during “11th Five-year” (2006–2010) was that the overall capacity should reach 800,000–1,000,000 m³/day to 2010, which however was not reached. This is
unusual, since normally, and the objectives are always reached on schedule or even in advance in China [26]. The reason is mainly that there is no enough supporting policy and detailed implementing measures to achieve goals. The bottlenecks in the development, such as technology, device, investment and price, have not been fundamentally solved due to lack of supporting policy. Most desalination projects are individual schemes and the desalination industry has not formed the properly functioning system, since there are no laws or detailed executable guidelines to follow. And there are no clear provisions for which sectors should be responsible for desalination, which means that the projects invested by enterprise cannot get enough support from government, if any.

The lack of effective management system and policy fundamentally hinders the desalination development. For avoiding the “11th Five-year plan for desalination” same unsuccessful road, the development of relevant policy and forming management system are the most imperative. The proposals are as following:

One of the reasons for lack of management and policy is the lack of sufficient attention to the importance of desalination. The legal protection is the first and most important way to increase the attention in China. Desalination should be acknowledged as a safe water supply method in the national “Water Law”, and further on laws to provide legal basis for management and policy should be developed.

Guidelines for safe water quality and supply must be established, since the qualified and safe water is the basis for social and economic growth. The water quality of desalinated water is rather good, but it does not mean there is no any problem for safe use. Especially for municipal water supply, although desalinated water is purer compared with tap water, it is not better for health due to lack of some substance necessary for human. And when the desalinated water is mixed into tap water and distributed in municipal mains, it may cause some problems, such as rust formation and bacteria growth if not the total water quality is taken care of properly. This may in worst-case lead to unsafe water quality and health risk of users. Thus, the guidelines not only include the requirements for water quality, but also for the pipelines and indicate the precautions on how to guarantee the safe supply and use of water. The guidelines should have details and executable, not only on the principal level.

Establish special management sectors for desalination in all levels of water management institution. This would address the responsibilities of various departments for safe implementation of desalination in the water supply sector. It is very important to pick out special departments that are responsible for co-operation and coordination between internal sectors as well as other departments related to desalination. And it is better to have a competent department to integrate the management of all the aspects related to desalination to avoid the contradictions and conflicts or blank and overlapping management in parallel sectors with different or no responsibility.

Based on national laws and policy, the local governments should develop their own management guidelines and detailed policies according to local conditions, which naturally vary a lot in different areas of China. And the management of desalination should be combined with other water sources or supply methods, not be separated from the whole-water management system. That requires a strong cooperation with other departments and overall coordination and optimized planning for different water sources to get the optimal programme for utilization and to avoid wasting of resources and funds.

Develop and improve the supporting policy as indicated above, such as investment institution, price system, subsidy and preferential policy and so on. The policy should take all stakeholders, such as investor, supplier, users and manager, into account. At the same time of enabling investors the right to get some profit from the work, it is also central to allow the users obtain to get benefits from desalination. This will be accomplished if there is a gradual change of the view on desalination from political will or government imperative to a method among others for unified planning and management of water supply, multiple financing channels used for investment and market-oriented operation at the premise of the plants owned by government should be utilized.

Based on relevant policies, publicity and communication both to investors and users must be intensified, to attract more capital investments and increase the acceptance of the users for desalination as a water supply technology. People always do not want to use or invest something new which they do not know well. As desalinated water is regarded as an unconventional water resource, administrate departments should intensify information and education for the public. Modern media and channels, such as internet and TV, should be used fully to popularize and promote desalination knowledge. And education centres can be established for introducing the details about desalination to the public.

Develop clear incentive regulations to guarantee that the guidelines or policies can be executed strictly and effectively. At the same time, strengthen supervision and inspection efforts to make the regulation not only on the paper. And it is better to select the third
party unrelated to the interests to supervise and inspect the sensitive parts, such as water quality and the use of the funds to make the management more fair, open and transparent. And it is also important to establish the platforms for public supervision.

At the same time of developing desalination, the government should pay attention to the impacts of desalination on marine environment and biological life. Lots of research shows that the concentrated water discharged directly to the ocean will change some characteristic of offshore, such as temperature, pH and salinity, and adversely impact on marine life [27–29]. At present, there are not much research about this topic in China, since desalination itself has not been attached enough importance to, and the research mainly focus on how to reduce cost and develop markets. Thus, when government develops the laws and regulations, guidelines and policy, environmental impact analysis should be considered to avoid marine pollution by desalination projects. There should be clear provisions for how to treat concentrated water and clear punitive regulations. The way of ‘treatment after pollution’, like other industry development process, should not be repeated for desalination development. The principles of clear production should be implemented at the beginning of development even if it may increase the cost sometimes, since we cannot afford the cost of the ocean contaminate. Several methods, such as salt making by concentrated water and dilution by reclaimed water, can be selected or combined used by producer, according to different local conditions.

4. Compare and integrated use of desalination and wastewater reuse in China

At the situation of scarcity of conventional water source, the unconventional water use should be developed a lot. Besides desalination, reclaimed water, which is widely used in water shortage countries, is another important unconventional water source. When facing many options, the critical point is how to optimal allocate and integrated use multiwater sources to make the maximum benefit both for society and environment.

From water quality perspective, desalinated water has much higher quality than reclaimed water. For reclaimed water, since the source is wastewater, which contains much pollution, the water quality, especially indicators of microorganism and toxic and hazardous substance, must be monitored to allow for safe use. The guidelines for use of reclaimed water for different application must be followed and preferably developed further, particularly on the aspects of microbial contamination. Compared with reclaimed water, the quality of desalinated water itself is not of a high risk. The problem happens when it is mixed into municipal pipelines as mentioned earlier above. Thus, for developing the guidelines for desalinated water, the focus should be on how to maintain the high safety and quality during distribution in the mains.

Different water quality can be used for different applications. In China, reclaimed water are mostly applied in fields with requirements for water qualities lower than tap water, such as agriculture, landscape water, industry and urban non-potable miscellaneous water. The indirect application, such as groundwater recharge, is very limited, since it requires higher water quality which means advanced technology and more cost. Desalinated water is mostly used for fresh water supply to islands or industry that needs water purer than tap water for special process requirements. If in an area, it is possible to use both desalination and wastewater reuse, stakeholders and the government should not only consider the cost but also efficient water supply by different water quality requirements and avoid waste caused by high-quality water used in low-requirement fields or unsafe due to use water unqualified.

Mainly because of different technologies, the cost and price of desalinated water is higher than for reclaimed water, which is one of the main reasons for why wastewater reuse is more widely applied in China. Even if using membrane technology, reclaimed water which has less salinity than seawater and lower requirement for water quality, have lower cost and price than seawater desalinated water. Thus, as mentioned previously, the profit from reclaimed water could be used to subsidised desalination projects. At the same time, reclaimed water can be used for dilution of retentate (brine) from desalination plants. For example, in Tianjin, the seawater of Bohai Bay has poor mobility, which means that the discharge of retentate directly into the sea will have a negative impact on sea ecology. Desalination is generally used in regions with freshwater shortage, where there is not enough freshwater for dilution. Using reclaimed water for dilution not only can solve the problem of brine discharge but may also save tap water and lower the cost. The only problem to be observed is the safe water quality of reclaimed water, to avoid bringing more chemical or microbial pollution to the sea. Thus, the requirements for dilution water should be set up.

From management and policy perspective, wastewater reuse has developed ahead of desalination in China. There have been management sectors, laws,
regulations, guidelines and policy on both national and local level for wastewater reuse, although they are far from complete have various flaws. The development for management system and policy of desalination can learn the experience from wastewater reuse, such as investment institution and water quality guidelines. At the same time, it should be possible to learn the lesson to avoid the same mistake. Furthermore, to develop the policy and detailed incentive regulations to encourage integrated use of desalination and reclaimed water to avoid fragmented work should be possible. And to establish unified management systems for better overall planning, such as quantity, quality and pipe network contribution.

From the public acceptance perspective, desalination is easier accepted for its higher quality, while reclaimed water is accepted by its lower cost. But the benefits of them need to be communicated clearly and pedagogically, since they are both unconventional water resources. The information can be done together and form fixed publicity system in multifaceted and long-term campaigns.

5. Summary

In China, there is feasibility and necessity to develop desalination, especially in the eastern coastal regions. Whether from water shortage status or the situation of different types of water sources perspective, desalination should be an important water supply method and have broader market and potential for development. At present, from the perspective of market demands and desalination capacity, China is still at the primary stage. Multifactors lead to the slower development of desalination market than it expected is. For long-term development, proposals are summarized as following:

- Take effective methods to reduce the cost, especially accelerate the development of key technology and equipment with independent intellectual property rights.
- Government should increase the attention and investment.
- Develop rational investment institution and price system to promote market-oriented operations. Broaden the investment channels and comprehensively consider the pricing of different water sources.
- Management systems such as laws and regulations, guidelines, regulations and management sectors should be established or improved, not only programmatic objectives without any detailed procedure and action.
- Relevant supporting policy should be developed, which can learn from the policy for wastewater reuse, and there should be regulations to guarantee the enforcement.
- According to local conditions, optimal allocation and rational overall planning of different water sources, both quantity and quality, to make benefit for both society and environment.
- Intensify the integrated use of desalinated water with other water sources, especially reclaimed water.
- Pay more attention to the impact of desalination projects on ecological environment and make clear regulations for minimize the impact.
- Use of various means of media to increase the publicity of unconventional water sources. Make the public know more about the knowledge, such as pros and cons, why and how to use it, which can make unconventional water sources more accepted by public.

From '12th Five-year plan for desalination', we can see the government attitude and opportunity for development of desalination. But if there is no actual action, the objective will miss again like the plan during 11th five-year. And the development should learn the experience and lesson from wastewater reuse to avoid detours.

References


Paper II

Situations of water reuse in China

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Situations of water reuse in China

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Abstract

Water reuse is a cost-effective solution that is carried out in many water-shortage countries on different levels. China, which is the most populous country in the world, is facing a serious water crisis, with great demand and feasibility to use reclaimed water to deal with freshwater shortage and pollution. Although much progress has been made, challenges and problems still exist, which hinder the development of the water reuse market. Accordingly, a strategy should be made from a sustainable use perspective. In this paper, the driving forces, the situations of applications, the social institutions and cultural backgrounds related to water reuse in China are reviewed and presented by a literature review and survey. The obstacles and challenges are discussed from management system, safety of reclaimed water quality, economy and policy perspectives. Beijing and Tianjin are selected for case studies in some aspects. Through review and analysis, it can be concluded that the management system, price system, safe supply of reclaimed water and supported policy are the main factors affecting the development of water reuse in China. The paper also identifies strategies for further sustainable and safe water reuse.

Keywords: Guidelines; Management; Policy; Price; Reclaimed water quality; Water reuse

Introduction

Water is not only an irreplaceable matter by which all life lives, but also an important and indispensable resource for social development. The available freshwater, which is closely related to human society and ecological environment protection, only accounts for 0.34% of the total water on the globe (The Earth Sciences, 2006). Water scarcity along with water pollution and an uneven distribution on the Earth has caused a global water crisis.

Much effort has been made to deal with the water crisis, and water reuse, which has been carried out in many countries, is considered to be the most cost-effective solution. Generally, water reuse can be divided into two types: direct and indirect reuse, both of which include potable and non-potable applications. According to Asano et al. (2007), the applications of water reuse include: agriculture irrigation; industrial uses, such as manufacturing (both process water and cooling water) and construction.
industries; landscape irrigation, such as irrigation for gardens, golf courses, sport and recreational lands; urban non-irrigation uses, such as toilet flushing, car washing, fire-fighting, street washing, dust suppression and snowmaking; environmental and recreational uses, such as water for the restoration and re-creation of existing or creating new aquatic ecosystems, recreational water bodies and fish ponds; groundwater recharge, such as aquifer recharge through infiltration basins and injection wells for water storage and saline intrusion control; and potable reuse (both direct and indirect), which is not discussed in the paper because there is no practice of potable reuse in China.

Water reuse has many benefits from environmental, ecological and economic perspectives. For the non-potable applications, water quality does not necessarily meet the drinking water quality standards. Reclaimed water, which is ‘municipal wastewater that has gone through various treatment processes to meet specific water quality criteria’ (Asano et al., 2007), can be used in those applications to lower the demand for freshwater and control any over-abstraction. And also from energy and ecological costs aspects, the costs of water reuse are normally lower when compared to other methods such as deep groundwater extraction or pumping, importation, impoundment or desalination. In addition, intelligent water reuse can be a method to reduce the costs of nitrogen and phosphors removal in wastewater treatment plant when the effluent is applied for irrigation, since plants use nutrients from the water. Hence, if applied correctly, it is a method to reduce nutrient discharge to the environment and the loss of freshwater to the sea, which are both beneficial for water environment protection and saving freshwater. Further on, when developing brownfield sites, water reuse can increase the value of land and offer drought-proof irrigation or be used to increase local ecological benefits, flood protection and tourism. Also, reused water can be applied to create and restore wetlands or be used in urban irrigation to develop greener cities. The need for and cost of long sea outfalls can finally be minimised when water is reused instead of discharged to the sea.

With these benefits mentioned above, water reuse should be widely carried out in China, which has much demand and feasibility to use reclaimed water because of a serious freshwater crisis and severe water environment. However, the water reclamation and reuse industry has developed more slowly than expected in China. The reclaimed water was only 0.5% of the total water supply in 2011, according to the data of China’s Environment Bulletin (2011). It is important to know the obstacles and problems for further development. In this paper, the driving forces, the situations of applications, the social institutions and cultural backgrounds related to water reuse in China are reviewed and presented. The obstacles and challenges are discussed from management system, safety of water quality, economy and policy perspectives. Beijing and Tianjin are selected for case studies in some aspects. The paper also identifies the impact factors and strategies for further sustainable and safe water reuse.

Driving forces and the feasibility of water reuse in China

Listed on the most water-poor thirteen countries in the world, China needs to implement water reuse to ease the water crisis and protect the water environment. The shortage of freshwater and serious pollution are well documented in the literature and bulletins (Hong, 2003; Yan, 2004; Yang, 2004; Yu, 2004; Ministry of Environmental Protection of China, 2011). It is predicted by experts that by 2050, the shortage of water would increase to $3.71 \times 10^{11}$ m$^3$/a, and the output value impacted by urban water shortage would be up to more than $2.0 \times 10^{11}$ Yuan RMB/a, with about 40 million of the population affected (Wan, 1999). Due to water scarcity, uneven distribution and severe pollution, there are becoming more and more obstacles and problems for the water supply in China. Moreover, from
we can see that both water consumption per capita and total water consumption per year are increasing. This means that the imbalance between supply and demand is expanding.

To deal with the water crisis, the Chinese government has established related policies and made important decisions taking both supply and demand parties into account for saving and better using water. These include policies concerning emission reduction; the development of water-saving agriculture, e.g. avoiding flooding irrigation and reducing channel seepage; strengthening the research and promotion of water conservation technologies (such as sprinkler irrigation, drip irrigation and subsurface irrigation); for agricultural and industrial purposes, the policy of fixed amount and paid supply, and stopping supply or double charge for over-use; the development of the low-water consumption industry and promoting water recycle systems, and technological innovation regarding old enterprises with a large water consumption; use of economic means to prevent the waste of domestic water; promotion of the appropriate use of sea water resources, waterways technology and the use of treated wastewater; carrying out the South-to-North Water Diversion Project to distribute the imbalance in the area of water resources. Compared with other water sources in water supply measures, water reuse has advantages as already described in the Introduction, such as both saving freshwater and reducing pollution discharge, as well as being cost effective. Whereas long-distance water transfer and desalination measures, not only cost much but also may cause adverse impacts on the environment and ecology. There are some policies, such as the emission reduction policy, water price reform, the development of recycling economy and so on, that provide a good opportunity for the development of water reuse.

Applications of water reuse in China

The background and history of development of water reuse

In China, the use of reclaimed water can be traced back to the 1950s when China adopted the method of sewage irrigation to reuse treated wastewater. In the late 1980s, thanks to the fruitful reform and
opening policies and consequent economic development and improvement of the living standard, water demand increased sharply. At the same time, water pollution was increasing seriously because many enterprises illegally discharged untreated wastewater into natural water for the blind pursuit of economic interests. In addition, the waste of water resources was widespread, mainly due to the inaccurate low pricing of the water resource. The growth of mega-cities also started during this period. The research and practice of water reuse developed rapidly in this period, and aimed to address the increasing water shortage and pollution (Li et al., 2007). In 1989, China’s first water reuse demonstration project was designed and constructed in the Dalian Chunliu wastewater treatment plant, and was officially put into operation in 1992 (Yao, 2006). Reclamation of sewage was included in succession in the key science and technology research of ‘the seventh, eighth and ninth five-year plans’. Up to the period of ‘the tenth five-year plan’ (2001–2005), reclaimed water for the security of water resources was officially written into this planning framework and the scientific and technological research was subsequently carried out. (Wei et al., 2006). To make reclaimed water the second water source for urban areas, China began to initiate water reuse on a nationwide scale. By 2009, in total, 243 reclaimed water plants had been built, with a total production capacity of 18.54 million m³/d. Reclaimed water pipelines were built to a length of 4,344 km (Zhong et al., 2012).

However, for several reasons wastewater treatment and water reuse are still developing slowly although some progress has been made. By 2011, China had built and put into operation 3,974 sewage treatment plants, with a total amount of treated wastewater of $4.03 \times 10^{10}$ m³ in 2011 (Ministry of Environmental Protection of China, 2011). Compared with the total sewage and wastewater discharge, which was $8.07 \times 10^{10}$ m³ in 2011 (Ministry of Water Resources of China, 2011), the treatment rate is about 49.9%. Wastewater treatment development is uneven. The rates of some cities are 70–90%, even up to 100%, while many places have no wastewater treatment at all. In 2011, the amount of reclaimed water produced was only $1.29 \times 10^9$ m³, $9.6 \times 10^8$ m³ of which is actually used (Ministry of Environmental Protection of China, 2013). The rate of water reuse (the amount of water reused/the amount of wastewater treatment) is rather low and varies a lot for different cities from zero to 60%. Accordingly, whether from the water demand or the amount of treated wastewater, water reuse still has great potential for development and needs to be improved.

**Application status of reclaimed water**

As mentioned in the Introduction, non-potable application is the main mode of water reuse in China. Figure 2 shows the proportion of reclaimed water used for different applications in 2009. The applications are named by the regulation of the national standard of *The Reuse of Urban Recycling Water – classified standard* (GB/T 18919-2002). Some water reuse projects and their main applications are shown in Table 1.

As the primary industry in China, agriculture occupies the most important position of society and economy and takes up the largest proportion of water consumption (Figure 3). Since it has been studied that irrigation water generally does not need to meet the standards for drinking water, and great benefits are provided by using reclaimed water for irrigation, agriculture irrigation is a very important application of water reuse. The development of sewage irrigation in China can be roughly divided into three stages (Liu & Xu, 2002; Wei et al., 2006; Wang et al., 2010) (Figure 4). Before 1957, the sewage irrigation was self-organised by farmers. Sewage irrigation was listed in national research programmes in 1957 and increased fastest from the end of the 1970s until the middle of the 1990s. After the Cultural
Revolution at the end of the 1970s, a reform of agricultural institutions was carried out. Since then, the right to work the land has belonged to individual families instead of people’s communes. Due to the reform and the ensuing changes in the allocation of interest greatly stimulating farmers’ enthusiasm for production, agriculture developed rapidly at that time. At the same time, the rapid development of industry, especially township enterprises in South China, caused large amounts of sewage discharges. Nitrogen and phosphorus in the waters are suitable for irrigation, along with the rapid development of agriculture, the situation of water shortage and the amount of discharge of wastewater made sewage irrigation increase sharply from the end of the 1970s. By 2010, the total sewage irrigation area was more than about $3.62 \times 10^{10}$ m$^2$ (Wang et al., 2010). In 2012, the area irrigated by reclaimed water in Beijing reached $3.87 \times 10^8$ m$^2$ (Yang, 2012). In terms of geographical distribution, the sewage irrigation of farmlands is concentrated in the northeast of China, where there is a serious water shortage. The basins of the Haihe River, Liaohe River, Yellow River and Huaihe River account for about 85% of the total sewage irrigation area in China (Liu & Xu, 2002) (Figure 5).

Although sewage irrigation has developed rapidly in recent years, the proportion of water reuse for irrigation in Figure 2 was only 23.4% in 2011, which is a wide gap when compared with that of the USA (62%) and Israel (42%) (Zhou et al. 2004). Many problems hinder the development of sewage irrigation, with the most serious issue of substandard water quality leading to severe pollution of farmland and food insecurity. That is mainly because there is no effective institution of management and supervision. In China, generally the education level of farmers is low. Most farmers cannot identify the hazard of applying sewage without any treatment. In addition, theories, techniques, monitoring and management systems have seriously lagged behind, which also hinder the development of irrigation using reclaimed water. Therefore, effective guidance and supervision, such as how to improve efficiency, how to use reclaimed water for irrigation in an intelligent way and how to avoid the health risks, are especially important for sewage irrigation.

Industry is the second major water consumer in China, and industrial wastewater discharge without treatment is one of the main reasons for the deterioration of water quality. Water reuse is recommended...
<table>
<thead>
<tr>
<th>Project</th>
<th>Scale (m$^3$/d)</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beijing Gaobeidian Reclaimed</td>
<td>1,000,000 (Expansion in progress)</td>
<td>Agriculture irrigation, scenic environment use (river course replenishment), industrial use and urban miscellaneous water</td>
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<tr>
<td>Water Plant</td>
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<tr>
<td>Beijing Beixiaohe Reclaimed</td>
<td>60,000</td>
<td>Scenic environment use and urban miscellaneous water</td>
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<tr>
<td>Water Plant</td>
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<tr>
<td>Beijing Qinghe Reclaimed</td>
<td>150,000 320,000 (construction of</td>
<td>Scenic environment use (river course replenishment)</td>
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<td>Water Plant</td>
<td>Second Phase in progress)</td>
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<tr>
<td>Beijing Xiaohongmen Reclaimed</td>
<td>600,000</td>
<td>Agriculture irrigation, scenic environment use, and urban miscellaneous</td>
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<tr>
<td>Water Plant</td>
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<td>water</td>
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<tr>
<td>Beijing Daxing Distrcit Huangcun</td>
<td>120,000</td>
<td>Scenic environment use (landscape river replenishment)</td>
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<tr>
<td>Reclaimed Water Plant</td>
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<tr>
<td>Tianjin Jizhuangzi Reclaimed</td>
<td>70,000</td>
<td>Industrial use, urban miscellaneous water and scenic environment use</td>
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<td>Water Plant</td>
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<tr>
<td>Tianjin Dongjiao Reclaimed</td>
<td>60,000</td>
<td>Industrial use, urban miscellaneous water and scenic environment use</td>
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<tr>
<td>Water Plant</td>
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<tr>
<td>Tianjin Xianyanglu Reclaimed</td>
<td>50,000</td>
<td>Industrial use (cooling water), urban miscellaneous water</td>
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<td>Water Plant</td>
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<tr>
<td>Tianjing Zhangguizhuang Reclaimed</td>
<td>50,000</td>
<td>Industrial use and urban miscellaneous water</td>
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<td>Water Plant</td>
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<tr>
<td>Shijiazhuang Qiaoxi Reclaimed</td>
<td>100,000</td>
<td>Scenic environment use (river course replenishment)</td>
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<td>Water Plant</td>
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<tr>
<td>Qinhuangdao Haigang Reclaimed</td>
<td>20,000</td>
<td>Industrial use (coal terminal industry)</td>
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<td>Water Plant</td>
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<tr>
<td>Handan North Reclaimed Water</td>
<td>40,000</td>
<td>Industrial use (power plant cooling water)</td>
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<tr>
<td>Plant</td>
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<tr>
<td>Qingdao Haibohe Reclaimed</td>
<td>10,000</td>
<td>Urban miscellaneous water (flushing, pouring), industrial use (cooling water)</td>
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<td>Water Plant</td>
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<tr>
<td>Weihai Reclaimed Water Plant</td>
<td>5,000</td>
<td>Industrial use (cooling water for power plant)</td>
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<tr>
<td>Anshan</td>
<td>200,000</td>
<td>Industrial uses</td>
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<tr>
<td>Dalian Chunliuhe Reclaimed</td>
<td>80,000</td>
<td>Industrial uses (cooling water and process water)</td>
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<td>Water Plant</td>
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<tr>
<td>Dalian Malanhe Reclaimed</td>
<td>120,000</td>
<td>Industrial use (cooling water), urban miscellaneous water</td>
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<td>Water Plant</td>
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<tr>
<td>Dalian Fujiazhuang Reclaimed</td>
<td>10,000</td>
<td>Scenic environment use</td>
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<td>Water Plant</td>
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<tr>
<td>Taiyuan Beijiao Reclaimed</td>
<td>10,000</td>
<td>Industrial use (blast furnace cooling water)</td>
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<td>Water Plant</td>
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<tr>
<td>Taiyuan Nanyan Reclaimed</td>
<td>50,000</td>
<td>Industrial use (chemical industry region)</td>
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<td>Water Plant</td>
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<tr>
<td>Taiyuan Yangjiabao Reclaimed</td>
<td>50,000</td>
<td>Industrial use</td>
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<td>Water Plant</td>
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<tr>
<td>Datong Dongjiao Reclaimed</td>
<td>10,000</td>
<td>Industrial use (power plant cooling water)</td>
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<td>Water Plant</td>
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<tr>
<td>Xian Dengjiacun Reclaimed</td>
<td>60,000</td>
<td>Scenic environment use, urban miscellaneous water and industrial water</td>
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<tr>
<td>Water Plant</td>
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<tr>
<td>Tongchuan</td>
<td>7,000</td>
<td>Industrial use (power plant cooling water)</td>
</tr>
<tr>
<td>Tai’an Water Reuse Project</td>
<td>20,000</td>
<td>Scenic environment use (river course replenishment) and industrial use</td>
</tr>
</tbody>
</table>
for saving water and reducing pollution; however, the efficiency of water use is still rather low. In 2011, China’s water consumption amount per unit output value of ten thousand Yuan is 78 m$^3$ (Ministry of Water Resources of China, 2011), while it is only 10 m$^3$ in developed countries (Li et al., 2009). On average, China’s industrial water recycling rate is about 60%, much lower than the 80% in developed countries. The main factors for industrial water reuse are water quality, quantity and cost (Wei et al.,...
In a market economy system, which the management of the industry of China presently embraces, the primary goal for most enterprises is to maximise the short-term profit. Thus, for promoting water reuse in industry, the key way is to develop an intelligent pricing system for different water supplies and the charge for sewage discharge to allow enterprises to get economic stimulus and benefits from using reclaimed water. The benefits should be superior to using tap water and compensate the cost for the treatment process for reclaimed water and the operation fee of reuse system for internal use or the price for buying reclaimed water from municipal reclaimed water treatment plants. Additionally, water reuse should benefit more than the saving from illegally discharging the wastewater to receiving water without any treatment. Thus, the inspections and penalties for illegal discharges of sewage are very significant to the use of reclaimed water. Incentives, regulations and fines are necessary tools to be used here.

While the situation of water shortage and water pollution is getting worse, more and more cities use reclaimed water for scenic environment (landscape) and urban miscellaneous water. Figure 2 illustrates that scenic environment purposes take up the highest proportion of all applications. It is recommended by the related policy to be the preferential use, since it requires large amounts of lower quality water and offers more social benefits for the city (Urban Water Reuse Technological Policy, Ministry of Construction and Ministry of Science and Technology [2006] No.100). The scenic environment has become the major use of reclaimed water. At present, there is also much research being conducted on the reclaimed water quality standard and the impact of water reuse on the landscape. For example, Wang et al. (2002) performed a study on the quality standard for the reuse of reclaimed water in scenic waters; Fan & Lv (2005) discussed the feasibility of using reclaimed water for the landscape and analysed the
environmental and economic benefit; 

Wu et al. (2007) performed a study on the dominant algae of landscape ponds supplied by reclaimed water and the indicated index of algae bloom; Meng et al. (2011) performed a study on water quality variations and improvement measures of reclaimed water reuse in scenic water in Beijing.

For reclaimed water as urban miscellaneous water use, Beijing may be the best representative city. By 2007, a year before the Olympic Games, the city of Beijing had completed and put into use more than 160 water reuse facilities in the city. The total amount of reused water was $2.4 \times 10^4$ m$^3$/d mostly concentrated in the hotels, restaurants and universities (Qian, 2007). In some large water-shortage cities, such as Beijing and Tianjin, there are related local policies that urge new buildings or residential areas over a certain size to have a water reuse system. Nevertheless, water reuse for urban non-potable water has not been applied as much as it should be. For example, in Beijing, the amount of reclaimed water used for urban non-potable water (including toilet flushing, green space irrigation, vehicle washing and road sweeping) was about 30 million m$^3$ in 2010, which is only 4% of total production of reclaimed water (Anonymous, 2011). As the total domestic water consumption is 1.47 billion m$^3$ (Beijing Water Authority, 2010), there is a huge potential for the development of reclaimed water to apply to urban miscellaneous water use. The problems causing the big difference between supply and demand concentrate in the construction of transmission and distribution network, reclaimed water quality and the public’s psychological acceptance. The planning and construction of a pipe network is increasingly difficult, especially in the old town. To deliver reclaimed water, the Reclaimed Water Company in Beijing has to provide a vehicle for water supply to meet the needs of users who are not covered by the pipe network. But this service increases the price which sometimes exceeds the tap water price and reduces the users’ interest in using reclaimed water. In addition, an unskilled reuse of water may affect the users’ trust regarding reuse even if it only happens occasionally. Further on, the public’s ‘prejudice’ against reclaimed water and their experience of (subsidised) low tap water price are also barriers to urban miscellaneous applications.

On the worldwide level, reclaimed water for groundwater recharge is also an important application, especially in areas where the groundwater is seriously exploited, such as the USA and Germany. Different from the application above, this is an indirect application, and an important tool for long-term water environment protection. However, researches on reclaimed water for groundwater recharge started late in China, with less-experienced practice than other applications. The constraints have so far been technology and cost. The slow development is also affected by policy, which depends on economic conditions for developing countries. The Urban Water Reuse Technological Policy mentions that ‘when determining the application of reclaimed water, it is better to choose the uses which require a large amount, need low water quality, can utilize available technologies, have low costs and can produce significant economic and social benefit’ (Ministry of Construction and Ministry of Science and Technology [2006] No.100). Groundwater recharge needs high-quality reclaimed water, which leads to the requirement of advanced treatment technology and a higher cost. The national economic situation cannot afford the wide application of reclaimed water for groundwater recharge. Blind application without considering actual conditions may cause groundwater pollution due to the insufficiently treated reclaimed water. Nevertheless, groundwater recharge is an important application for the sustainable development of water use, which can bring more long-term ecological benefit, especially where there has been a serious, illegal exploitation of groundwater. While the constraints for the application are technology and cost, the development and gradually decreasing cost of membrane technology will provide water quality and economic security for groundwater recharge.
using reclaimed water. Thus, water reuse for groundwater has a potential market in China, if it can get more policy support.

Management system of water reuse

A sound management institution is one of the most important guarantees for healthy development. For the safe use of reclaimed water, the Chinese government has established a security management mechanism for water reuse, including a security system of policies and regulations, a standards system, technical support and security management methods (Wu & Zhu, 2004). Nevertheless, there are many defects and problems in the implementation process. Since water reuse is still something of a new concept compared to the conventional water supply and wastewater discharge and treatment, the management institution is still being investigated and improved.

Laws and regulations

China has implemented a Water Law (Presidential Decree No. 74 of the People’s Republic of China, 2002, 29th August) and a Water Pollution Control Act (Presidential Decree No. 87 of the People’s Republic of China, 2008, 28th February) for water resources management and pollution control. To encourage water reuse, the improvement of reclamation and use of treated wastewater have been written in the Water Law, but so far, there has not been any national comprehensive law for water reuse. The management is mainly based on rules and regulations enacted by water sectors and local government (city or province level). In China, the force of the law is a multi-level structure, in which local law is on the lowest force level. Even so, with a few cities as exceptions, such as Tianjin, Beijing and Qingdao, which have enacted clear local laws, other areas’ regulations for reclaimed water use are often ambiguous. In some national laws, such as the Cleaner Production Promotion Law (Presidential Decree No. 54 of the People’s Republic of China, 2012, 29th February) and the Circular Economy Promotion Law (Presidential Decree No. 4 of the People’s Republic of China, 2008, 29th August), although there are some provisions involving water reuse, the laws are very general and abstract without any details (Wang & Qi, 2008). Legislation can effectively promote the development of water reuse. The lack of legislation as a guarantee causes many problems in management. For example, the enforcement of rules is far from enough; there is no effective reward and punishment mechanism; responsibilities are unclear; and there is an absence of relevant legal regulations for production, operation, supervision, charge and subsidy of reclaimed water.

During the Fifth Session of the Eleventh Period of the National People’s Congress (NPC, the highest authority of state power in China) and the Political Consultative Conference (which is an important institution of multi-party co-operation and political consultation under the leadership of the Communist Party of China) some representatives suggested improving the use of reclaimed water and to make water reuse a basic national policy (Cheng, 2012; Zhu, 2012). But so far, there has not been any proposal about legislation for water reuse submitted to the NPC. The status of the legislation reflects that although water reuse has been considered an important way to solve the water crisis, the degree of attention is far from enough. The attention is more focused on the control and reduction of pollution, while the awareness that treated wastewater is also a resource has not been stressed enough. Another reason is that treated wastewater is a particular resource. Although in Chinese academic circles there is some
research and appeal for legislation, it still lacks sufficient support conditions from the state legislative bodies (Wang & Qi, 2008; Li et al., 2010; Wu et al., 2010). Controversies still exist regarding whether the law should enforce the use of reclaimed water. The particularity of treated wastewater causes many problems and controversies from the perspective of technology, safety and public acceptance, making the legislators more cautious. Additionally, legislation is a complicated and long process, especially in China which is a sizable developing country with a large population and a vast territory. The situations vary in different areas. Thus, in order to enact national compensative law for water reuse, more investigation and research work, which demands great amounts of funds and manpower, should be done.

The governing bodies

Despite the absence of legislation, insufficient law enforcement and unclear responsibilities of enforcement agencies are common problems in the management of reclaimed water. According to the Chinese Constitution in 1982, there are three levels for basic administrative regions: province (including autonomous regions and municipalities directly under the Central Government), county (including autonomous counties and cities) and township (including ethnic townships and towns). For reclaimed water management, vertically, there are central and local levels (mainly the province level); horizontally, the management of reclaimed water is the responsibility of the relevant government departments, such as all levels of water conservancy departments, environmental protection departments, and the construction sectors, and local reclaimed water companies. The departments have different functions and responsibilities. The water conservancy departments are responsible for guiding urban water reuse and developing other unconventional water resources; the environmental protection departments are responsible for developing relevant principles, policies, regulations and administrative rules; the construction departments are responsible for guiding the urban water supply (including reclaimed water) and water-saving municipal facilities, urban planning, putting forward reclaimed water quality standards and the approval of projects; and the reclaimed water companies are responsible for the planning for reclaimed water use, the construction of recycled water plants and water treatment facilities, the production of reclaimed water and water quality, the operation and maintenance of reclaimed water plants, pipe laying, and the sale and use of reclaimed water.

Although some local governments have established policies and laws for water reuse, in the process of implementation and enforcement, many problems still exist because of unclear responsibility and the lack of effective co-ordination and a supervision mechanism. According to management policy, reclaimed water is managed by ‘the water administration departments and operating units’. However, there is no clear definition of duties for each administration department, which leads to some confusion in the management process. In the old management system, water was managed by different sections that made decisions decentralized and only according to their own responsibility and benefit. Taking Tianjin as an example, Table 2 shows the management departments involved and their responsibilities for water management. There are overlapping management responsibilities between departments. This means that it demands good co-ordination and co-operation among all departments, which actually has not been done enough. In water affairs management, the different departments’ interest is different, and the obligation and understanding of water resources’ economic and ecological value are not uniform. These lead to differences in strategic perspective, planning, regulations, policies and measures and even to contradictions in some aspects. For example, almost all management departments’ design
plans for reclaimed water use have a different emphasis due to different obligations, which causes con-
fusion in the implementation process. The management is overlapping and concentrated where there is
interest or benefits, while there is no management where there are problems or high costs (Zhang et al.,
2007). It is suggested that integrated management of water should be an effective solution to avoid the
overlapping of management functions and the coexistence of management absence.

In recent years, with the development of the integrated management of water, cities and provinces
gradually set up Water Authorities, which are in charge of the implementation of the integrated manage-
ment of the water supply in both urban and rural areas. They are responsible for the development, use,
conservation, protection and management of water resources as well as the prevention and control of
water damage. In 2009, following the other three municipalities (Shanghai, Beijing and Chongqing),
the Tianjin Water Authority was set up. The Drainage Management Office, which is included in the
Tianjin Water Authority, is responsible for the administration of reclaimed water, while the Tianjin
Reclaimed Water Company is responsible for the production, sale, water plants operation and mainten-
ance. From the old management institution shown in Table 2 to the establishment of the Water
Authority, there has been progress to a management system with clearer responsibilities, but this
does not mean that there is not a problem. For example, in Beijing, the Development and Reform Com-
mnission is responsible for projects and approval; the Construction Committee is responsible for
implementation and construction; some departments in the Water Authority also manage some aspects
related to water reuse; the Beijing Water Group Company and the Drainage Group Company both have
separate reclaimed water companies. There are some function conflicts between different governing
bodies and confusion in management probably happens. In addition, in some cities following the old
management system, centralised reclaimed water plants are managed by municipal drainage depart-
ments, while according to the new system, the Water Authority is the administrative agency, with

<table>
<thead>
<tr>
<th>Management departments</th>
<th>Responsibility</th>
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<tbody>
<tr>
<td>Water Saving Office</td>
<td>Planning for the use of reclaimed water.</td>
</tr>
<tr>
<td>Development and Reform Commission</td>
<td>Examine and approve application for construction of reclaimed water plant and treatment facilities.</td>
</tr>
<tr>
<td>Water Conservation Bureau</td>
<td>Planning for of reclaimed water; Management of water source; Setting reclaimed water quality standards (Water Resources Ministry).</td>
</tr>
<tr>
<td>Urban Construction Bureau (Drainage Management Office)</td>
<td>Supervision of the construction, maintenance and operation of reclaimed water plant and pipe network, as well as the charge.</td>
</tr>
<tr>
<td>Price Bureau</td>
<td>Pricing for reclaimed water.</td>
</tr>
<tr>
<td>Environmental Protection Agency</td>
<td>Planning for the use of reclaimed water; Management of source of reclaimed water; Supervision of reclaimed water quality.</td>
</tr>
<tr>
<td>Reclaimed Water Company</td>
<td>Planning for the use of reclaimed water; Construction of recycled water plant and water treatment facilities; Production of reclaimed water and effluent quality; Operation and maintenance of reclaimed water plant; Pipe laying; Sale and use of reclaimed water.</td>
</tr>
</tbody>
</table>
enterprise responsible for production and plant operation. The transition from the old system to the new system has also caused some difficulties in management. Another problem is that the sectors which use reclaimed water are not responsible for any management. For example, agricultural irrigation, which is a large consumer of reclaimed water, is operated by the agricultural sectors, which do not have the rights to manage reclaimed water. Thus, sometimes the management sectors cannot take all of the practical problems into account due to the lack of co-ordination and communication between different sectors, which leads to a contradiction between the supplier and the users and reduces the users’ enthusiasm in using reclaimed water.

For dealing with multiple-management, it is better to enforce the integrated management of water and have a competent department to co-ordinate all the agencies related to reclaimed water. Having a Water Authority is progress for the integrated management of water. But due to the lag of the Administrative Organization Act, the establishment of a Water Authority has no legal basis, which has caused the function disputes between the Water Authority and other governing bodies (Chen, 2006). There should be more regulations formulated for management and more discussion seminars carried out to promote the communication between different management actors. Additionally, there should be a third party for supervision and inspection. For fair and effective supervision, the sector should not involve relevant interests. A systematic management institution, including planning, approval, investment, construction, operation, sale, charge, monitoring, feedback and co-ordination, is needed for the healthy development of the water reuse industry. The government should have clear provisions for responsibility and structure, to avoid overlapping and lack of management. Despite this, although the present management system is still in a transitional phase with many problems, it is on the way to clear responsibilities, good co-ordination and co-operation, and integrated management.

The lack of public participation and supervision is another issue regarding reclaimed water management. The process of planning of the total amount of reclaimed water, production and allocation is mainly decided by the government, without public participation and observation (Zhang et al., 2007). As reclaimed water is an unconventional water resource and administrative departments do not provide enough information and education, there is a public lack of understanding of relevant information and knowledge. In some countries and areas, such as Singapore and Arizona, USA, there are special publicity centres for water reuse. The centres, which are public-oriented, introduce detailed facts about reclaimed water, such as why use reclaimed water, what the treatment technologies are, how to use it and to what extent it is safe, to minimise the psychological barrier of the public about reclaimed water. However, similar attempts have not been seen in China. Additionally, public media such as TV and the internet, which have not been used a lot, are the most popular way to spread information and knowledge among the population. People do not always want to use something new which they do not know well. There is a lack of effective informational ads so that the public knows little about water reuse, especially the advantages and potential risks of using reclaimed water. At any rate, reclaimed water quality that cannot meet users’ requirements aggravates the situation that the public does not trust the safety of water reuse and is short of enthusiasm for using it. Excessive administration and confusion of responsibility also cause difficulty in dealing with public feedback and complaints. There are no platforms for the public to join in the management and monitoring. Additionally, when reclaimed water is applied, the users who are in contact with reclaimed water don’t know what to pay attention to protect themselves from potential health risks because they do not have enough relevant knowledge. To improve the situation, the Beijing Reclaimed Water Group recruited information communicators; however, this is still in an initial stage. Comprehensive utilisation of modern information
media and the establishment of public participation, observation and feedback platforms are necessary ways for the public to become involved in reclaimed water management. Additionally, young people can accept new things more easily, so they should be the key target audience; education and information should be started with the children.

The safety of reclaimed water quality

In 2002, authorities began to promulgate a series of water quality national standards and design specifications for urban water reuse for different application purpose. The national standards include six parts: Classification of Municipal Wastewater Reuse (GB/T 18919-2002) and water standards for five aspects (shown in Table 3). They are based on previous national and city standards for water and wastewater quality. The reclaimed water standard for fisheries has not been finished, so the previous Water Quality Standards for Fisheries (GB 11607-89) is used instead. In 2006, the state’s Ministry of Water Resources formulated and promulgated the water industry standard, the Reclaimed Water Quality Standard (SL 368-2006), which is based on national standards and includes all purposes for water reuse. In addition, there is one design standard, Code for Design of Wastewater Reclamation and Reuse (GB 50335-2002).

In general, water reuse projects provide reclaimed water products to multiple users. If the project is a dual water supply, the quality of the water supply is defined by water quality standards in accordance with the different application purposes; otherwise, the water quality is defined by the standard of the highest requirement. This is the most significant characteristic of reclaimed water projects, according

<table>
<thead>
<tr>
<th>Classification</th>
<th>Purpose</th>
<th>Reclaimed Water Quality Standards</th>
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<tbody>
<tr>
<td>Industry uses</td>
<td>Cooling water, Washing water, Boiler water, Process and Products water</td>
<td>‘The reuse of urban recycling water - Water quality standard for industrial uses’ (GB/T 19923-2005)</td>
</tr>
<tr>
<td>Scenic environment use</td>
<td>Entertainment landscape environment water Aesthetic landscape environment water Wetlands environmental water</td>
<td>‘The reuse of urban recycling water - Water quality standard for scenic environment use’ (GB/T 18921-2002)</td>
</tr>
<tr>
<td>Agriculture, forestry, husbandry and fishery</td>
<td>Agriculture irrigation, Forestation, Farm and pasture, Aquaculture</td>
<td>‘The reuse of urban recycling water - Quality of farmland irrigation water’ (GB 20922-2007) ‘Water Quality Standards for Fisheries’(GB 11607-89)</td>
</tr>
<tr>
<td>Water resources supplement</td>
<td>Groundwater recharge (surface and injection recharge)</td>
<td>‘The reuse of urban recycling water - Water quality standard for groundwater recharge’ (GB/T 19772-2005)</td>
</tr>
</tbody>
</table>

to different users, in a project evaluation conducted to determine the available renewable water quality (Wu & Zhu, 2004).

Presently, there are mainly three groups of the problems in reclaimed water quality. One issue is whether the standards are reasonable, which is under discussion and study. China has not established a risk management mechanism for water reuse. The limits in the standards are the only basis for managing water quality. However, the problem is regarding the existing standards, it is unknown whether it is really safe for users and how much risk there is when reclaimed water is used. Chinese national reclaimed water quality standards mainly focus on the limitation of physical and chemical pollutants, which are always monitored before the water leaves plants. There are no strict requirements about treatment, distribution, storage and how to safely use reclaimed water, as well as what should be considered to protect users, what perhaps causes the deterioration of water quality making it unsafe for use. For the safe use and special requirements of management, there is only some instruction on the level of policy or principle without details for implementation. Further, the formulation of Chinese national standards mainly uses former relevant standards and foreign guidelines for reference, combined with China’s national conditions. Chinese standards do not provide a detailed scientific basis and explanation for the formulation or values, especially for microbial indicators, which are less strict than guidelines in some other countries. Although there are quite a lot of physical and chemical indicators required to be monitored, some of the indicators are not strict enough, such as nitrogen and phosphorus, which perhaps cause eutrophication if reclaimed water is stored for a long time. Some researchers point out that the risk to humans of using reclaimed water mainly comes from pathogenic microorganisms (Toze, 2006), such as enteric viruses, the rotavirus, Escherichia coli, Giardia lamblia, Cryptosporidium parvum and helminth. Regarding Chinese standards, the requirements for microorganisms, mainly the faecal coliform, are less strict than some other countries and even less strict than World Health Organization (WHO) guidelines in irrigation applications. According to the social and economic situation, China could not achieve such a strict level as the US Environmental Protection Agency at present, since water reuse has not been implemented as widely and in such a sophisticated way as in the USA. A health risk assessment method, such as the Quantitative Microbial Risk Assessment model, should be used for checking and improving the standards, since it is a cost-effective method and very powerful. It has been widely studied and applied in many guidelines, including WHO. Additionally, some microbial indicators, which have strong infectiousness and pathogenicity, should be added for different applications according to different ways of exposure. As the situations vary greatly in different areas, local guidelines are needed. The local guidelines can provide more details for implementation and thus be more operable. The reclaimed water quality standards should be improved to make the water reuse safe for all people who can directly or indirectly contact reclaimed water. Another issue is that the standards cannot be strictly enforced due to technology and cost, especially in irrigation because farmers’ awareness and knowledge of food security is not strong enough, combined with ineffective management and supervision; this leads to insecurity in the use of recycled water. In addition, as mentioned above, most of the public and users do not have the knowledge of how to reduce the risk and protect themselves when using reclaimed water. More steps should be taken towards the safe use of reclaimed water, since the safety is closely related to users and is the basis of the market.

**Investment and price system**

In the initial stage of reclaimed water development, the investments are mainly derived from central and local government since it belongs to the construction of the infrastructure. With the market-oriented
reform of the municipal sectors, the construction of the infrastructure is gradually becoming more market-oriented. New ways of financing, such as BOO (Build–Own–Operate), BOT (Build–Operate–Transfer) and TOT (Transfer–Operate–Transfer), for reclaimed water projects are opening up in some cities, which alleviates the problem of a shortage of municipal funds for construction. For these cities the investment bodies are the government and listed companies. The financial sources are central budget, local budget and others which include loans, corporate self-financing, use of foreign investment, and direct financing (including the issuance of stocks, bonds, etc.). By 2009, the total investment for reclaimed water plants and pipe network was $1.15 \times 10^{10}$ Yuan RMB and the share of different financial sources was 13.6, 29.6 and 56.8% for central budget, local budget and others, respectively (Zhong et al., 2012).

This paper takes Tianjin for example. The Tianjin local government encourages and attracts social capital and foreign funds to participate in the construction, management and operation of reclaimed water. In 2005, the promulgation of the ‘Tianjin management approach for municipal public utilities franchises’ by the Tianjin local government (Tianjin Municipal People’s Government Decree No. 91, 2005), which incorporated reclaimed water into the franchise, established the investment and financing system, that government is responsible for pipelines and enterprise is responsible for plants. The enterprises, which have the franchise authorised by the government, raise funds for the investment in plant construction and collect charges as a return on their investment in order to realise the rolling investment. The government is responsible for the investment in a public trunk pipeline network by charging a ‘large ancillary’ fee. The dedicated pipelines for reclaimed water, which are not included in the ‘large ancillary’, such as for some industries, receive investment from users. The pipelines in residential areas receive investment from developers. Furthermore, the investment for reclaimed water projects enjoys some preferential policies, such as discounted interest or interest-free for construction loans and the relevant policies of land for urban infrastructure. The principle of ‘policy conduct and market-oriented operation’ followed by the formation of financing mechanisms effectively solves the problem of the shortage of funding for infrastructure construction and encourages the enterprises to better manage the operation of reclaimed water. Tianjin is a successful example for places which have not established market-oriented operation mechanisms for water reuse. Diversification of the sources of funding provides the economic foundation for the development of water reuse.

The cost is related to multiple factors, such as scale, water source, technology, reclaimed water quality, energy and distribution. Table 4 (Yang et al., 2011) presents the production cost of reclaimed water in some reclaimed water plants (not including the cost of pipeline construction and the distribution fee). At the present stage, the cost of reclaimed water is about 0.5–3 Yuan/m$^3$, while the desalination cost is 4–7 Yuan/m$^3$ and the cost of long-distance water transfer (such as the South-to-North Water Transfer Project) is about 2–20 Yuan/m$^3$ (Baidu Encyclopedia, 2013). Compared to desalination and long-distance water transfer, reclaimed water has obvious cost benefits. Zhang et al. (2004) used cost-effectiveness analysis under static and dynamic conditions to compare water reuse and long-distance water transfer. It was found that if the same water supply requirement is satisfied, the water reuse project is more cost effective.

Currently, the country’s price policies for reclaimed water are not uniform. Some cities, such as Beijing and Tianjin, Qingdao and Shenzhen, implement a classified pricing policy for different applications of reclaimed water. Beijing provides prices for industrial users as 1.00–1.79 Yuan RMB/m$^3$ (Cheng, 2010) and 1 Yuan RMB/m$^3$ for other users. Up to now, the price has not been adjusted since it was regulated in 2003. The prices of reclaimed water in Tianjin is 1.5 Yuan RMB/m$^3$ for industrial use, 1.1 Yuan RMB/m$^3$ for residential water, 4.0 Yuan RMB/m$^3$ for vehicle washing and 3.1 Yuan RMB/m$^3$ for...
greening and road sweeping water (Liu, 2010). Some cities, such as Tangshan (0.91 Yuan RMB/m³ (Liu et al., 2011)), Xiamen and Dalian, apply the same price for different uses, with the average price of 1 Yuan RMB/m³ (Wu et al., 2010). To encourage water reuse, some local governments formulate preferential policies for producers and users of reclaimed water. Beijing and Tianjin stipulate an exemption from water resource charges and sewage treatment charges for the use of reclaimed water. The production and operation of reclaimed water can have the concessions of the reduction of various taxes and parity electricity tariffs. Local governments also provide subsidies to make up the deficit, since the return on investment takes rather a long time in the reclaimed water industry.

From the economic perspective, the main problem is how to establish an intelligent price system for the development of water reuse. On one hand, at present, the cost recovery comes from two supplies: the sale of reclaimed water and government subsidies. For example, the operations cost of the BOT reclaimed water plants in Beijing is about 1.7 Yuan RMB/m³, in which 1.0 Yuan RMB/m³ comes from the price (from the users) and 0.7 Yuan RMB/m³ from the government; in Kunming, the government subsidises 0.7 Yuan RMB/m³. However, in the market economy, reclaimed water should be regarded as a commodity. For the healthy development of water reuse, the price of reclaimed water should be adequate to meet the cost requirements and maintain the normal operation of enterprises and reclaimed water plants. The increase of the reclaimed water price is an inevitable and necessary trend. On the other hand, price is an important factor in market demand. To encourage water reuse, reclaimed water must have price superiority to other water resources, especially to tap water.

### Table 4. Production cost of reclaimed water in some Reclaimed Water Plants (not including the cost of construction of pipe network and distribution fee) (Yang et al., 2011).

<table>
<thead>
<tr>
<th>Reclaimed Water Plant</th>
<th>Scale (10,000 m³/d)</th>
<th>Stand-by cost (Yuan RMB/m³)</th>
<th>Operating cost (Yuan RMB/m³)</th>
<th>Total cost (Yuan RMB/m³)</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beijing Shuiyuan Sixth Reclaimed Water Plant</td>
<td>17</td>
<td>285</td>
<td>0.7</td>
<td>–</td>
<td>Urban miscellaneous water</td>
</tr>
<tr>
<td>Beijing Qinghe Reclaimed Water Plant</td>
<td>8</td>
<td>1250</td>
<td>1–1.5</td>
<td>1.5–2.0</td>
<td>Waterscape of the Olympic Park and replenishment of Qinghe River</td>
</tr>
<tr>
<td>Tianjin Jizhuangzi Reclaimed Water Plant</td>
<td>3</td>
<td>1261</td>
<td>0.43</td>
<td>0.56</td>
<td>Industrial use (cooling water)</td>
</tr>
<tr>
<td>Tianjin Taida New Resource First Reclaimed Water Plant</td>
<td>3 + 1</td>
<td>1267</td>
<td>1.25–2</td>
<td>3.0</td>
<td>Industrial use and urban miscellaneous water</td>
</tr>
<tr>
<td>Tianjin Xianyanglu Reclaimed Water Plant</td>
<td>5</td>
<td>2686</td>
<td>–</td>
<td>2.49</td>
<td>Industrial use and urban miscellaneous water</td>
</tr>
<tr>
<td>Xi’an Beishiqiao Reclaimed Water Plant</td>
<td>5</td>
<td>964</td>
<td>0.60</td>
<td>0.88</td>
<td>River course replenishment and urban miscellaneous water</td>
</tr>
<tr>
<td>Qingdao Haibohe Reclaimed Water Plant</td>
<td>4</td>
<td>500</td>
<td>0.51</td>
<td>0.61</td>
<td>Industrial use (cooling water) and urban miscellaneous water</td>
</tr>
<tr>
<td>Huhehaote Jinqiao Thermal Power Plant</td>
<td>3</td>
<td>1800</td>
<td>0.7</td>
<td>1.31</td>
<td>Process water of Thermal Power Plant</td>
</tr>
</tbody>
</table>
Nevertheless, due to the implementation of the planned economy in the past, the price of tap water has long been on the low side with the average price at 1–1.5 Yuan RMB/m³, which is still applied in some regions now. The low price gives users a lack of awareness of the water resources shortage and water saving. Furthermore, it means that users who use reclaimed water cannot get more benefit, which hinders the widespread use of reclaimed water. After 2000, with the reform regarding the price of water and the rise in the water tariff, the situation has gradually been improving. In some places, such as Beijing and Tianjin, reclaimed water has shown price superiority in some applications.

Compared to the simple adjustment in price, the change in concepts is more important. From the concept that the reclaimed water should be recognised as a kind of resource in the same way as natural water, overall plans should be made for different water resources including tap water, natural water, reclaimed water, desalination and long-distance water transfer, not only for the amount and quality, but also in the pricing system. Comprehensive consideration of cost, demand, quality, acceptance for users, and policy support for different water resources is important for the establishment of the pricing system. The prices for different water qualities should have a clear gradient, and the benefit from a higher price can be as subsidies for the deficit for reclaimed water or desalination. To encourage the use of reclaimed water, the anti ladder-type price which means the more used the cheaper charged for the unit price, may be more effective. To establish the market for reclaimed water and provide guaranteed funding for the healthy operation of the water reuse industry, an intelligent charge system and pricing mechanism should be built (Zhou et al., 2004).

Policy and market

The government has formulated the plan that the reused ratio of urban treated wastewater should reach 10% in 2015, with an investment of 28 billion RMB from 2011 to 2015 (in the approval process). It means that the market for reclaimed water has huge potential and a broad space for development. To achieve the target and keep the sustainable development of the reclaimed water industry, related supporting policies have been made, which have had an important impact on the market. In 2006, the Ministry of Construction and the Ministry of Science and Technology jointly developed the Urban Water Recycling Technology Policy. Many municipalities, such as Beijing and Tianjin also have developed local policies. For example, to encourage the use and operation, the relevant incentives policies have been made at both the government and the local level. ‘The notice on the value-added tax (VAT) policy of comprehensive utilization of resources and other product’ (Finance and Taxation [2008] No.156) by the Ministry of Finance and State Administration of Taxation and ‘The identification and management methods on the comprehensive utilization of resources encouraged by the state’ (2006] No.1864) by the National Development and Reform Commission, Ministry of Finance and State Administration of Taxation, stipulate a free VAT policy on the sale of reclaimed water; the Beijing government sets the policy that the user of reclaimed water is exempt from the water resources fee and the sewage treatment fee; the Tianjin government formulates that there is a lower price and free water resources fee and city utility surcharges for reclaimed water users (Wu et al., 2010). Besides preferential policies, other policies, some of which have been analysed above including usage modes, application ways, water quality, safety guarantee, planning, facilities construction, related management and operation regulations, have been made successively under the premise of overall supported strategy by the state regarding the water reuse industry.
Certainly, the policies provide opportunities and promote the development of markets. However, that does not mean it has been done enough. In the 11th Five-Year Plan (2006–2010) on urban sewage treatment and construction of facilities for water reuse, it was said that the use of reclaimed water would be more than 20% of the treated wastewater in 2010. Obviously, the target was not reached in 2010, and the target that the water reuse ratio should be more than 15% of the treated wastewater in 2015, during 12th Five-Year Plan (2011–2015) has been made lower than target of 11th Five-Year Plan (National Development and Reform Commission, Ministry of Construction of China, Ministry of Environmental Protection of China, 2006, 2012). The development is not as fast as planned, which illustrates that there should be more management initiatives and possibly policies added to solve the problems.

Of all the policies that should be improved, the development of the intelligent pricing system discussed above and more integrated supporting financial policies to improve the operations that are market-oriented as well as the development of risk-assessment and risk-management mechanisms are most needed and should be considered. As in the former analysis, the intelligent pricing system can bring a benefit not only for the producers, but also for the users and even others in the water industry. In addition to encouraging investment and stimulating the market demand for reclaimed water, it also promotes the comprehensive and rational use of different water sources. China is in a market economy system, although still during the transition period. The regulation and control can not only depend on government-oriented initiatives, but also economic means, such as financial policies. Besides the incentives for production and use of reclaimed water, the policy of investment should also be greatly improved. Through making policies, the government should increase the investors’ confidence regarding the reclaimed water industry, to broaden the financial channels and attract more capital. Especially at the beginning of the reclaimed water industry, the making of related investment and preferential policies, such as concerning preferential loans, is an important way to increase the interest of investors. Later on, the development of a risk-assessment and risk-management system is also an important policy, since it is related to the safety of water reuse, which is the basis and guarantee of the market. Only safe water quality and safe supply can make more users become accepting, thereby making the market much broader. Besides developing the reclaimed water market, it is also important to make the policy for driving other markets of relevant subsidiary industries, such as membranes and pipes markets. Apart from direct reuse, the policy to encourage indirect reuse, such as groundwater recharge, should be developed for long-term water environment protection. For instance, an increase in government investments on research and the establishment of demonstration projects on groundwater recharge is necessary. When making and improving policies, the policy-makers should integrally consider all stakeholders, including users, investors, managers and producers, as well as maximise the overall benefits in the whole system.

**Summary**

The increasing water shortage and severe water pollution, and the advantages of reclaimed water use compared with other water sources especially for economic and ecological advantages, are the main driving forces of water reuse in China. Although much progress has been achieved, challenges and problems still exist, which hinder the development of the market in China. The use of reclaimed water has not been an enforced action with the exception of certain fields in a few places. Overall, the reclamation rate and the use of the design capacity are both rather low. The reasons for the low use rate mainly include the following: (a) substandard water quality, inadequate management system and after-sales service; (b) the
construction of the reclaimed water pipeline network cannot meet demand; (c) public awareness and psychological acceptability: water users cannot correctly view the water resource and the use of recycled water; (d) lack of an intelligent price system of various water resources; and (e) some important supported policies have not been regulated enough. Thus, through review and analysis of the situation of water reuse in China, it can be concluded that the important factors affecting the development of water reuse in China are mainly management system, safe supply of reclaimed water, investment and price system and supported policy, which are listed as followed and some strategies are given.

One of the most important factors affecting the development of water reuse is the weakness in the management system. Firstly, the vacuum in the legal system leads to an insufficient legal basis and guarantee for reclaimed water use. Secondly, enforcement is not enough for existing regulations. Thirdly, the duties of various governing bodies are not clearly regulated, which causes loopholes in management. The management from different sections has a lack of co-ordination and co-operation, so they cannot form a resultant force. The lack of an effective supervision system and inadequate participation of the public are important defects in the management system. Some steps should be taken to improve the situation, such as the improvement of laws and regulations, both on national and local levels, which should include not only general but also detailed regulations for planning, production, use, investment, charges of reclaimed water and the responsibility of governing bodies and so on; the establishment of an effective supervisory and monitoring system, for example, supervised by a third party without any interest involved; regulating clear penalty ordinance for improving the laws and supervision enforcement; the promotion and deepening of integrated management of waterworks, establishing a competent department to co-ordinate all the agencies related to reclaimed water and increasing communication and co-operation between different departments. It is foreseeable that a comprehensive integrated management system with clear responsibilities is the development trend in the future. The platform should be built for public participation and the education and propaganda should be increased for more acceptance of reclaimed water by users.

The safe supply of reclaimed water, which includes quantified water quality and accessible water supply, is of great significant for the users, and thus, is the basis for the market of water reuse. For the security of reclaimed water use, although authorities promulgate a series of water quality standards and design specifications, there are still controversies about the reasonability and effectiveness of the standards. The standards should be greatly improved in areas such as treatment, distribution and storage. Risk-assessment methods are recommended for checking and improving the reclaimed water standards and for evaluating the risk for individual cases before the water reuse projects are carried out to reduce and control the potential risk. The risk-management mechanism should be built for security enhancement. The reclaimed water should be obviously marked with, for example, ‘not for drinking’. Detailed security measures should be clearly regulated for different applications and strictly enforced, since the ways of exposure to the risk vary for the different applications and the security measures should be different accordingly. And the persons, such as farmers, workers and the public, who may be in contact with reclaimed water, should know what to pay attention to protect themselves when using reclaimed water. In addition, the construction of a supporting pipe network should be speeded up to reduce the distribution fee and give users access to reclaimed water. The relevant departments should jointly improve the planning of the pipe network for different applications to solve the difficulties for laying of the pipelines for reclaimed water.

With the background of a market economy, reclaimed water should be regarded as a commodity. Besides water quality, price is another critical factor to affect users’ behaviour and greatly influence the market. Thus, investment and the price system are critical to the development of water reuse. An
economic lever is one of the most important ways to promote the use of reclaimed water. At present, to promote the market-oriented operation of reclaimed water, government has adopted a series of preferential policies for investment, operation and use, such as preferential loans and subsidies. The investment channels are being broadened to solve the financial problems, and almost half of the cost recovery comes from government subsidies. Besides subsidy, the anti-ladder-type price can be used to encourage the use of reclaimed water. Although the preferential policies and the increase in the water tariff make the reclaimed water show economic advantages, the economic value of various water resources is still not reasonably reflected by price differences in many cities. It is essential to establish an intelligent price system for the protection and rational use of different water resources.

The development of water reuse cannot be separated from the guidance and support of policy. For the promotion of the development of water reuse, both central and local governments formulate policies on different aspects, such as planning, operation, technology, water quality, investment, subsidies and so on. However, still more good policies should be added. The policy related to intelligent investment and price system and risk management are the most important to be considered as analysed above. Later on, for long-term water resource protection, groundwater recharge, as an indirect reuse, should be greatly encouraged for both research and projects. The government should formulate relevant policy, such as increasing investment to encourage the applications of reclaimed water.

No matter what kind of impact factors are there, the improvement depends on the view of reclaimed water and the degree of attention both from government and public. Only the correct understanding that reclaimed water is an important water resource and paying enough attention to it will make the government and public make more efforts to promote the development of water reuse.

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References


Paper III

Estimating microbial risk in treated wastewater for reuse- a case study in Lund, Sweden

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Water Reuse and Desalination (submitted)
Estimating microbial risk in treated wastewater for reuse- a case study in Lund, Sweden

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Abstract

The potential microbial risk from using treated wastewater is a burning issue for being studied. In Sweden, only a small part of treated wastewater is reused directly, although water reuse could be beneficial. Disinfection is virtually never practiced and no protective guidelines for water reuse are found in Sweden.

Based on a one year monitoring programme of water quality, this paper estimates the microbial risk of *E. coli* and *rotavirus* in treated wastewater for different applications of irrigation, landscape, industry, unban non-potable water. A Quantitative Microbial Risk Assessment model is used and the samples were collected from the pond system of Källby wastewater treatment plant in Lund, Sweden. The results are used to evaluate if the treated wastewater after tertiary treatment process combined with pond system can be reused for different applications from a microbial point of view. The risk assessment results show that the studied water is only suitable for agriculture irrigation, while additional treatment or disinfection are needed for other applications since the potential risks are higher than the value can be accepted. The protective guidelines are discussed based on the process and results of risk assessment and suggestions for establishing a structure of guidelines in Sweden presented.

**Keywords:** E. coli, guidelines, Quantitative Microbial Risk Assessment, reuse, rotavirus, treated wastewater
Introduction

As the global water crisis is increasing, direct water reuse, which is recognised as a cost-effective way both for the easing of water shortage and the protection of water environment, is carried out in more and more countries at different levels. Of all challenges for further development, the safety of reuse is subjected to the most attention and studied. Although the concentration significantly lowers after treatment, many pollutants, especially the pathogenic microorganisms (e.g. bacteria, virus and parasites) pointed by some researchers that from which the risk of wastewater reuse to humans mainly comes, still can be detected in treated wastewater (Zhao et al. 2010; Toze 2006). Although much effort is put into the area, such as the regulations, guidelines and standards constantly developed and improved, the potential health risk from using treated wastewater, especially from microbial aspects, is still a burning issue to be studied and is considered seriously when treated wastewater is applied. To control the health risk and improve the safety of reuse, the microbial risk assessment work is recommended to be an additional measure to guidelines which consider general situations and use indicator parameters, for improving the safety of reuse treated wastewater for different applications.

In virtually all of Sweden, there is no incentive for directly using treated wastewater because abundant resources can meet all needs (SWWA 2000). Nevertheless, direct reuse of treated water may be needed and has been carried out in some cases for the reasons as in the following. Firstly, treated wastewater can provide a stable alternative water source and reduce the loss of harvest caused by water shortage in parts of Sweden, such as the southeastern part and Skåne County, which experienced dry and hot summers expressed as low precipitation and high evaporation sometimes in, for example, 2008, 2010 and 2013 (Stockholm News 2008; Radio Sweden 2010; The Local 2010; Johansson 2013). In addition, water reuse is an ecological solution to reduce the discharging of treated wastewater to the receiving water. From an economical perspective, the reuse of treated wastewater can minimise infrastructure costs and save the fertilizer by recycled nutrients in treated wastewater for farming, and thus be profitable both for Water Utility and users (Raso, 2013). In the rational and sustainable use of water resources points of view, the practice of reuse contributes to the prevention of the excessive diversion of water from alternative uses, such as to conserve groundwater for other uses (Vigneswaran & Sundaravadivel 2004; Raso 2013). Also, water reuse can be developed for sanitation or environmental protection purposes in response to increasingly stringent environmental regulations (Angelakis et al. 2013), such as is consistent with the EU policy of water reuse.

Nevertheless, so far only a small part of treated water has been reused directly, mostly for agricultural irrigation and industry; also, there are no relevant guidelines founded and few studies for health risks aimed at water reuse cases in Sweden. One example is Carlander et al. (2002) who investigated the hygienic risk of wastewater irrigation on short-rotation
willow coppies at three Swedish sites. The content of indicator organisms and specific pathogens (Salmonella, Campylobacter, Cryptosporidium and Giardia) were analysed and no increased risks of waterborne diseases were found at the sites studied.

In this paper E. coli and rotavirus were chosen as representatives for microbial risk assessment of direct reuse of treated wastewater for different non-potable applications, which were irrigation, landscape, industry water and urban non-potable water. The treated wastewater from Källby Wastewater Treatment Plant in Lund, Sweden, was studied and a Quantitative Microbial Risk Assessment model was applied for assessment in the work. The study is to evaluate if the treated wastewater after the tertiary conventional treatment process combined with the pond system, which is the typical wastewater treatment process in Sweden with lower energy consumption and lower cost than some advanced technologies, for example, a microfiltration- reverse osmosis system, could be safely reused for different application from a microbial point of view. The objective and scope of the study is to focus on providing a reference to water managers to formulate health-based protective guidelines and reuse policy according to the process and results of risk assessment.

**Methods**

**Water Sampling**

The samples studied in the work were collected from the Källby Wastewater Treatment Plant (WWTP) located in the south of Lund, which is a city in the province of Skåne, southern Sweden. The WWTP treats an average of about 350 L/s (28,000 m³/day) wastewater from 80,000 residents in Lund. The wastewater is treated by the tertiary treatment process, which is typical process flow in Sweden (SWWA 2000) including physical (screens, grit removal basins, primary and secondary clarifiers), biological (activated sludge in anoxic and aerobic conditions) and chemical treatment (ferric chloride is added to precipitate residual phosphorus), followed by chemical clarifiers and a sedimentation system using ponds with a total average detention time of two days for final polishing. After passing through six ponds, the effluent is discharged into the receiving water-stream Höjeå (VASYD 2010). This area is frequently used for recreation by the citizens of Lund, who enjoy walking or running on pathways along the ponds. The samples were normally collected biweekly from January to December 2012 but occasionally obstructed by the severe weather, such as snow and rain. 20 samples were collected in total for each sampling point. The grab samples were collected at around 0.5-1m depth of the outlet of ponds 1 to 6 (Point 2 to 7) and the outlet of WWTP (treated wastewater before flowing into the pond system as Point 1). The location for sampling is shown in Fig. 1.
Selection of Microorganisms

*E. coli* and *rotavirus* are selected for risk assessment in the paper. Most stains of *E. coli* cause no harm when they are in the normal intestinal flora of humans and animals. However, in other parts of the body, *E. coli* can cause serious disease, such as urinary tract infections, bacteremia and meningitis (WHO 2008). In addition, a limited number of enteropathogenic strains such as enterohaemorrhagic *E. coli* (EHEC), enterotoxigenic *E. coli* (ETEC), enteropathogenic *E. coli* (EPEC) and enteroinvasive *E. coli* (EIEC) can cause acute diarrhea (WHO 2008). The testing of pathogenic *E. coli*, which is more complicated and costly than total *E. coli*, is not practical for daily monitoring at a wastewater treatment plant. Therefore, total *E. coli* was chosen as an indicator for the assessment of a general microbial risk. This is further on in accordance with what important guidelines for water reuse suggest, such as US EPA, which recommends it as the best indicator of health risk from water contact (US EPA 2010). Its presence indicates the potential for the co-existence of pathogenic organisms (An et al. 2002). Since dose-response models have not been developed for total *E. coli*, the best-fit dose-response parameters for the ingestion of non-enterohaemorrhagic strains (except O111) of *E. coli* defined by Haas et al. (1999) are used in QMRA, which was adopted by An et al. (2002) and used in this paper. The actual risk of pathogenicity is expanded for this replacement, but it could be safer for users if any protective guidelines or measures are formulated according to assessment results of expanded risk.

*Rotavirus* is a representative of the *enteric viruses* group which can survive longer in water than most intestinal bacteria and are very important and commonly used in microbial risk assessment since they can cause most waterborne infections in developed countries and are
highly infective (Hamilton et al. 2006; Muñoz et al. 2010; CDW 2010). Rotavirus could cause gastroenteritis and are highly infectious (Hamilton et al. 2006; Muñoz et al. 2010), and it is the most important single cause of death in children in the world (WHO 2008). In addition, rotavirus has a higher resistance to disinfection than E. coli. Thus, E. coli is not a reliable indicator of its presence/absence and infectious risk (WHO 2008). Additionally, Sweden does not have a vaccination programme yet although it is being considered (National Board of Health and DACEHTA 2012). As there is a lack of data about enteric viruses, the concentration of rotavirus in this paper is estimated based on the concentration of fecal coliforms, using a rotavirus: fecal coliform average ratio of 1:10^5. The relation has been suggested in the study by Muñoz, et al. (2010).

**Testing Methods for testing and data input**

The samples were sent to the laboratory of VASYD Company, Malmö, Sweden, to test E.coli and fecal coliform. The method of IDEXX Colilert quanti-Tray® which is the standard method of ISO (ISO 9308-2:2012) and approved by US EPA was used for analysing fecal coliforms and E. coli which are incubated in 37 °C and 44 °C for 48 hours, respectively. The concentration data of fecal coliforms (FC) and E. coli (EC) is shown in Table 1 and Fig 2a) and b). From the effluent of WWTP to pond 6, the fecal coliform and E. coli are reduced 0.3-1.2 log and 0.5-3.3 log, respectively. The concentration of fecal coliform and E. coli in ponds 2 to 6 are lower and the removal efficiency of E. coli is a little higher in the summer time (from May to August) than other seasons probably due to the UV effect from much stronger sunshine and physicochemical conditions in that period (Curtis, et al. 1992; Davies-Colley et al., 1999; Roberto et al. 2011). The extreme values (including outliers) of density in different periods are used for input in QMRA to calculate the risk range including the potential maximum risk for different scenarios.

**Table 1** the concentration range of fecal coliform and E. coli in samples from January to December 2012

<table>
<thead>
<tr>
<th>Unit: st/100ml</th>
<th>Point 1</th>
<th>Point 2</th>
<th>Point 3</th>
<th>Point 4</th>
<th>Point 5</th>
<th>Point 6</th>
<th>Point 7</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fecal coliform</strong></td>
<td>2.40×10^3- &gt;2.42×10^5</td>
<td>2.25×10^3- &gt;2.42×10^5</td>
<td>9.68×10^3- 1.73×10^5</td>
<td>7.15×10^3- 1.3×10^5</td>
<td>6.11×10^3- 7.27×10^5</td>
<td>4.11×10^3- 5.48×10^4</td>
<td>2.8×10^4- 5.17×10^4</td>
</tr>
<tr>
<td><strong>E. coli</strong></td>
<td>7.55×10^3- 1.20×10^5</td>
<td>4.50×10^3- 2.42×10^5</td>
<td>1.06×10^3- 6.13×10^4</td>
<td>3.60×10^3- 5.79×10^4</td>
<td>2.60×10^3- 2.76×10^5</td>
<td>80- 2.14×10^4</td>
<td>30- 1.96×10^4</td>
</tr>
</tbody>
</table>
Assessment method - Quantitative Microbial Risk Assessment Model (QMRA)

The Quantitative Microbial Risk Assessment Model (QMRA), which is a useful tool for quantifying the microbial risk, was applied in the work. The model has been widely studied and used in many conditions of estimating the microbial risk from using treated wastewater. For example, the QMRA model has been used as methodology for the assessment of implications of the evidence on the health risks from wastewater use on international guidelines (Blumenthal et al. 2000), Zhao et al. (2010) in Tsinghua University applied the QMRA model to determine the concentration limits of Cryptosporidium parvum and Giardia lamblia for using the treated wastewater to irrigate the urban green land (Zhao et al. 2010) and some studies applied QMRA to assess the

**Exposure assessment**

In the paper, QMRA is applied for four exposure scenarios of direct wastewater reuse for non-potable applications as follows: Scenario 1 - agricultural irrigation; Scenario 2 - industrial cooling water; Scenario 3 - landscape water for recreational impoundment; Scenario 4 - urban non-potable water for the irrigation of green space.

**Scenario 1:** The potato is used as an example crop for assessment since it is the most common crop with the largest irrigated area in Sweden and irrigated during July and August when the shortage of water sometimes happened. Thus, it is assumed that the farmers and children are exposed for 60 days during the irrigation period. The irrigation technology in the south of Sweden is mainly spray irrigation. For the potato, which is always eaten prepared (normally cooked), the risk of exposure mainly comes from aerosol inhalation rather than food intake. Children who are vulnerable and more easily infected by the pathogens, especially the rotavirus, and may be near, for example, playing in the irrigation area are also considered in the work. Thus, the exposure risks, both for farmers and neighbouring children, through the route of inhalation for the reclaimed water irrigation is assessed in scenario 1. The exposure dose is calculated according to the equation (1) developed by US EPA (1997).

\[ \lambda_1 = C_{air} \cdot v \cdot t \]  

Where \( \lambda_1 \) is the exposure dose of respiratory pathway (st/d); \( C_{air} \) is the pathogen concentration in air (st/m\(^3\)); \( v \) is the respiration rate (m\(^3\)/d or m\(^3\)/h), and selected according to US EPA (1997), yard work scenario for farmer and play scenario for child, respectively; \( t \) is the exposure time per day. \( C_{air} \) is calculated according to the method, developed by Xie et al. (2009), which uses the equations (2) and (3) developed by Camann (1980). The parameter in the equations is selected according to the local conditions.

\[ C_{air} = Q \cdot D \cdot R + B \]  

Where \( Q \) is the emission source intensity (st/s); \( D \) is the microbial aerosol diffusion coefficient (s/m\(^3\)), calculated by the Gaussian dispersion models and its value is a complex analytical function of atmospheric stability, downwind distance, wind speed and aerosol plume height (Camann 1980; Xie et al. 2009; Petterson & Ashbolt 2003), and the spray height is assumed to be 1m, while the evaluation point is assumed to be 3 meter away from the spray point in the downwind direction; \( R \) is the attenuation coefficient of pathogenic
microorganisms, and 1 is used since no die-off of pathogens is assumed for the worst possible case as the same assumption by Hyu. et al. (2007); B is the concentration of pathogenic microorganisms in the background (st/m$^3$), which generally could be ignored (≈0).

$$Q = C_w \cdot q \cdot A$$  \hspace{1cm} (3)

Where $q$ is the spray intensity (m$^3$/s), estimated by the irrigation area and water need which are reported in ‘Water use for irrigation’ (Brundell 2008) and ‘Water withdrawal and water use in Sweden 2010’ (SCB 2010a); A is the atomization efficiency factor, and 0.01 is used for the worst case; $C_w$ is the pathogen concentration in water (st/m$^3$), and the data from July to August is used for assessment. In addition, the wind speed is assumed to be 6m/s for the average according to the statistics data (Windfinder Home 2012), and the heights of an adult and a child are assumed to be 1.8m and 1.2m, respectively.

**Scenario 2:** Cooling water is assessed for industrial application since it is the most common way of water recycling and consumes the most water in industry water use (SCB 2010b). The exposure way is mainly breathing in aerosols from cooling tower drift (Workplace Health and Safety Queensland 2007), which is recycled water containing all the minerals, chemicals and bacteria that are in the tower. The exposure dose is calculated with the same methods for recycled water atomization used for scenario 1. The quantity of drift is calculated according to equation 4 (Kunz 2010):

$$Q_d = c \cdot Q_r$$  \hspace{1cm} (4)

Where $Q_d$ is the rate of water loss per second via drift (m$^3$/s); c is the drift percent, which typically is 0.1-0.3% of the circulation rate (Betz Laboratories 1962; Kunz 2010). 0.3% is used here for the worst condition; $Q_r$ is the circulation rate (m$^3$/s) and 10 m$^3$/s is used here for the condition of power plant with installed capacity of 150MW (Huang et al. 2006). The height of the cooling tower is assumed to be 3m for mechanical draft and 100m for a natural draft cooling tower. The exposure times are assumed to be eight hours per day of five days a week for 52 weeks per year (260 days per year) for workers. The respiration rate is selected according to US EPA (1997), and the maximum for the walking scenario for adults is used. Other assumptions are the same as scenario 1.

**Scenario 3:** Recreational impoundment, which is one type of landscape water, is used for assessment, as this needs large amounts of water and is easy for individuals, especially the children, to have had access to the reclaimed water and have been exposed to the pathogens. The route of exposure is mainly body (such as hand) contamination and the resultant transfer to the mouth or open wounds. A person is assumed to intake 100ml of treated wastewater in a day (Haas 1983) and have access to the recreational impoundment for once a week over five month period, which means 20 times per year, considering the
climate in the south of Sweden. The data from May to September is used for assessment. No die-off of pathogens is assumed for the worse possible case (Hyu. et al. 2007).

**Scenario 4:** The irrigation of golf courses is selected for assessment in the applications of urban non-potable water, since it needs large amounts of water. The irrigation of golf courses with an area of 500,000 m$^2$ needs about 2700 m$^3$ of water per day (Green Friends Machinery Group Co., Ltd. 2010). The exposure ways are mainly inhalation for occupational groups due to spray irrigation and direct contact for the public. The exposure dose of inhalation is calculated with the same method as scenario 1, and 1ml per day is assumed for direct contact for the public (Asano et al. 1992). It is assumed that the occupational groups are exposed 8 hours per day for two days in a week and once a week for the public over the time of March to September considering the climate in the south of Sweden. In addition, the spray height is assumed to be 3m, and the evaluation point is assumed to be 3 metres away from the spray point in the downwind direction. Other assumptions are the same as scenario 1.

**Dose-response modelling**

The Beta-Poisson model is used for the dose-response analysis of E. coli and rotavirus and the equations (Haas et al. 1993) are the following:

$$P_I(\lambda) = 1 - (1 + \lambda/N_{50} \left( 2^{1/\alpha} - 1 \right))^{-\alpha}$$  (5)

Where $P_I(\lambda)$ is the daily probability of infection from viruses; $N_{50}$ is the median infectious dose (mass); $\alpha$ is the slope parameter; $\lambda$ is the exposure dose per person per day (mass).

The annual probability of infection $P_I(A)$ can be calculated by equation (6):

$$P_I(A) = 1 - (1 - P_I(\lambda))^N$$  (6)

Where $N$ is the number of exposure events per year (day). Equation (5) is described by two parameters: $N_{50}$ and $\alpha$. According to Haas et al. (1993) and Haas et al. (1999), $N_{50}$ is 6.17 and $\alpha$ is 0.2531 for rotavirus, while $N_{50}$ is $8.60 \times 10^7$ and $\alpha$ is 0.1778 for E. coli, respectively. The model was calculated straight-forwardly using Excel 2007.

**Risk characterisation**

The annual acceptable microbial probability of infection of $10^{-4}$ is applied for risk characterisation, which is suggested by USEPA (1989). If the $P_I(A)$ is below the benchmark of $10^{-4}$, it means that in that scenario the water is acceptable for reuse for the purpose.
Results and Discussion

Results and discussion of QMRA

The annual probability of infection calculated by dose–response modelling for the different scenarios is shown in Table 2. It should be known that the ponds have rich wildlife, particularly birds such as ducks, swans and fish. Fecal material from the animals may in some cases randomly cause an increase in indicator organism content. From the results of the dose-response model, the availability of reuse regarding the water can be discussed. It can be seen that the annual probability of infection of E. coli and rotavirus for farmers in scenario 1 is lower than 10^{-4} in ponds 2, 3, 5 and 6, which means that this part of the water is safe for farmers to use for irrigation from the microbial point of view. However, it is not safe enough for children since the probability of infection of rotavirus is over 10^{-4}. Additionally, the annual probabilities of infection of rotavirus in other scenarios are all over 10^{-4}, which means the water cannot be accepted for safe reuse although most of the probability of E. coli is low enough. The difference between the risk of E. coli and rotavirus is mainly because of the median infectious dose.

Normally in the same scenario, the potential risk gradually decreases as water passes different sampling points. Nevertheless, there are some abnormal results existing. The risk of rotavirus of point 5 in scenario 1 is unusually larger than in points 3 and 4, which is probably caused by deviation due to limited sampling. Averaging multiple sampling could reduce the deviation.

Table 2 The annual probability of infection for different scenarios of the reuse of treated wastewater

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>farmer</td>
<td>child</td>
<td>3 m</td>
<td>100 m</td>
</tr>
<tr>
<td>E. coli</td>
<td>8.0<em>10^{-7}-3.0</em>10^{-6}</td>
<td>3.1<em>10^{-5}-1.2</em>10^{-4}</td>
<td>3.6<em>10^{-2}-4.4</em>10^{-1}</td>
</tr>
<tr>
<td>Rotavirus</td>
<td>8.1<em>10^{-5}-6.7</em>10^{-4}</td>
<td>3.1<em>10^{-5}-2.6</em>10^{-2}</td>
<td>9.8<em>10^{-1}-9.9</em>10^{-1}</td>
</tr>
<tr>
<td>worker</td>
<td>public</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E. coli</td>
<td>8.2<em>10^{-7}-5.7</em>10^{-6}</td>
<td>3.2<em>10^{-5}-2.2</em>10^{-4}</td>
<td>2.2<em>10^{-1}-6.8</em>10^{-1}</td>
</tr>
<tr>
<td>Rotavirus</td>
<td>3.1<em>10^{-5}-6.7</em>10^{-4}</td>
<td>1.2<em>10^{-5}-2.6</em>10^{-2}</td>
<td>4.7<em>10^{-1}-9.9</em>10^{-1}</td>
</tr>
<tr>
<td>child</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E. coli</td>
<td>5.0<em>10^{-8}-1.8</em>10^{-7}</td>
<td>1.9<em>10^{-6}-7.1</em>10^{-6}</td>
<td>5.1<em>10^{-3}-2.6</em>10^{-1}</td>
</tr>
</tbody>
</table>
Data input in QMRA

As described in the section of ‘Materials and methods’, the extreme data including outliers in different periods were used as data input in QMRA to calculate the range of potential risk of using treated wastewater for different scenarios. Whether an outlier should be included or excluded from a data analysis is both dependent on the reason why it is an outlier (e.g. provenance of the data, how they were collected and analysed) and the objective of analysis (Ministry of Environment, B.C. 2001). In this study, most outliers of FC and EC were concentrated in February, while others appeared in the samples at the beginning of March. That means the unusual values are representative to some extent and maybe not outliers in the data of longer-period (several years) sampling. They were probably caused by weather conditions in that period, such as extremely low temperatures of the year, snow and freezing on the surface, and the physicochemical conditions influenced by the weather. As there is a short data collection period (only one year) and limited data, it cannot conclude that the outliers are occasional samples or errors. More data collection of a longer period, for example two or three years of sampling should be needed for evaluation of outliers. In the paper the objective is to estimate the maximum

<table>
<thead>
<tr>
<th></th>
<th>Rotavirus</th>
<th>E. coli</th>
<th>Rotavirus</th>
<th>E. coli</th>
<th>Rotavirus</th>
<th>E. coli</th>
<th>Rotavirus</th>
<th>E. coli</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point 4</td>
<td>2.7<em>10^5 - 6.6</em>10^5</td>
<td>1.1<em>10^-2 - 2.6</em>10^-1</td>
<td>9.3<em>10^-1 - 9.9</em>10^-1</td>
<td>1.0<em>10^-2 - 1.8</em>10^-1</td>
<td>6.4<em>10^-1 - 9.5</em>10^-1</td>
<td>3.9<em>10^-2 - 6.8</em>10^-2</td>
<td>1.1<em>10^-2 - 1.8</em>10^-1</td>
<td></td>
</tr>
<tr>
<td>Point 5</td>
<td>1.7<em>10^-5 - 9.4</em>10^-8</td>
<td>6.6<em>10^-3 - 3.6</em>10^-6</td>
<td>1.7<em>10^-5 - 2.4</em>10^-1</td>
<td>6.4<em>10^-4 - 1.0</em>10^-4</td>
<td>7.2<em>10^-1 - 3.4</em>10^-2</td>
<td>2.5<em>10^-3 - 4.0</em>10^-4</td>
<td>3.6<em>10^-2 - 5.8</em>10^-5</td>
<td></td>
</tr>
<tr>
<td>Point 6</td>
<td>3.1<em>10^-2 - 1.0</em>10^-4</td>
<td>1.2<em>10^-1 - 4.0</em>10^-3</td>
<td>8.7<em>10^-1 - 9.9</em>10^-1</td>
<td>7.6<em>10^-1 - 1.4</em>10^-1</td>
<td>5.4<em>10^-1 - 9.6</em>10^-1</td>
<td>2.9<em>10^-1 - 5.1</em>10^-2</td>
<td>8.4<em>10^-1 - 1.4</em>10^-1</td>
<td></td>
</tr>
<tr>
<td>Point 7</td>
<td>1.2<em>10^-5 - 7.7</em>10^-8</td>
<td>1.3<em>10^-3 - 3.0</em>10^-5</td>
<td>1.3<em>10^-2 - 1.3</em>10^-2</td>
<td>4.6<em>10^-4 - 4.9</em>10^-5</td>
<td>5.2<em>10^-1 - 1.6</em>10^-2</td>
<td>1.8<em>10^-1 - 1.5</em>10^-4</td>
<td>2.6<em>10^-2 - 2.2</em>10^-5</td>
<td></td>
</tr>
</tbody>
</table>

- Acceptable risks are in bold font
risk that may occur. All of the data including outliers which actually occur should be considered for the worst case.

The detection of viruses is a rather time consuming, complex and expensive procedure due to pathogen variability, especially when large volumes of water must be tested (Shuval & Katzenelson 1972; Ferguson et al. 2012). For the preliminary study as presented in this paper, it is better to find a straightforward way to obtain the data since the study focuses on the risk evaluation process and the development of protection guidelines based on QMRA rather than detection method and procedure. The data input of rotavirus used in the study was obtained based on the data of rotavirus and fecal coliform which was originally presented by Oragui et al. (1987) who studied the removal of excreted bacteria and viruses in waste stabilisation ponds which are a similar situation as this study. The ratio was adopted by Muñoz et al. (2010) for the assessment of microbial risk from using treated wastewater for agriculture. The use of the ratio could simplify the detection, but the statement of the ratio is only supported by little evidence. The ratio of virus, not special for rotavirus, and fecal coliform was presented as 5:10^5 in the study by Cohen & Shuval (1972). A very weak correlation between rotavirus and fecal coliform was found in some studies (Grassi, et al. 2010; He et al. 2012; Ferguson 2012), which means the reliability of quantitative relationship should be questioned by the little supported evidence. For that reason, more detection testing is needed for rotavirus data collection in further study. In practical projects, for avoiding complicated and expensive testing, the model could be developed and applied for estimating the density of target pathogens according to other parameters which are easier to be monitored or obtained.

Discussion on the assumption in exposure assessment

Many assumptions have to be used in the process of exposure assessment. The assumptions were defined mainly according to a) previous studies for similar situations and documents, e.g. intake volume per day in scenario 3 and the definition of parameters’ value in aerosol experiments; b) general local conditions, e.g. height of person, wind speed and the height of the cooling tower; c) the worst case, e.g. the exposure time and no die-off of pathogens. The assumption inevitably causes the deviation of estimation of potential risk. For example, there were no aerosol experiments conducted to determine microbial aerosol diffusion coefficients in the study, which directly affect the density of pathogens in the air possible to be in contact with humans. The calculation method and the determining of parameter value from literature and documents were supposed to be suitable for local conditions. The aerosol diffusion model and relevant parameters should be defined based on the data of local situations, such as weather conditions and topography which should be collected by monitoring experiments in the practical project for individual cases. The assumption for the worst case with low probability of occurring probably expanded estimates as well. For example, a worker is probably not exposed for all working time (8h per day) when the treated wastewater is used for the cooling tower or irrigation. However,
this assumption has to be used for obtaining the maximum potential risk because there was no reference which could be learned and no relevant data was collected. Also, the assumption of no die-off of pathogens was used since it is possible that the person is in contact and ingests the pathogens at the very beginning when no die-off happens.

The overestimation of potential risk will cause a too strict treatment process with higher costs than needed, which reduce cost-effective ways of reusing treated wastewater, although it is good for protecting users by excessively serious measures based on estimates. To improve the reliability of the results, a lot of investigation work should be done for data collection in future study or practical cases. For example, questionnaires could be designed and applied for collecting the data of, for example, the frequency and timing of exposures, detailed information such as the distance from the spray source and water swallowed when swimming, and basic demographic characteristics such as age, gender, socioeconomic status and physical health. In addition, the adoption of assumption causes uncertainty of risk assessment, which should be considered in the assessment process to make the results more significant and reliable.

**Discussion on the uncertainty of QMRA**

There are two fundamental approaches to construct a QMRA model: deterministic, of which the inputs are represented as point estimates and stochastic of which the inputs are probability density functions and describe uncertainty both in the model inputs and outputs (Benke and Hamilton 2008). Deterministic modelling is promulgated as a practical approach in several major national and international guidelines (US EPA & US AID 2004; WHO 2004; NRMMC and EPHC 2005) since it has the pragmatic advantage of simplicity in analysis and results and is more readily embraced by water resource managers (Benke and Hamilton 2008); it is used in this study because the scope of the study is to provide the reference views to water managers regarding if the treated wastewater could be reused for different applications and the development of protection guidelines according to the results of QMRA. The characteristic of simplicity and more easily understood by managers are needed by the scope of the study.

However, the deterministic modelling has the defect of failing to address the inherent uncertainty in the estimates of risk and probably overstating the true risk if the single values obtained from this method are considered as upper bound estimates of risk to a maximally exposed individual (Hammonds et al. 1994), as did in this study. The uncertainty should be analysed and modelled for further study to fully characterise the risk and evaluate the implications and limitations of the risk assessment (EPA 1992), which is increasing in popularity amongst researchers in recent years, such as Nauta (2000), Schmidt and Emelko (2011) and Donald et al. (2011). The uncertainty comes from three parts according to the EPA (1992): a) uncertainty of event background, e.g. incompleteness of analysis caused by description of event and missing information; b)
uncertainty of the parameters’ selection and c) uncertainty of the models, e.g. model simplification and extrapolation. Specific to this study, the limited data of pathogen density and background information, amounts of assumptions, e.g. the parameters’ selection involved in the exposure process discussed above and the dose-response model, e.g. $N_{50}$ and $\alpha$, extrapolated from data of animal experiments, are the main sources of uncertainty. Several methods for quantitative analysis of uncertainty have been developed, such as sensitivity analysis, Taylor Series Approximation (mathematical approximation), Monte Carlo Analysis (simulation approach) and Bayesian statistical modelling (IEHIAS 2013). Of these, Monte Carlo simulation which is based on statistical sampling techniques to produce a stochastic approximation of the result and evaluate the uncertainty surrounding estimated values represented by credibility intervals is the most widely used in quantitative analysis (Haas et al. 1999; Jaidi et al. 2009). For example, An et al. (2007) used the Monte Carlo model based on QMRA to estimate the microbial risk of E. coli in reclaimed wastewater irrigation on paddy fields; Tanaka et al. (1998) used Monte Carlo simulation to calculate the risk of infection resulting from food crop irrigation with secondary effluents; WHO used this approach in the latest version of wastewater reuse guidelines (WHO 2006). Monte Carlo simulation could be used for further study to evaluate uncertainty and inherent variability and obtain a more nuanced characterisation of risk by the resulting distribution of risk than the simpler point-estimation approach used in the paper.

**Discussion on the benchmark of acceptable risk**

According to Haas et al. (1993), the range of $10^{-4}$ to $10^{-6}$, which is used by the USEPA as a target reference risk for carcinogens in drinking water was considered a reasonable level of risk for communicable disease transmission, and annual risk values of above $10^{-4}$ were considered high for infection. The value of $10^{-4}$ (1 per 10,000 people infected per year) developed by the USEPA was used in this preliminary study as the benchmark of annual acceptable risk used to examine whether or not the studied water is acceptable for different applications. It is the most commonly applied benchmark in risk assessment (Regli et al. 1991) and adopted in many studies of assessment of microbial risk from using treated wastewater, such as Muñoz et al. (2010), An et al. (2007), Zhao et al. (2010) and Ryu et al. (2007).

However, Petterson and Ashbolt (2003) proposed that it may be argued that the acceptable risk of infection from a particular disease should be dependent upon the duration and severity of the symptoms rather than using the same benchmark. The reference level of acceptable risk could be expressed in Disability Adjusted Life Years (DALYs) which is calculated as the sum of the Years of Life Lost (YLL) due to premature mortality in the population and the Years Lost due to Disability (YLD) for people living with the health condition or its consequences (Petterson & Ashbolt 2003; WHO 2013). WHO suggested a level of $\leq 10^{-6}$ DALY per person per year (pppy) as a tolerable additional disease burden.
for wastewater use in agriculture. The tolerable risk of infection could be translated from the tolerable additional annual burden of disease by the equation (7) due to the pathogen of concern (WHO 2006). The expression as DALYs could be adopted for further study to make the benchmarks more targeted for pathogens due to the different characteristics rather than too general for all pathogens.

\[
\text{Tolerable disease risk pppy} = \frac{\text{Tolerable DALYs pppy}}{\text{DALYs per case of disease}} \tag{7}
\]

Additionally, the need to establish some measure of acceptable or tolerable risk for wastewater reuse has been widely acknowledged (Petterson & Ashbolt 2003). Relevant authorities in Sweden should set up their own benchmark according to local situations which vary greatly in different countries. There are several approaches such as a predefined probability approach, a ‘currently tolerated’ approach, a disease burden approach, an economic approach and the public acceptance of risk approach, and it is suggested by WHO that all of them should be relied on by public health practitioners when establishing acceptable risk (Hunter & Fewtrell 2001).

Discussion on the development of protection guidelines based on QMRA

For protecting the users from using treated wastewater, some measures in terms of the microbial perspective should be formulated and applied. From the QMRA model point of view, the factors affect the risk of infection not only concerning the density of pathogens in the treated wastewater, but also in the ways of application, the length of exposure time, the distance from the source, the intensity of use, etc., which should also be included in the guidelines of safe reuse for different applications. For the water sources and scenarios in the paper, some suggestions for protection measures are listed as follows:

The concentration of pathogens in treated wastewater is one of the main factors affecting the risk. From the assessment results, it can be seen that the pathogens in the water are too high to be safely reused except regarding irrigation in scenario 1 if there is no disinfection process added. In that case the reduction of pathogens mainly relies on natural disinfection by UV from sunlight (Curtis et al. 1992; Davies-Colley et al. 1999; Roberto et al. 2011), which is not stable and not efficient enough, especially for the fecal coli form which is the indicator of pathogens in most of the water reuse guidelines. Thus, two methods from the technique perspective could be applied for the improvement of the reduction of pathogens. One way is the adding of the disinfection process. For this way, UV which has a high effect in a short contact time on all kinds of pathogens, e.g. bacteria, viruses, spores and protozoa, is recommended previous to chlorination and ozone since UV does not produce harmful by-products and dissolved solids, and no chemical involved in the process, as well as it is ecological and environmentally friendly (Liu 2004). Another way is by increasing the hydraulic retention time of ponds or storage time to extend the duration of sunshine.
However, the change of water quality during the long-term storage should be considered and some measures should be taken for safe reuse. Based on the results of QMRA, agriculture is recommended to be a preferred application in Sweden since it needs amounts of water with lower quality than other applications and no additional treatment process needed for meeting basic health security requirements from a microbial perspective.

When the treated wastewater is applied for agricultural irrigation as described in scenario 1, there should be the regulation for prohibiting children close to the spray source since the annual probability of infection for children is higher than adults and children who have a weaker self-protection awareness. When infected by pathogens, children do not have such a strong resistance as adults and fall ill easier. In addition, the methods and intensity of irrigation are also important factors. When using treated wastewater, the drip irrigation is recommended to reduce the atomization and spread of treated wastewater, and the large intensity of spray should be avoided.

For irrigation, whether agricultural or urban green space (golf courses and park), by affecting the microbial aerosol diffusion coefficient, the distance from the spray source seriously affects the risk of infection for occupational groups. The person should not stay in a downwind direction near a spray source. The ‘safe distance’ during irrigation should be regulated in guidelines. Further, the wearing of suitable equipment such as masks is needed for occupation groups.

The treated wastewater should be marked obviously to the public when it is used for recreational water or the irrigation of urban green space, and the public should not be exposed to it immediately. The time for die-off of pathogens is needed, and how long is safe should be studied and regulated. Further, the public should avoid contacting reclaimed water, and washing after contact is necessary to avoid the ingestion of treated wastewater accidently.

For cooling water of industry application, the results show that the height of the cooling tower affects the probability of infection significantly. As the height increases, the risk of infection decreases although it still cannot be accepted. Thus, the treated wastewater is recommended to a natural draft cooling tower which always is much higher than a mechanical draft one. If the treated wastewater is applied for a lower cooling tower, the pathogens in water should be reduced greatly before use, and the factors such as ‘safe distance’, protection wears and residence time for workers in a risk area should be regulated.
Conclusion

Treated wastewater is an important unconventional water source both for easing the water shortage and the protection of the water environment. The safe reuse, especially the microbial aspect, is an important issue being studied a great deal. In the study the results of the QMRA model show that the treated wastewater by tertiary treatment combined with the pond system is only available for agriculture irrigation, recommended as a preferred application, in the south of Sweden, while the risks for other applications are higher than the value that can be accepted if no further treatment or disinfection are added. The method is straightforward and easy to apply for different scenarios. It also gives a good first estimate of where any increased risk may occur for the different ways of water reuse practices. It gives basic advice for risk assessment regarding water reuse.

For safe reuse, the health-based protective guidelines using QMRA should be formulated, not only focusing on the pathogen limits but also considering the exposure conditions for different applications. The regulation of the ways of reducing the risk of exposure and infection are as important as the technical reduction of the pathogens concentration in treated wastewater.

The study, however, has limitations of which the most important are: there are some assumptions used for the calculation of the model, which could deviate from the actual conditions; the risk could be overestimated since the assumptions and parameters are selected for the worst case; and the uncertainty was not analysed which should be done in a further study. No evaluation of chemical risks has been performed in this work. When implementing a water reuse scheme, the chemical risk assessment should also be done.

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Paper IV

Suggestions for the development of water reuse guidelines – examples from Sweden

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Water Environment Research (submitted)
Suggestions for the Development of Water Reuse Guidelines – Examples from Sweden

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Abstract

Water reuse is carried out in some areas of Sweden for e.g. agriculture irrigation and industry uses. So far, there have not been relevant guidelines regulated for safe reuse of treated wastewater. In this paper, recommendations for development of water reuse guidelines in Sweden are discussed and concluded based on the quality of treated wastewater from Källby wastewater treatment plant, learning from existing guidelines and Principal Component Analysis (PCA).

The results from monitoring of water quality and learning from other water reuse guidelines gives the suggestions for the selection of water quality parameters, the approach to set microbial parameters and regulations of wastewater treatment. PCA suggests that the significant factors affecting the water quality, which should be considered when formulating the guidelines. Some indicators with strong correlation from PCA can be removed from the daily test schedule. Protective measures which should also be included in the guidelines are discussed.

Key words: treated wastewater, guidelines, Principal Component Analysis (PCA), reuse, monitoring

Introduction

The hydrological cycle results inevitably in water reuse, either directly or indirectly. Many countries blessed with large freshwater resources tend to ignore this fact and trust that wastewater will be diluted with other freshwater resources when discharged. Water reuse, which has been carried out in many countries at different levels, is considered as one of the most cost-effective ways both for dealing with water crisis and improving water environment protection. In general, Sweden is a country with rich fresh water resources. In most parts of Sweden, there is no incentive for using treated wastewater directly because abundant resources can meet almost all needs (Swedish Water & Wastewater Association [SWWA], 2000). Indirect water reuse is however common. Nevertheless, direct reuse of
treated water is also needed for some reasons. Firstly, parts of Sweden, such as south eastern and Skåne county, experienced dry and hot summer expressed as low precipitation and high evaporation in some year e.g. 2008, 2010 and 2013, which caused restrictions on irrigation and results bad harvest (Stockholm News, 2008; Radio Sweden, 2010; The Local, 2010; Johansson, 2013). In these cases, reclaimed water can provide a stable alternative water source and reduce the loss caused by water shortage. In addition, water reuse is an ecological solution to reduce the discharging of treated sewage water to the receiving water. From economical perspective, reuse of treated wastewater can minimize infrastructure costs and thus be profitable both for Water Utility and users. Nutrients in the treated wastewater are recycled to farm land, which can save the cost of wastewater and sludge treatment. A water utility can sell water instead of constructing and operating expensive sewage treatment plants or in addition to treating wastewater. For the farmers, they can save cost for fertilizer and get water cheaper than constructing their own irrigation systems (Raso, 2013). Harvest can be secured by the access to a stable water source especially in dry summer. From rational and sustainable use of water resources perspective, the practice of reuse contributes to prevention of excessive diversion of water from alternative uses, such as conserve groundwater for other uses (Vigneswaran and Sundaravadivel, 2004; Raso, 2013). Also, water reuse can be developed for sanitation or environmental protection purposes in response to increasingly stringent environmental regulations (Angelakis, Lazarova, Marecos do Monte, Tisserand, & Hochstrat, 2013). For these and other reasons, water reuse has grown in importance, not least in the European Union in the last decade.

Actually, there have been some practises to use the treated effluents directly even in Sweden. In the south eastern region of Sweden there is an interest in reusing the tertiary treated effluents of WWTP for irrigation. And over 40 reuse projects are implemented (Raso, 2013). The industrial wastewater, after proper treatment, is used for cooling, district heating and so on. In addition, energy extracted from treated wastewater is another important application (Salter, 2006). The reclaimed water not only reduces freshwater consumption, but also saves energy. Besides, there are also some demonstrations in eco-villages, such as Toarp (Fittschen & Niemczynowicz, 1997), which reuse treated wastewater for non-potable application, such as irrigation for agriculture and garden.

Reuse of treated wastewater is needed and has been practised in some areas of Sweden. But so far, there are no guidelines/standards, which are important steps for safe water reuse, have been found (Raso, 2013) and few studies of how to reuse the treated wastewater safely in Sweden. There is no clear criterion for reclaimed water quality, which probably causes health risk and environmental pollution from using unqualified reclaimed water. Based on empirical data, the objective of the study is to give recommendation from different perspectives which are selection of parameters, approach to set microbial parameters, wastewater treatment, protection measures and the application of statistic...
methods, for formulating guidelines for safe reuse treated wastewater in Sweden. Treated wastewater from Källby wastewater treatment plant (WWTP) in Lund was used for a case study to collect water quality data. Guidelines and standards from different countries were used for references for selection of water quality and the approach to set microbial parameters. Principal Component Analysis (PCA) was used for recognition of impact factors of water quality and simplification of routine monitoring parameters in guidelines, which can improve the safety and reduce the human and material cost for testing. The suggestions for control the risk and treatment required, which should also be included in the guideline, are discussed from the perspectives of monitoring data and risk assessment. The study is carried out only from the scope of recommendations for the approaches to set guideline and contents should be included, but does not involve the quantitative of limits for water quality parameters which should be based on more studies and experiments.

Methodology

Water Studied

The studied water comes from Källby Wastewater Treatment Plant (WWTP) in the south of Lund, a city in the province of Scania, southern Sweden, where sometimes dry summers happen and resulting temporarily water scarce. The WWTP treats an average of about 350 L/s (28,000 m³/day) wastewater from 80,000 residents in Lund. The wastewater is treated by tertiary treatment process, which is typical process flow in Sweden (Swedish Environmental Protection Agency [SWWA], 2000) including physical (screens, grit removal basins, primary and secondary clarifiers), biological (activated sludge in anoxic and aerobic conditions) and chemical treatment (ferric chloride is added to precipitate residual phosphorus), followed by chemical clarifiers and a sedimentation system using ponds for final polishing. After passing through six ponds, the effluent is discharged into the receiving water-stream Höjeå (VASYD, 2010). The values of some water quality parameters of influent to the plant, effluent after tertiary treatment and the last pond are tested by the lab of WWTP and shown in Table 1. There is no regular monitoring for other ponds except last pond, neither any data for microbial indicators which are required and important for assessing a safe directly reuse.

Sampling and Monitoring Experiments

The water sampling was collected from January to December 2012. The monitoring parameters were selected according to requirements in Chinese reclaimed water quality standards (China's State Administration of Quality Supervision and Inspection and Quarantine & China National Management Committee for Standardization, 2002-2007), which have the detailed limits of parameters for different applications. The samples were generally collected weekly for physical and chemical parameters, biweekly for microbial parameters and monthly for metals. The sampling was influenced by the severe weather,
such as snow and rain. Seven different samples were collected as grab samples each time at around 0.5-1m depth at the outlet of each pond and the effluent from WWTP before discharged into pond system (expressed as Eff. following).

Quality parameters were analysed with standard methods in laboratory. The testing methods and instruments used are shown in Table 2. The description of detailed parameters of instruments and the matching reagents can be found in the web of HANNA instruments (HannaNorden Company, 2013).

**Analytical Methods**

**Principal Component Analysis (PCA)**

Principal Component Analysis (PCA), which is a powerful tool to reduce the noise and simplify data, was used to analyse impact factors of water quality for safe reuse and simplify the routine monitoring parameters in the guideline. PCA is a multivariate statistical technique that finds the least possible orthogonal vectors to characterize data characteristics. Through a linear transformation, PCA reduces the dimensionality of a data set consisting of a large number of inter-related variables, while retaining as much as possible the variability present in data set, and provides information on the most meaningful parameters (Kebede & Kebedee, 2012; Ma, Guo & Liu, 2010; Singh, 2004). In addition, PCA can also show the association between variables (Kebede & Kebedee, 2012; Vega, 1998). PCA has been widely used for analysis and assessment of water quality data for different water bodies (Kebede & Kebedee, 2012; Mazlum, Özer, & Mazlum, 1999; Ying, 2005; Mishra, 2010).

In this paper, PCA was compiled by Matlab. Since the results of PCA on raw data showed that the variance of water quality indicators was distributed among several components, the rotation of PCA, which reduces the number of PCs by eliminating some relatively unimportant components (Mazlum et al., 1999), was applied for the data. Varimax rotation, which is the most widely used rotation in PCA, was used here to make the interpretation easier (Mazlum et al., 1999). The principal components (PC) for rotation were selected according to Chateld and Collins (1980), which stated that components with an eigenvalue of less than 1 should be eliminated. Thus, the components with an eigenvalue of more than 1 were rotated by varimax methods.

The explained variance represents how much percentage of the variance is explained by components which are the important patterns that appear in the field. In the paper, bi-plots of loadings show the relationships in different indicators for each sampling point and overall situation. The loadings represent how much of the indicators explained by the information in that component. In general, component loadings which are larger than 0.6, should be taken into consideration in the interpretation (Mahloch, 1974). The indicators
which have high loadings in the same component and close to each other are in the same group, which indicates that they have strong co-variance and are probably affected by the same factors. The indicators which are close to origin are not well explained by that component.

**Water Reuse Guidelines**

Guidelines or standards have been developed in many countries with the practice of reuse, but not in Sweden yet. In this study, the reclaimed water guidelines/ standards developed by World Health Organization (WHO) and some countries such as US, China, Portugal, Spain, Cyprus, and Italy, were used as a reference for e.g. parameters, treatment and approach in the work of formulating guideline in Swedish situation. The WHO guidelines (focusing on microbial pollutants), which takes both developing and developed countries’ conditions into account, is the basic requirements for safe reuse and is used as a reference by many countries when they develop guidelines for water reuse (Blumenthal, Peasey, Ruiz-Palacios & Mara, 2000); guidelines developed by US EPA are more strict for risk control, especially for microbial risk; Chinese standards are used as baseline for treated water quality and as reference for selection of monitoring parameters in laboratory testing. The reason for that is Chinese standards, although not as strict as US guidelines, have specific requirements for more parameter’ limits (chemical, physical and metals parameters) for different applications than the other two. And at present, it is blank for any regulations of reuse treated wastewater at all in Sweden. It could be wise to start with a draft guideline from those countries that focus on low-cost solutions for water reuse. It is maybe better to approach the development in steps and start with simple, straight-forward guidelines such as Chinese ones, rather than go from nothing to the most complicated and regulated standards, such as US ones, in one step. It probably technically and economically reduces the interest of reuse treated wastewater if heavy and very strict guidelines are introduced at initial phase. Besides, guidelines in some European countries summarized in Angelakis et al. (2013) where water reuse is practised earlier and refined can also be a reference for Sweden.

**Results and Discussion**

**Formulation of water quality parameters in guideline**

**Monitoring Results of Studied Water Quality**

Table 3 shows the results of monitoring water quality data of physical, general chemical, specific metal and microbial parameters and relevant limits in Chinese reclaimed water quality standards for different applications. As an open system, the water quality and treatment effect is affected not only by the process in WWTP, but also by external environment factors such as temperature, precipitation and sunshine. The variation of
colour, turbidity and SS is obviously consistent with the changes in temperature. There is an increasing trend in the three parameters from Eff. to pond 6, especially in summer time. The pH of all sampling points is moderate and close to ambient. TDS is generally stable through the time, and a certain degree of reduction takes place when the water runs through the set of ponds. For chemical parameters, in most cases, the concentration of NH$_4$-N decreases pond by pond; LAS, COD$_{Cr}$, NO$_3$-N and TP are also reduced, but not so significantly; BOD$_7$ increases slightly in summer; Chloride and hardness keep stable and low value all the time except individual samples; there is no significant reduction by ponds for other parameters. The reduction of metals depends on chemical precipitation, thus, the results keep low values and are stable in most time. There is a slight reduction of Mn, As, Hg and Cd, and a clear reduction of Fe from pond 1 to 6. The concentration of FC and EC in ponds 2 to 6 are lower in the summer time (from May to August) than other seasons probably due to UV effect from much stronger sunshine, but the removal efficiency by pond system is not so high (maximum 3.3 log for EC, 1.1 log for FC from pond 1 to pond 6).

Selection of Water Quality Parameters

The selection of water quality criteria should combine considering local situation such as wastewater treatment technology and economic constraints, and reference from WHO and other countries’ guidelines. For physical parameters, turbidity and suspended solid which are mostly common parameters in different guidelines, should be formulated, since some chemical and microbial pollutants attach to the solid particles which could be indictors related to the amount of pollutants. pH is also a normal parameter for its influence of components and reactions. For irrigation, salinity should be controlled by limits for soil protection in form of TDS or conductivity. In terms of studied water, pH and TDS are stable and can meet the requirements in other guidelines. The occasional monitoring is recommended instead of regular testing. For chemical parameters, BOD and COD or TOC should be formulated for organic pollution for all applications; Nutrition (N, P) is not necessarily formulated for irrigation but required for other applications especially landscape to avoid eutrophication. In terms of studied water, the monitoring data shows the current treatment process can guarantee some parameters such as LAS, phenol and hardness which meet the requirements for safe reuse. Thus, those parameters could be excluded in Swedish guidelines when the proper treatment required. Similarly, the concentration of heave metals such as As, Cd, Cr and Hg, which are include in some guidelines by e.g. Portugal, Italy and China, are rather low after tertiary treatment. Nevertheless, considering the recalcitrance, bioaccumulation and chronic toxicity of heavy metals, it is recommended that heavy metals could be regulated as optional monitoring indicators or monitored occasionally according to local situations. FC, EC and helminth egg are normally used for microbial pathogens indicators, but the limits vary a lot. The approaches for microbial parameters are discussed in the following section. Besides,
Persistent Bio-accumulative Toxins such as Methylmercury, PCBs, DDT and dioxins, and emerging components such as pharmaceutical and personal care products (PPCPs), antibiotics and endocrine disruptors, which are not widely included in the existing guidelines at present, are recommended to indicate in Swedish guidelines for protection of users and environment.

Discussion on the Approaches to Set Microbial Parameters

The risk of wastewater reuse to human mainly comes from pathogenic microorganisms (Toze, 2006). Generally, faecal coliform, E.coli and total coliform are used for microbial indicative parameters since it is not economical and practical to test all pathogens in daily monitoring. But the limits in different guidelines vary a lot, suggesting the political nature in setting guidelines. Some countries, such as US, adopt approach 1 which means faecal contamination should be absent and no potential infection risk should be present (Havelaar, Blumenthal, Strauss, Kay & Bartram, 2001). Considering the cost and practicality of water reuse, WHO guideline was setting based on approach 2 from epidemiological perspective that is “no measurable excess cases in the exposed population”, which aims at there should be no actual risk of infection (Blumenthal, et al., 2000). The third approach is based on the risk exposure assessment, which means a microbiological quality guideline would then be set so that a quantitative microbial risk assessment (QMRA) model produces an estimate of annual risk which is below the regulator’s acceptable annual risk.

Sweden, as a developed country, could afford strict guidelines similar to US. For the water reuse applications where people likely may be in direct contact with or exposure to the water, the strict guidelines should be formulated for avoid potential risk of faecal contamination, although this reduces the economic advantage of water reuse. The formulation of guidelines should taking both safety and economy into account and find a balance between the two to make the max profit for water reuse in the premise of no actual health risk. Considering this, for the applications with less possibility of direct contact, such as irrigation and industry, Sweden could adopt the approach used by WHO guidelines which has amounts of evidence supporting but also controversy about its reliability. For improving safety, it is better to combine the risk assessment approach with the epidemiological studies. After setting the limits based on epidemiological studies, the potential risk of using the water with microbial indicators same as the limits could be evaluated to check if the maximum risk is acceptable. Also, the acceptable risk could be set firstly, and a limit can be regulated based on acceptable risk (Zhao, Hu, Xie, Wu & Huang, 2010). The limit should be compared with the one which is set based on epidemiological studies and the lower one of the two limits should be regulated in the guidelines.

For risk assessment approach, the critical steps are the selection of pathogens to be evaluated and the calculation of exposure dose. FC and EC are not reliable index to all
pathogens of their presence/absence since several pathogens have higher resistance to conventional treatment processes involving disinfection or stronger ability to adapt to unfavourable environment than indicator organisms have (WHO, 2008). Whether for approach 1 or 2, the risk assessment for special pathogens is an important step to improve the reliability of the guidelines. As stated before, it is impractical and virtually impossible to regulated limits for all pathogens in the guidelines. The selection of pathogens should be based on the testing and analysis the composition of pathogens in treated wastewater locally and then the ones with high possibility of infection and pathogenicity should be chosen to evaluate. For example, rotavirus, which has a higher resistance to disinfection than E. coli, could cause gastroenteritis and are highly infectious (Hamilton, Stagnitti, Premier, Boland & Hale 2006; Muñoz et al. 2010), and it is the most important single cause of children death in the world (WHO, 2008). If it is found in the studied water with high enough concentration to cause infection, the risk assessment should be done for its limits and it should be added to the guidelines as a supplementary to indictors. Besides, the calculation of exposure dose should be done according to worse cases based on local situations. And the parameters for dose-response model should be defined by epidemiological studies, which have been done for several pathogens (Haas & Eisenberg, 2001).

**Regulation of Wastewater Treatment in Guideline**

Through comparison with different guidelines, it can be seen parts of studied water quality cannot meet the requirements of safe reuse. The treatment process, which is one of important barriers to remove pollutants, should be regulated in guideline to guarantee the qualified water as many countries e.g. US, Portugal and Cyprus (only for irrigation purposes) did. Compared with the treatment required in other guidelines, the biggest flaw of process for studied water is a lack of disinfection step, rarely done for treated wastewater in Sweden. The treatment process required should be regulated in guidelines for different applications. The notes are recommended as following:

- For agriculture irrigation which is the application with most development potential in Sweden because its requirements of large amount and lower quality of water than others, secondary treatment include various types of activated sludge process, biological filters and natural system is necessary and disinfection should be stressed since the monitoring data exceed most of requirements in other guidelines. Membrane methods have better retention of chemical and microbial pollutants than the conventional activated sludge process but also higher cost. Feasibility studies are needed to identify which treatment methods are needed for treating wastewater to water reuse standards.

- For industry uses, urban non-potable water and scenic environment use, tertiary treatment as well as disinfection should be required. The monitoring data of studied
water shows that advanced process such as enhanced coagulation and sedimentation or filtration is needed to remove colour, turbidity, SS, organic matter and algae, especially in summer.

- For disinfection which is main process for pathogens removal, UV which is high effect in short contact time on all kinds of pathogens e.g. bacteria, viruses, spores and protozoa is recommended previous to chlorination and ozone since UV does not produce harmful by-products and dissolved solids, and no chemical involved in the process and is ecological and environmental friendly (Liu, 2004). Besides, the investment and operational cost of UV is lower than ozone and operation and management is easier (Liu, 2004). UV can also be used for algae removal in summer. The flaw of UV is no follow-up effect on pathogens regrowth during long-time distribution and storage. The secondary disinfection by users should be required in that case.

- If chlorination is used for keeping long-time disinfection, the impact factors for producing by-products, such as the dose, the components e.g. organic precursors and pH in wastewater should be controlled and regulated in guidelines.

- Monitoring data shows the variation of water quality with time. Longer storage time is recommend both for degradation of pollutants and stabilizing and balancing the water quality. The storage time should be studied based on local situation.

Regulation of Protection Measures in Water Reuse Guidelines

Guideline should not only regulate wastewater treatment and the limits of water quality parameters, which is only one of the barriers for improving the safety from water supply-side, but also health protection measures for risk control from user’ perspective should be included. The guideline should provide in what conditions that reclaimed water should/shouldn’t be applied, which is not only for safe reuse but also can be guideline for planning and design, and what should be done to avoid risk and protect the users and environment when it applied. The protection guidelines could be setting based on risk assessment process. Take agriculture irrigation for example. The factors, such as irrigation technique, weather condition, the amount of water and the frequency of irrigation, irrigation period, and crop types, which affect the potential risk of infection, should be stipulated in the guideline to provide clear instruction to users who maybe do not have much background knowledge. In addition, protection guideline should be specific for applications since the exposure ways to the risk vary greatly and the protective measures should be different accordingly. Furthermore, distribution should be included, e.g. pipes with reclaimed water should be marked clearly to distinguish from tap water which is drinkable directly in Sweden. For protection of source of drinking water, such as wells which are common water source in Sweden, safe distance should be given. The education
of public about the knowledge such as potential risk and relevant protective measures should be stipulated. Normally, the guideline is applied for general situations which maybe cannot considering individual cases due to different local conditions. Risk assessment should be formulated in the guidelines as complementary approach to guarantee safe reuse in that case. Also, the effective supervision and monitoring for the implementation of protective measures should be clearly regulated in guidelines.

**Applied Statistical Methods in Formulating Reclaimed Water Quality Guidelines**

**Identification of the Impact Factors for Reclaimed Water Quality**

In addition to the limits of water quality parameters, the guideline should also provide how to make the water meet the safe requirements from controlling impact factors of water quality perspective. The identification of impact factors which is the first step to set the regulations could be realized by PCA.

The explained variance of rotated PCA for each sampling point is shown in Table 4. From explained variance and loadings shown in bi-plots, the main factors affecting the variation of water quality can be obtained. For example, analysis from data of all sampling points (shown in Figure 1 (a) to (d)) shows that NH$_4$-N and NO$_2$-N close to each other and strongly contributed to PC 1, as well as pH and alkalinity. That indicates that PC 1 gives the information of redox state. COD, turbidity and colour which increase in summer are in the same group and mainly explained in PC 2 which is probably related to algae. The important contributors to PC3 are FC and EC which represent microbial pollutant. Temperature is explained mostly in PC4, as well as LAS, which indicates the main process behind the component seems to be changes with time. TDS and Fe are both explained mostly in PC5 and have co-variance to some extent, and they both decrease with the water pass though the ponds (spatial variation). Thus, PC5 mainly gives the information about the treatment by pond system. The explained variance of rotated PCA for all data shows that the first five PCs give information of similar importance. Thus, the significant factors affecting the overall water quality are mainly redox state, algae, microbial pollutants, seasonal effect (temporal variation) and treated by pond system (spatial variation). The impact factors are similar for other ponds although the degree of importance varies in different ponds. Besides, for Eff., the treatment process in Källby WWTP is one of the significant factors, which is shown in component 4 of Eff. (not shown in the paper).

The recognition and regulation of key impact factors could be used for improvement of safety of reuse by controlling those factors in treatment and storage process of treated wastewater. For example, the controlling of algae especially in summer which is good for improving water quality, the adjustment of redox state which is good for nutrients (N) removal, the controlling of temperature which is probably an effective way to control EC which is correlated to temperature in some ponds, and wastewater treatment which have
been discussed in Section 3.3, should be regulated in guideline to provide the clear instruction for operating and managing treatment process to meet the requirements of safe water quality.

Simplification of Reclaimed Water Quality Parameters

One of the objectives of guidelines is to give quantitative standard to qualified reclaimed water for safe use. Theoretically, the more parameters are included, the higher reliability. However, in practical routine monitoring, it is not possible to test all hazardous substance, such as pathogenic viruses and parasites, since it will cause so much cost of human and material resources that probably make water reuse prohibitive. Under the premise to ensure the safety of water quality, the selection of indicative parameters and simplification of parameters system when formulating the guidelines by the correlation between substances are effective way to make the guidelines more practical and cost-effective, which can be realized by statistic methods, such as PCA and statistical models e.g. Singular Value Decomposition (SVD) model (a model can be used for obtaining the quantitative relationship). For example, the correlation between parameters can be obtained in PCA correlation matrix. The parameters of high correlation coefficients with significance (p<0.001) in pond 5 are shown in Table 5. Some parameters, such as FC and EC, turbidity and colour, NH$_4$-N and NO$_2$ and so on, are strongly correlated and alternative to each other. For the whole pond system, COD$_{Cr}$ is always strongly correlated to turbidity. And the quantitative relationship could be defined by statistic model. Similarly, some toxic and hazardous substances, such as PPCPs, Endocrine Disrupting Chemicals and pathogens, existing in reclaimed water and induce potential health risk to users but normally not include in guidelines due to complicated and costly for daily testing, the correlation between which and conventional water quality parameters could be analysed by e.g. PCA and SVD in the process of formulating guidelines to simplify the parameters system and improve the reliability of reclaimed water quality guidelines.

Conclusion

Sweden has demands and possibility to reuse treated wastewater both for its own situations and consistent with the EU policy. Water reuse guideline is needed for planning, operating and managing reuse project and importantly protection of users and environment. The paper provides the recommendations of setting water reuse guidelines from different perspective. For the parameters, besides regular ones, considering hazardous, the toxic and emerging pollutants should be include although it is not common in the guidelines developed by other countries. Microbial parameters should be set combined using epidemiological studies and QMRA for balancing the safety and economy. Water treatment required should be formulated in the guidelines especially disinfection process for Swedish WWTPs. UV is recommended mainly for no by-products producing and easy for operating. Besides, the guideline should also include protection measures which could
be formulated from risk exposure and controlling perspective. Furthermore, statistic methods such as PCA could be for setting guideline from two aspects: a) identification of the key impact factors which should be instructed in guidelines how to control to improve treatment process; b) simplification of water quality parameters tested in routine monitoring and improvement of the guidelines by obtaining the correlation between indicators difficult to be tested and conventional water quality parameters.

The study has limitations mainly due to the limited amount of data. Some parameters, such as precipitation, algae and toxic pollutant should be monitored. And the study is only based on one WWTP which make the results insufficient for generalisations. The guidelines especially the limits of parameters should be set based on more cases. Some results from PCA cannot be well interpreted since the data of one year may be not enough. The collection of monitoring data for longer time is needed for stronger statistical significance. Improper frequency of observation of data and errors in analyzing the quality variables in the laboratory may also contribute to this failure (Mazlum et al. 1999).

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Reference


Table 1 Value of Some Water Quality Indicators from January 2010- May 2011 © [Källby Wastewater Treatment Plant].

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Influent (mg/L)</th>
<th>Effluent after chemical treatment (mg/L)</th>
<th>Effluent from last pond (6th) (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biological Oxygen Demand (7days)</td>
<td>81-330</td>
<td>0.67-12</td>
<td>1.1-8.5</td>
</tr>
<tr>
<td>Chemical Oxygen Demand (Cr)</td>
<td>160-600</td>
<td>18-62</td>
<td>21-38</td>
</tr>
<tr>
<td>Total Phosphorus</td>
<td>1.4-12</td>
<td>0.1-2.8</td>
<td>0.04-0.4</td>
</tr>
<tr>
<td>Total Nitrogen</td>
<td>17-58</td>
<td>3.7-19</td>
<td>6-13</td>
</tr>
<tr>
<td>Ammonia-Nitrogen</td>
<td>23-38</td>
<td>0.2-6.7</td>
<td>0.2-4.6</td>
</tr>
<tr>
<td>Suspended Solid</td>
<td>20-750</td>
<td>1.3-36</td>
<td>0.4-16</td>
</tr>
<tr>
<td>pH</td>
<td>7.34-7.96</td>
<td>6.91-8.18</td>
<td>7.2-8.22</td>
</tr>
<tr>
<td>Total Organic Carbon</td>
<td>About 90</td>
<td>No data</td>
<td>6.1-8.8</td>
</tr>
</tbody>
</table>

Note: Data coming from Laboratory of Källby Wastewater Treatment Plant

Table 2 Testing Methods and Instruments

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Abbreviation</th>
<th>Methods</th>
<th>Instruments or laboratory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td></td>
<td>Glass electrode method</td>
<td>HI-98312</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>Glass electrode method</td>
<td>HI-98128</td>
</tr>
<tr>
<td>Colour (PCU)</td>
<td></td>
<td>Colourimetric platinum cobalt (ISO)</td>
<td>HI-83099</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td></td>
<td>Spectrophotometry (ISO)</td>
<td>HI-98703</td>
</tr>
<tr>
<td>Suspended solids (mg/L)</td>
<td>SS</td>
<td>Weight</td>
<td>Filter membrane 0.45μm</td>
</tr>
<tr>
<td>Total dissolved solids (mg/L)</td>
<td>TDS</td>
<td>Glass electrode method</td>
<td>HI-98312</td>
</tr>
<tr>
<td>Anionic surfactant (Linear alkylbenzene sulfonate) (mg/L)</td>
<td>LAS</td>
<td>Adaptation of the USEPA methods 425.1</td>
<td>HI-96769</td>
</tr>
<tr>
<td>Alkalinity(mg/L)</td>
<td></td>
<td>Bromocresol green</td>
<td>HI-83099</td>
</tr>
<tr>
<td>Dissolved oxygen (mg/L)</td>
<td>DO</td>
<td>Iodometric method (ISO)</td>
<td>HI-83099</td>
</tr>
<tr>
<td>Nitrate nitrogen (mg/L)</td>
<td>NO₃-N</td>
<td>Alkaline potassium persulfate digestion spectrophotometry</td>
<td>UV</td>
</tr>
<tr>
<td>Ammonia nitrogen (mg/L)</td>
<td>NH₃-N</td>
<td>Nessler</td>
<td>HI-83099</td>
</tr>
<tr>
<td>Nitrite nitrogen (mg/L)</td>
<td>NO₂-N</td>
<td>Diazotization</td>
<td>HI-83099</td>
</tr>
<tr>
<td>Total Phosphorus (mg/L)</td>
<td>TP</td>
<td>Amino acid</td>
<td>HI-83099</td>
</tr>
<tr>
<td>Biological oxygen demand 7days (mg/L)</td>
<td>BOD₇</td>
<td>SS-EN 1899-1</td>
<td>VASYD lab</td>
</tr>
<tr>
<td>Chemical oxygen demand(mg/L)</td>
<td>CODCr</td>
<td>Potassium dichromate method (ISO)</td>
<td>HI-83099</td>
</tr>
<tr>
<td>Table 3 The monitoring results and limits in Chinese reclaimed water quality standards</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------------------------------------</td>
<td>-----------------</td>
<td>------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td><strong>Indicators</strong></td>
<td><strong>Eff.</strong></td>
<td><strong>Pond 1</strong></td>
<td><strong>Pond 2</strong></td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>Range</td>
<td>9.0-20.4</td>
<td>2.0-19.8</td>
</tr>
<tr>
<td></td>
<td>Ave.</td>
<td>15.5</td>
<td>13.5</td>
</tr>
<tr>
<td></td>
<td>Limits</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>pH (Dimensionless)</td>
<td>Range</td>
<td>6.4-7.5</td>
<td>6.6-8.4</td>
</tr>
<tr>
<td></td>
<td>Ave.</td>
<td>6.9</td>
<td>7.1</td>
</tr>
<tr>
<td></td>
<td>Limits</td>
<td>a: 5.5-8.5; i: 6.5-9.0; u,s:6.0-9.0; g1: 6.5-8.5</td>
<td></td>
</tr>
<tr>
<td>Color (PCU)</td>
<td>Range</td>
<td>39-172</td>
<td>54-193</td>
</tr>
<tr>
<td></td>
<td>Ave.</td>
<td>98</td>
<td>108</td>
</tr>
<tr>
<td></td>
<td>Limits</td>
<td>i, u, s, g1: 30; g2: 15</td>
<td></td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>Range</td>
<td>1.24-6.70</td>
<td>1.96-13.40</td>
</tr>
<tr>
<td></td>
<td>Ave.</td>
<td>2.74</td>
<td>5.70</td>
</tr>
<tr>
<td></td>
<td>Limits</td>
<td>i : 5/10/20; s: 5/NR; g1 : 10; g2 : 5</td>
<td></td>
</tr>
<tr>
<td>TDS</td>
<td>Range</td>
<td>270-840</td>
<td>280-840</td>
</tr>
<tr>
<td>Parameter</td>
<td>Unit</td>
<td>Ave.</td>
<td>Range</td>
</tr>
<tr>
<td>-----------</td>
<td>------</td>
<td>------</td>
<td>-------</td>
</tr>
<tr>
<td>Hardness</td>
<td>mg/L</td>
<td>120,6</td>
<td>123,5</td>
</tr>
<tr>
<td>CaCO₃</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TP</td>
<td>mg/L</td>
<td>87.1</td>
<td>90.5</td>
</tr>
<tr>
<td>Phophenol</td>
<td>mg/L</td>
<td>11.7</td>
<td>4.7</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>mg/L</td>
<td>87.1</td>
<td>90.5</td>
</tr>
<tr>
<td>LAS</td>
<td>mg/L</td>
<td>30-160</td>
<td>45-145</td>
</tr>
<tr>
<td>Chloride</td>
<td>mg/L</td>
<td>20-75</td>
<td>16-85</td>
</tr>
<tr>
<td>BOD₅</td>
<td>mg/L</td>
<td>3.23</td>
<td>3.22</td>
</tr>
<tr>
<td>NH₄-N</td>
<td>mg/L</td>
<td>0.1-5</td>
<td>0.05-3.75</td>
</tr>
<tr>
<td>NO₃-N</td>
<td>mg/L</td>
<td>2.9-30.0</td>
<td>1.8-24.3</td>
</tr>
<tr>
<td>NO₂-N</td>
<td>mg/L</td>
<td>0.01-0.10</td>
<td>0.01-0.10</td>
</tr>
<tr>
<td>TP</td>
<td>mg/L</td>
<td>0.1-3.9</td>
<td>0.1-1.5</td>
</tr>
<tr>
<td>Phenol</td>
<td>mg/L</td>
<td>0.10-0.20</td>
<td>0.10-0.20</td>
</tr>
<tr>
<td>Hardness</td>
<td>mg/L</td>
<td>120.6</td>
<td>123.5</td>
</tr>
<tr>
<td>CaCO₃</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parameter</td>
<td>Unit</td>
<td>Range</td>
<td>Ave.</td>
</tr>
<tr>
<td>-----------</td>
<td>------</td>
<td>-------</td>
<td>------</td>
</tr>
<tr>
<td>Fe (mg/L)</td>
<td></td>
<td>0.51-3.88</td>
<td>1.92</td>
</tr>
<tr>
<td>Mn (mg/L)</td>
<td></td>
<td>0.028-0.183</td>
<td>0.063</td>
</tr>
<tr>
<td>Cr&lt;sup&gt;6+&lt;/sup&gt; (µ g/L)</td>
<td></td>
<td>2-75</td>
<td>19</td>
</tr>
<tr>
<td>As (µ g/L)</td>
<td></td>
<td>0.757-3.216</td>
<td>1.362</td>
</tr>
<tr>
<td>Cd (µ g/L)</td>
<td></td>
<td>0.005-0.063</td>
<td>0.017</td>
</tr>
<tr>
<td>Hg (µ g/L)</td>
<td></td>
<td>0.001-0.029</td>
<td>0.010</td>
</tr>
<tr>
<td>Pb (µ g/L)</td>
<td></td>
<td>0.001-0.354</td>
<td>0.112</td>
</tr>
<tr>
<td>FC (st/100mL)</td>
<td></td>
<td>2.40×10&lt;sup&gt;-3&lt;/sup&gt;-2.49×10&lt;sup&gt;3&lt;/sup&gt;</td>
<td>1.19×10&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>EC (st/100mL)</td>
<td></td>
<td>7.55×10&lt;sup&gt;-4&lt;/sup&gt;-1.20×10&lt;sup&gt;5&lt;/sup&gt;</td>
<td>4.37×10&lt;sup&gt;5&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Note: a: agriculture irrigation; i: industry use; u: urban non-potable use; s: scenic environment use; g1: groundwater surface recharge; g2: groundwater injection recharge; NR: no requirements; ND: none detected; -: the indicator is not included in the standard; /: the separated of different limits for the detailed classifications in that kind of applications
Table 4 Explained variance of rotated PCA (%)

<table>
<thead>
<tr>
<th>PC</th>
<th>Eff.</th>
<th>Pond 1</th>
<th>Pond 2</th>
<th>Pond 3</th>
<th>Pond 4</th>
<th>Pond 5</th>
<th>Pond 6</th>
<th>All data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19.82</td>
<td>21.50</td>
<td>24.15</td>
<td>21.58</td>
<td>19.58</td>
<td>27.26</td>
<td>25.37</td>
<td>18.47</td>
</tr>
<tr>
<td>3</td>
<td>11.38</td>
<td>13.09</td>
<td>14.66</td>
<td>14.05</td>
<td>17.28</td>
<td>14.67</td>
<td>14.32</td>
<td>12.68</td>
</tr>
<tr>
<td>4</td>
<td>10.75</td>
<td>12.38</td>
<td>12.82</td>
<td>13.20</td>
<td>14.10</td>
<td>11.69</td>
<td>14.10</td>
<td>12.67</td>
</tr>
<tr>
<td>5</td>
<td>10.70</td>
<td>10.32</td>
<td>11.63</td>
<td>11.20</td>
<td>13.50</td>
<td>8.73</td>
<td>9.53</td>
<td>10.15</td>
</tr>
<tr>
<td>6</td>
<td>9.07</td>
<td>8.10</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>9.18</td>
<td>-</td>
</tr>
<tr>
<td>Accumulation</td>
<td>77.01</td>
<td>81.60</td>
<td>82.43</td>
<td>81.41</td>
<td>81.90</td>
<td>83.91</td>
<td>87.60</td>
<td>68.83</td>
</tr>
</tbody>
</table>

Note: "-" means elimination

Table 5 Correlation coefficients with significance p<0.001 for water quality indicators in pond 5

<table>
<thead>
<tr>
<th></th>
<th>COD&lt;sub&gt;c&lt;/sub&gt;</th>
<th>Turbidity</th>
<th>NH&lt;sub&gt;4&lt;/sub&gt;-N</th>
<th>NO&lt;sub&gt;2&lt;/sub&gt;-N</th>
<th>NO&lt;sub&gt;3&lt;/sub&gt;-N</th>
<th>TDS</th>
<th>Colour</th>
<th>FC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbidity</td>
<td>0.73</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO&lt;sub&gt;2&lt;/sub&gt;</td>
<td></td>
<td>0.75</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Colour</td>
<td>0.78</td>
<td>0.82</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FC</td>
<td></td>
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<td>0.76</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>EC</td>
<td></td>
<td></td>
<td></td>
<td>0.70</td>
<td>-0.66</td>
<td>0.86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>0.76</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.64</td>
</tr>
</tbody>
</table>
Figure 1(a): Bi-plot of component 1 and 2

Figure 1 (b): Bi-plot of components 2 and 3
Figure 1(c): Bi-plot of component 3 and 4

Figure 1(d): Bi-plot of component 4 and 5
Paper V

Discussion on stakeholders of water reuse

Shuang Liu, Kenneth M Persson

Water Policy (submitted)
Discussion on Stakeholders of Water Reuse

Shuang Liu, Kenneth M. Persson

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Abstract

To deal with the water crisis, water reuse is one of the most important methods and widely carried out all over the world. Nevertheless, there are many obstacles and challenges which make the development of water reuse not as sound as expected. The development of water reuse is affected by multiple factors, such as management, investment, quality, policy, laws and regulations which are related to different stakeholders. The stakeholders’ behaviour and acceptance are the key factors for promoting and realising sustainable water reuse. Although stakeholders’ analysis and management have been used in integrated water resources management, there is less study and analysis of stakeholders in particular for water reuse.

The paper identifies the key stakeholders of reclaimed water which are, namely, policymakers, administrators, suppliers, investors, customers, the public, researchers, land users and other waters sectors, and analyses their interests and impact on water reuse and interaction, as well as how to improve the stakeholders’ acceptance to promote the sustainable development of water reuse. The paper also analyses the challenges and strategy for sustainable water reuse in China from the perspective of the stakeholders’ communication and participation.

Keywords: water reuse, stakeholders, acceptance, interaction, communication

Introduction

Water reuse has been carried out in many countries for dealing with a water shortage and improving water environmental protection since water crises are increasingly serious. Although much progress has been made, there are still many challenges and problems regarding different aspects, such as management, investment, quality, price, policy, laws and regulations which are related to different stakeholders, making the development of water reuse not as sound as expected. More efforts and contributions should be made by stakeholders of reclaimed water to promote the sustainable development of water reuse.
A stakeholder, described as Freeman's now-classic definition (Freeman, 1984), is "any group or individual who can affect or is affected by the achievement of the organization's objectives". In other words, stakeholders are the actors (persons or organisations) who manage, work with, directly or indirectly contribute to, have a vested interest in or are affected in a positive or negative manner by the programme of work or its outcomes (Schmeer, 1999; WRMS, 2000; Llewellyn, 2009). Stakeholders’ analysis and management are important to the successful development and implementation of projects, and the stakeholders theory has been increasingly used by policy-makers, regulators, governmental and non-governmental organisations, businesses and the media (Friedman and Miles, 2006) in many different fields for different purposes, such as corporations, management and decision makers.

Stakeholders’ participation is considered to be an important part in integrated water resources management, as well as important for water reuse, since reclaimed water is a kind of marginal water, and it cannot develop without the participation of stakeholders. There are some case studies for communication with stakeholders in water reuse projects, such as the study on stakeholders’ attitudes toward the reuse of treated wastewater by Ogilvie, Ogilvie & Company (2010), the survey of public perception regarding water reuse in Arizona by Rock et al. (2012), the participation of stakeholders in the project of recycled water study in the city of San Diego (Brown and Caldwell, 2012), the participation of stakeholders in the recycled water program for the city of Los Angeles, etc.

The stakeholders’ acceptability and contribution are significant for the application of reclaimed water, since their behaviours directly or indirectly influence the factors such as management, investment, quality, policy, laws and regulations, which affect the development of water reuse. As an unconventional water resource, reclaimed water is an emerging concept compared to conventional water. Additionally, the source of reclaimed is probably the treated wastewater which contains chemical and microbial pollutants to some extent. The prejudices and misconceptions happen easily, which make some obstacles for acceptance by stakeholders and the participation not as positive and effective as expected. Additionally, the failure of communication and participation of stakeholders probably causes the problems during the implementation of water reuse projects. Thus, how to improve the stakeholders’ acceptance and promote the application of reclaimed water from the perspective of stakeholders’ participation and contributions is one of the crucial problems for the development of water reuse.

The paper identifies the key stakeholders of reclaimed water which are named policymakers, administrators, suppliers, investors, customers, the public, researchers, land users and other waters, and analyses their interests and impact on water reuse and interaction, as well as studies on how to improve the stakeholders’ acceptance to promote
the sustainable development of water reuse. The paper also analyses the challenges and proposals strategy for sustainable water reuse in China from the perspective of the improvement of stakeholders’ communication and participation.

**Identify the key stakeholders of reclaimed water**

Identification of the stakeholders is the first step of stakeholder management. Identification of key stakeholders who have a significant influence upon or importance within the project of water reuse is the important basis for further analysis. A stakeholder map, which can identify all interested parties both inside and outside the project, is helpful for identifying the stakeholders (Llewellyn, 2009). There are several commonly used techniques for stakeholder mapping, such as the Power/Influence vs. Interest Grid, the Power/Dynamism Matrix, the Power/Legitimacy and Urgency Model, the Problem-Frame Stakeholder Map and the Participation Planning Matrix (Ham, 2011). The Power-Impact Grid developed by the Office of Government Commerce, UK (2003) and the Influence-Interest Grid developed by Imperial College, London (2007) are in combination used in this paper since the techniques can determine the communication needs by the stakeholders’ interests and power/influence, which are important characteristics of stakeholders and necessary for stakeholders’ management. The Influence-Interest Grid is shown in Figure 1, and the list of key stakeholders for the water reuse project which includes the analysis of stakeholders’ impacts and interests is shown in Table 1. The stakeholders with both high influence and interest should be fully engaged; high influence but low interested stakeholders should be provided sufficient information to ensure that they are up to date but not too much; low influence but interested stakeholders should be adequately informed to ensure that no major issues arise; and low influence and low interested people should be minimally communicated to prevent boredom (Imperial College, 2013).

![Figure 1 Influence - Interest Grid](Imperial College London, 2007)
Table 1 List of key stakeholders for water reuse

<table>
<thead>
<tr>
<th>Stakeholders</th>
<th>Power/ Influence</th>
<th>Interest</th>
<th>Communication needs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Policymakers (central and local government)</td>
<td>High Impact on multiple aspects, such as the management, investment and market, leading the level and direction of development by formulating and promulgating relevant policy, planning and strategy</td>
<td>High Have interest in the outcome of water reuse (environmental and economic benefit)</td>
<td>Actively Engage</td>
</tr>
<tr>
<td>Administrators (different levels of administrative departments and reclaimed water companies)</td>
<td>High Impact on the process of production, supply and use, as well as the market development by developing the management and supervision system, including laws, regulations and guidelines</td>
<td>Low Have interest in the sound operation of the water reuse system and market</td>
<td>Keep Satisfied</td>
</tr>
<tr>
<td>Supplier /maintainer (reclaimed water companies and plants)</td>
<td>High Impact on production (facilities, reclaimed water quality) and supply</td>
<td>Medium Have interest in good service and the resulting benefit</td>
<td>Keep Satisfied</td>
</tr>
<tr>
<td>Investors</td>
<td>High Impact on the investment and price. Provide funding and get profit from the service of reclaimed water supply</td>
<td>High Have interest in the economic benefit</td>
<td>Actively Engage</td>
</tr>
<tr>
<td>Customers (farmers, industries, municipalities, residents, and service sectors, such as hotels, the car wash industry, golf courses, office buildings and schools)</td>
<td>High Impact on the use and the market of reclaimed water, as well as the feedback to policymakers, administrators and investors.</td>
<td>High Have interest in the reclaimed water service and resulting economic benefit</td>
<td>Actively Engage</td>
</tr>
<tr>
<td>Public (communities, NGOs, media)</td>
<td>High Impact on multiple aspects, such as policymaking, investing, research and users’ acceptability. Support or oppose the use of reclaimed water in different ways, such as feedback to policymakers, providing funding and the communication platform for researchers, propaganda in media.</td>
<td>Medium Have interest in the environmental benefit from water reuse</td>
<td>Keep Satisfied</td>
</tr>
<tr>
<td>Researchers</td>
<td>High Provide advanced technology for the production and distribution to reduce the cost and methods for better management</td>
<td>Medium Have interest in the practical application of the technology</td>
<td>Keep Satisfied</td>
</tr>
</tbody>
</table>


### Interaction of different stakeholders

The stakeholders are not self-existent. Their behaviours are affected by each other. The principle interaction of key stakeholders is shown in Figure 2.

![Figure 2 Interactions of stakeholders of reclaimed water](image)

Policymakers, which are always central and local governments, are one group of the critical stakeholders since they have decision-making power and can decide the level and lead the direction of development by formulating and promulgating relevant policy, planning and strategy. In a centralised country like China, the importance of involving policymakers is crucial for the potential success of water reuse. In general, policymakers affect almost all other stakeholders, and this is particularly true for China. The
administrators develop management and supervision systems, such as guidelines and regulations which are based on related policy to control the production, supply and use of reclaimed water. For investors, what is most concerning is the economic benefit from the investment for the water reuse industry. Thus, investors’ decisions are greatly affected by the policy related to the investment and market development. Policy orientation also has an impact on the customers to use reclaimed water, since customers’ behaviours are required to some extent by the laws and regulations which are formulated based on relevant policy. As researchers, their aims are to provide scientific and technological solutions to solve the problems for societal development. The policy orientation and the water crisis are the basis and the power for researchers to do the relevant studies, and the supported policy is the guarantee for the successful implementation of research and can guide the direction of research. As reclaimed water is one part of the water environment and the use of reclaimed water and any adjustment of the utilisation inevitably have an impact on the water environment and other waters, the policymakers also can influence the other water utilisation and water resources situations through the formulation and adjustment of the policy of water reuse, such as charges and subsidies policy, water saving policy and water pollution control policy. For the implementation of water reuse, there are undoubtedly the policies related to the collection of wastewater which can affect the land users since the treated wastewater is the source of reclaimed water and the effective collection of wastewater is the premise of reuse. On the other hand, policymakers’ behaviours are also affected by other stakeholders since they need to develop the policies in line with the requirements of related stakeholders and check the effect of existing policies as well as revise them according to the feedback from others. The water resources status, acceptability of customers, the attitude of the public, the requirements of investors and the research results from researchers are the significant basis for policymakers to develop and adjust the relevant policies. Policymakers can be seen as a ‘hub’ of all stakeholders, since they directly and indirectly affect other stakeholders, accept the feedback, make adjustments and influence others again. The circle constantly improves the operation of the whole system and promotes the sound development.

Besides policymakers, customers are also critical stakeholders, since they can directly decide the use of reclaimed water and affect the development of the market. Thus, their attitude directly affects the investors’ interest in investing. Similar to policymakers, customers’ attitudes and behaviours are affected by multiple factors, including quality of service, the risk and the safety of water reuse, the reclaimed water quality and the benefit expressed as price and subsidies, which are related to administrators, suppliers, researchers and policymakers. The situation of other water resources also influences the selection of customers, since the water situation can be reflected in terms of the economical form or policy-otted. The impact from the public is mainly by the media environment. For example, the media, which is the main information source for most customers, can spread
the related knowledge, research results and positive/negative opinions from communities in different ways, which can probably affect the customers’ attitude to reclaimed water since reclaimed water is an unconventional water resource and not as familiar as other types of water, combined with the controversy happening in all fields. In Singapore, the media has been a very important actor to inform of the Singaporean water reuse system, the New-water concept.

For administrators, besides policymakers, it should also be affected by the public in terms of inspection, which does not happen as expected in some countries and regions. The lack of public participation in the management system is one of the obstacles regarding communication by stakeholders and not conducive to the implementation of water reuse. Additionally, administrators also receive the feedback from customers to improve the management for fulfilling the customers’ requirements. At the same time, the administrators’ behaviour, such as management efforts, directly affects the quality of the reclaimed water supply through the management and supervision system, thus, impacting the suppliers’ behaviour and the customers’ satisfaction.

The suppliers, who are responsible for the production and supply of reclaimed water, are the stakeholders the most close to the water quality and service, which have the greatest concern of the customers. Thus, the suppliers’ behaviour has a significant impact on that of the customers. Additionally, the suppliers’ demands always provide topics to researchers and affect the study direction. In addition to administrators, the suppliers are also impacted by researchers who can provide advanced technology to improve the service, and the investors who provide funding for the whole reclaimed water production and supply system.

The public, including communities, NGOs and the media, is also a stakeholder who affects and is affected by multiple stakeholders. Besides the analysis above, its attitude to water reuse is mainly affected by the situation of water resources and the studied results from researchers. In addition, it influences the researchers in several ways, such as by providing the communication platform and funding support to the research projects, as well as propaganda for the results by media.

As the stakeholders directly or indirectly connect with each other, the poor functioning or mistake in any one link probably leads to a vicious circle in the whole system and obstructs the development of water reuse. For example, the inadequately supported policy for investment probably affects the investors’ interest in investing, which lowers funding for the reclaimed water production and supply as well as possibly influences the reclaimed water quality, and thus makes the customers’ satisfaction decrease. In addition, the poor feedback that lowers the interest in use from customers perhaps makes the policymakers reduce the supported policy, which forms a vicious circle. The definiteness of the
interaction between the stakeholders can greatly contribute to keeping the system well-functioning and promote water reuse by improving the perspective of the behaviours of different stakeholders, which is possible to be positively or negatively affected by each other and form a combined effect regarding water reuse.

**Improvement of stakeholders’ acceptance of water reuse**

According to Johnson et al. (2008), acceptability is one of the factors on which the success of a strategy depends. The strategy is acceptable if it could meet the identified stakeholders’ expectations including expected return (financial and non-financial benefits) and the expected level of risk (probability and consequences of a failure) (Kukkula et al. 2009). The acceptance of reclaimed water by the key stakeholders, which is more difficult to reach but more importantly needed for reclaimed water than other water resources in that reclaimed water is a special and emerging water and controversy always happens, is the premise of the reality of the sound development of water reuse. Stakeholders’ acceptance is impacted by the behaviour of others. How to improve the acceptance is discussed from the perspective of the policymakers, investors and customers in this part since they are in charge of decision making, funding and use, respectively, which are significant factors directly affecting the market of reclaimed water.

For policymakers, their expectation is to obtain environmental benefits from water reuse, such as fresh water saving and reducing pollution in the water environment. The risk is that the failure of strategy and policy probably causes the dissatisfaction and lack of support by other stakeholders, especially by customers and the public, which can lead to that the investment (human and material resources) cannot be paid back and the objective cannot be reached. The acceptance by policymakers is dependent on two aspects: the situation of water resources and the environment, and the feedback from other stakeholders, especially from researchers and customers. One of the main factors which can improve the acceptance of water reuse by policymakers and induce their decisions is that situations are becoming increasingly serious regarding water shortages and the deteriorating water environment which forces the policymakers to develop and accept the reclaimed water to deal with the water crisis; another is the superiority of the reclaimed water of stable and cost-effective water sources, which causes it to be accepted by policymakers when compared to other solutions, especially in developing countries. Also, the effective support obtained from researchers, such as advanced technology and research findings which can provide technology guarantees for the safety of water reuse, can greatly increase confidence and improve the acceptance by policymakers. Further, support from both the public and customers is also an important aspect for the acceptance by policymakers, since the ultimate goal of the work of policymakers is to provide service for them and be beneficial for the community.
As analysis regarding Table 1, the investors’ expectation is financial benefit from water reuse and the risk is economic losses which are caused by the customers’ resistance to use reclaimed water and resulting in the recession of the market. The improvement of investors’ acceptance is greatly affected by policymakers who can make policy to ensure investors’ interests and increase the investors’ confidence in the water reuse industry, and the customers’ perceptions which directly decide the sale and market of reclaimed water. If the water pricing is inadequate, such as is the general case in China (Liu and Persson, 2013), the investors may find it very complicated to cover their actual costs for water reuse investments.

Through the above analysis, it can be seen that the customers’ perceptions are greatly affected by the policymakers’ and investors’ acceptance of water reuse. The improvement of the customers’ acceptance is critical to the development of water reuse. The expectations of customers are to obtain a high quality water supply and service as well as the resulting economic benefit of using reclaimed water (lower price than other water). The risk concerning this is the harm for health and the environmental risk caused by using reclaimed water. The fundamental way for the improvement of the customer’s acceptance is to reduce their concern about risk and to provide good service regarding the safety and high quality of the reclaimed water supply. Actually, with the development of technology, treatment processing is not the critical constraint for the development of water reuse. The advanced treatment trains, such as activated carbon adsorption, coagulation and sedimentation, and membrane technology, generally can reduce the concentration of organic contaminants (e.g. pharmaceuticals, personal care products, and illicit drugs) and microbial pathogens in the wastewater to a relatively safe level which rarely poses acute risks to public health or aquatic ecosystems (Gerrity et al., 2011; Gerrity & Snyder, 2011). The health risks caused by using reclaimed water, which are the greatest concerns of customers and are always a common reason for resistance to the use of reclaimed water, should not be obstacles of water reuse if proper technology is used and security measures are strictly followed. Nevertheless, the concerns about the safety of reclaimed water quality, which are generally unfounded (Rock et al., 2012) are still the important factors affecting the customers’ acceptance of reclaimed water. Correcting the misconception and making the users trust the proof of the safety of reclaimed water is important to the improvement of the acceptance of reclaimed water. For improving the acceptance by the customers, some methods could be helpful. Firstly, in order to clear what the problems are, the solution can be to find out. The data of the perceptions of different groups of customers should be collected, which is the first step for the improvement. The information about genders, ages, education and cultural background, major information sources, the experience of using reclaimed water, the reasons of using/resistance to use, the expectations and suggestions for further water reuse, which could influence the perceptions should be investigated and analysed. The survey should be targeted to and distinguished
regarding different groups of customers and carried out in multiple ways such as a questionnaire, an individual interview and a telephone interview, which are suitable for different groups. Further, the building of a platform for the participation of customers is an important way for improving acceptance, since it is not only a process for getting feedback but also more importantly, the participation makes customers feel as if they have an initiative in the decision rather than passively accepting which always leads to antagonism and resistance. The long-term communication strategy should also be formulated. The conceptual changes which are not possible to complete overnight need long-term sustainability and subtle influence. The education and propaganda of relevant knowledge and information should be strengthened by all kinds of forms, such as school education, media (network, newspaper, radio and TV), gallery, education centres and leaflets. The education and propaganda should not only include the advantages, but also the potential risks and more importantly, how to control and avoid the risks in order to obtain more safe water reuse. People do not always trust or use that which they do not know or control well, especially the reclaimed water as it is related to their health and economic benefit. The comprehensive introduction (both positive and negative aspects) is help to increase the customers’ trust of the advocates and better control the reuse, and thus promote the acceptance of reclaimed water. Additionally, the education of youth should be made through more efforts, as the youth can more easily accept the new conception and influence in comparison to the older people in some ways. Also, the demonstration projects are important to the customers’ acceptance; the water reuse surveys mentioned by Hartiey (2006) indicated that people are more trusting of their own intuition than conclusions based on peer-reviewed scientific research (Hartiey 2006). Thus, the facts of successful demonstration projects are more convincing than the theory or the proof from researchers for improving customers’ acceptance. Certainly, the qualified reclaimed water and good service is the basic guarantee of customers’ acceptance. Once the unqualified reclaimed water supply happens, the trust is difficult to recover, and it probably affects the perceptions of others, since it is a modern world with information exchanged at high speed.

Challenges and Strategy for stakeholder participation and its application in water reuse in China

In China the research for stakeholders theory started from the middle of the 1990s and is still in the initial stage (Zhang, 2011). Nevertheless, as the rulers introduced the idea of public participation in mainstream ruling ideas and ideologies for governance in the middle of the first decade of the 21st century, the stakeholders theory, especially the public participation in the management systems in fields such as sustainable development, has been developed in an ongoing way and implemented with experience from less to more (China Dialogue, 2012). Much progress has been made, such as modern means of communication, e.g. the internet and mobile phone, providing technical support for
stakeholders’ participation, the successive development and implementation of relevant laws, regulations and policy, such as the ‘PRC Price Law’ (Presidential Decree [1997] No. 92) and the ‘Environmental Information Disclosure Measures’ (State Environmental Protection Administration (SEPA) Order No. 35), regulating relevant aspects to promote public participation to some extent and to provide legal protection, the development and participation of nongovernmental organisations (NGOs), public participation and centralised actions in an unorganised state which increase and affect the decision-making process. There are successful cases of public participation in or affecting the decision-making process (China Dialogue, 2012). For example, in 2005, Yuanmingyuan Management Office drained the lake and laid large-scale impermeable membrane without an environmental impact assessment (EIA), which is widely questioned by society. SEPA held the first EIA public hearings on the matter, and the project eventually required the rectification; in 2007, thousands of residents processioned to resist the plan of construction of the PX chemical plant in Xiamen. Fujian Provincial Government and the Xiamen city government finally decided to obey public opinion, and the project was moved to Zhangzhou; in 2012, the State Council agreed to add the detection index of PM2.5 into the newly revised "ambient air quality standards", which was carried out four years earlier than scheduled in some areas encouraged by the public because of continuing haze which shrouded Beijing that caused much discussion about air quality over the internet. From the successful practice, it can be seen that the public awareness of the dominant position in participation is increasingly strengthened with the development of education and economy. The government being open and having a positive attitude to public opinion and timely feedback action are crucial to the success of public participation.

Although stakeholders’ participation has been successfully realised in some cases, it is still not universal. There are major reasons, such as the following: The relevant laws and regulations should be improved since public participation is not regulated as an essential link that is expressed as ‘ought’ or ‘should’, which makes such laws and regulations with a strong line, principles and policies of the mean and great flexibility in the implementation rather than explicitly mandatory. The regulation about public participation is too principled without any clear details of procedure and implementation steps (Li and Zhao, 2012). In addition, the governance model in China is profoundly impacted by traditional unilateral governance theory of ‘shareholder primacy theory’. It needs a long time, whether for administrators and policymakers or the public to accept and apply stakeholders theory. Also, as a populous country the public participation in China is traditionally an indirect participation in the form of ‘representative’, which reduces the public awareness to directly participate. The change in the forms of participation need long-term preparation, such as platform construction, supported laws and policy. Further, the educational level, personal qualities and ability are sometimes constraints for effective participation, since in some areas, especially the vast rural areas, the educational attainment is normally relatively low.
As Chinese citizens' awareness of their rights are being fully aroused as well as the development of economy and education, the multilateral governance especially the public direct participation should be inclusive and involved in the management parties since the traditional indirect participation sometimes cannot reflect all stakeholders’ demands because the interests and needs are increasingly diversified in modern society. Additionally, if the stakeholders’ interests and rights do not get sufficient attention, their initiative probably decreases which causes the projects to not be able to obtain enough support from them, and thus the integrated benefit will be reduced and even produce failure. Also, as stated in the analysis above, any stakeholders’ behaviour will affect the behaviour of others, and the missing of any stakeholders’ role will cause integrated loss. Only if all planks are long enough, the barrel can contain more water. All stakeholders’ effective participation is vital for the successful implementation of projects.

China is a developing country with a severe water crisis, which is well documented in the literature and bulletins (Hong, 2003; Yang, 2004; Yan, 2004; Yu, 2004; Ministry of Environmental Protection of China, 2011). Non-potable water reuse is an appropriate method to deal with the water crisis for China since it can both save freshwater and reduce pollution to the environment, as well as is cost-effective. However, for several reasons non-potable water reuse is still not developing as soundly as might be expected although some progress has been made. Of all reasons, the inadequate communication and participation of stakeholders are those which are responsible for many problems such as cost coverage, management, supervision and public participation, which obstructs the development of water reuse.

Although stakeholders theory is increasingly concerned, there is seldom relevant research and application of the stakeholders’ analysis in the field of water reuse in China. Besides the causes discussed above, the characteristic of reclaimed water itself is another reason for the absence. From the practical cases listed above, it can be seen that in the initial stage of application of stakeholders theory, what the public is highly concerned about and actively participating in to affect decision-making are the affairs very close to their benefit especially those which are a threat to health. At present, many people do not have the right understanding of the water crisis in China. Water reuse has not been carried out popularly and sophisticatedly, and its benefits and potential risks, which are not shown as obviously as air pollution and chemical pollutants, are not known well by the public. Thus, water reuse does not become concerned about sufficiently by the stakeholders, such as administrators, policymakers, investors and the public. The communication and participation of stakeholders is a weak link in the development of water reuse, which is reflected in the following aspects: there are not enough laws, regulations and supported
policy provided by administrators and policymakers (Liu and Persson, 2013); the process of making decisions and policy about planning, production and allocation of reclaimed water is mainly decided by the government, without effective participation and observation by other stakeholders, especially the public (Zhang, et al., 2007); there is a lack of legal and institutional safeguards and platforms for public participation, which reduces the public acceptance of water reuse and also creates difficulties for the administrators and policymakers to collect feedback from the public; the communication between different administrative organisations is not enough which leads to confusion and conflicts (overlapping or vacant) in the management process; the inadequate communication between administrators and customers causes the service of reclaimed supply which cannot meet the requirements of customers, etc.

To promote the sustainable development of water reuse, the effective communication and participation of all stakeholders are important aspects, since the stakeholders’ behaviour and decisions are affected by each other and any act or omission of them can affect the overall benefit and result. Public participation is particularly important as China is a populous country and the reclaimed water supply is a service for the public. To improve the situation, the following strategies are recommended:

The improvement of relevant laws and regulations is a recommendation in order to provide a legal basis and guarantee for the participation of stakeholders. The general public always belongs to vulnerable groups (Li et al., 2008), which need legal support to contend with powerful interest groups and play the role better of the important part of the power operating mechanism. The dominant position of public participation should be regulated in the laws, and the details of participation procedure and implementation steps should be clearly elaborated to make the regulations more practical and executable. Also, what is mandatory should be strengthened in the expression of the law to make the stakeholders’ participation a compulsory part of the decision-making process.

Building effective and diversified communication platforms and mechanisms to make all stakeholders involved, not only between the different groups but also in the same groups of stakeholders is a recommendation as well, for example to provide funds and platforms such as research projects for researchers to study how to improve the safety of water reuse, e.g. the improvement of existing guidelines. Additionally, to promote the communication and co-operation of different administrators including administrative departments of other waters in the form of, for instance, regular meetings and seminars since reclaimed water is one part of water resources and the governance should be integrated but not overlapping or conflicting with what presently exists (Liu and Persson, 2013). Most importantly, set up the feedback channels in the form of, for instance, interviews, surveys and hearings, for customers and the public with policy and decision makers and administrators to improve
the public acceptance and participation and to ensure the effectiveness of public participation. The communication platforms for all stakeholders will greatly improve the management system of water reuse.

Establishing incentive mechanisms has the ability to stimulate public initiative in participation, which can increase the public acceptance of water reuse and help them to establish the concept of their own dominant position of stakeholders with corresponding rights and responsibilities. Improving the publicity of information and education of background knowledge (including benefits, potential risks and the ways to control risk) can be done to ensure that the customers and the public have enough ability to participate and give proper and effective feedback.

Another recommendation is to learn from the experience of domestic and foreign success stories. There are seldom cases for the application of stakeholders theory in the field of water reuse in China, but it is also possible to learn from successful examples in other fields which are listed in previous text. Also, there are some cases and studies from other countries such as the US where water reuse is more sophisticatedly carried out. For example, in a recycled water programme for the city of Los Angeles, to make more stakeholders involved, some activities were launched (Evelyn Cortez-Davis, P.E. and DeMonbrun, C., 2011), such as meeting with City Council Offices, identifying key stakeholders and concerns, meeting with key stakeholders and community leaders including neighbourhood councils, and soliciting stakeholder input on the Recycled Water Master Planning Document during its development. The participating stakeholders are over 1.5 million people with diverse representation of demographics, geography and interests, including a steering group, an advisory group and an information group. The advisory group can communicate directly with the Los Angeles Department of Water and Power and business owners, and five to eight workshops will be held per year for the next three to four years (Evelyn Cortez-Davis, P.E. and DeMonbrun, C., 2011). Methods could be learned combined with Chinese conditions, such as to solicit stakeholders’ opinions for planning, keeping long-term workshops and the establishment of the co-ordination group as a ‘bridge’ for communication and co-operation between different stakeholders, e.g. feedback from the public to administrators and suppliers.

It needs long-term work for the formulation and promulgation of laws, the change of concept and the improvement of education level, but the construction of communication platforms could more quickly be effective and could be viewed as an ‘easy’ start of stakeholder participation. For example, at the stage of the planning of water reuse projects, an investigation for relevant customers and the public could be done in different ways (internet, meetings, interviews and questionnaires) in order to collect stakeholders’ perceptions, such as what they are worried about, why they do not support the projects,
what they are interested in and the requirements. Then, improve the project according to the results of the survey to make the projects obtain more support and become successfully implemented. It can also help the stakeholders increase the awareness of their rights and responsibilities. The publicity of relevant information to keep stakeholders continuously informed about the details and progress of projects is also an effective way which could be implemented as the next step to make stakeholders, especially customers and the public, know more about water reuse for better participation; it can increase the trust of stakeholders in administrators and suppliers as well, which is the basis of other activities.

Summary

Stakeholders’ analysis has been applied in more fields since the 1960s and is considered to be an effective method for the management of projects (Zhang and Li, 2006). The projects cannot be carried out successfully without the support and participation of stakeholders, especially in the field of water reuse which is an emerging unconventional water resource where controversy has always existed. The effective communication of stakeholders is the premise and basic way of solving the problems which obstruct the development of water reuse.

The key stakeholders for water reuse are policymakers, administrators, suppliers, investors, users, the public, researchers, land users and other waters, which have different interests in and impacts on water reuse. Their behaviour is directly or indirectly affected by the other’s and the clarity of interaction is significant to the project’s management, such as the poor functioning or mistake in any one link probably leads to a vicious circle in the system and influences the overall benefit and result. The stakeholders’ acceptance is also critical to the implementation of water reuse projects, especially the customers’ acceptance since it greatly affects the acceptance by others. The factors affecting the acceptance and the ways for improving the stakeholders’ acceptance are discussed in the paper.

For China, some aspects should be improved for the sustainable development of water reuse from the stakeholders’ perspective since the communication and the participation of stakeholders are the weak links and have caused problems in the process of management and implementation. The legal basis and guarantee, communication platforms, publicity of information and education of background knowledge, as well as incentive mechanisms are needed for stakeholders to play the role better and promote the sound development of water reuse. The path for more stakeholder involvement in China has however been opened and must undoubtedly be continued in the future. There is no way back if safe and successful water reuse should be implemented.

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