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Probabilistic Assessment of Recycled Water Schemes in Australia Using MATLAB Toolbox

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ABSTRACT
Hundreds of recycled water schemes have been successfully established in Australia. However, water quality and risks on human health and the environment associated with particular end uses (e.g. irrigation, industrial uses, non-potable urban uses, groundwater recharges, indirect and direct potable reuses) are still of great concern which can limit the application and extension of recycled water. This study analyses representative recycled water schemes in Australia with regard to the sources and corresponding risks of recycled water, risk assessment approaches as well as practical risk control methods towards various end uses. To quantify the risks, this study proposes a probabilistic assessment approach for existing and future water recycling schemes. With the assistance of MATLAB toolbox, the model was able to fit observed data to probability distribution functions (PDFs) and express the percent removal in PDF rather than point values. This approach could be helpful in quantifying risk or percent removal of potential hazards which involve a degree of variability and randomness. The analytical results, when couple with other environmental assessment tools are convinced to be useful for integrated water planning and management in Australia.

Keywords: Recycled water schemes; End uses; Probabilistic assessment; MATLAB

1. INTRODUCTION

While Australia is the driest inhabited continent on earth, its per capita total water consumption (642 kilolitres per person per year) and per capita domestic water use (81 kilolitres per person per year) is the third and second highest in the world respectively (ATSE, 2004; ABS, 2010). The use of water resources in many of larger Australian towns and cities (e.g., Sydney, Melbourne, Brisbane, Perth and Adelaide) is approaching the limits of sustainability due to highly variable climate, increased population, prolonged droughts and deteriorated freshwater quality. Within 20 years, they will run out of water based on the current water situations. As new reservoirs are politically and environmentally unacceptable, mandatory water restrictions have been implemented in most of the state and territory capital cities, which not only limit the socio-economic growth but also bring some inconvenience to people. To alleviate water scarcity and environmental concerns, recycled water is considered as one of the most important contributions to water sustainability, which is able to increase available water resources for non-potable applications as well as decrease nutrient and contaminant loads to surface and coastal waters (Stenekes et al., 2006). Present-

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ly, the amount of treated effluent being reused in Australia is still low compared with the total output from sewage treatment plants (STPs) and the water management is considerable inconsistency across local, state and territory governments. While South Australia and Victoria use greater than 19.2% and 14% of the treated wastewater respectively, the reuse rate is only about 2% to 3% in some of the largest urban centres in other states, including Sydney, Melbourne and Perth (Radcliffe, 2006). As a result, there is an obvious need to intensify the water recycling opportunities in urban Australia with an address on several issues (e.g., risk issues, treatment infrastructure costs, recycled water pricing policies, community attitudes, etc.). Particularly, risk issues in terms of human health, environmental and system error aspects are one of the decisive factors to the success and extension of the existing water recycling schemes since the concentrations of physical, chemical and microbial hazards in source waters are significantly variable over diurnal and weekly periods. Even if the recycled water is treated to high grade, the excessive chemicals or pathogens still potentially generate a certain degree of risk to human and the environment (Khan and McDonald, 2010). These problems also strongly affect public perceptions as the hard-earned community trust being lost by a single risk incident is likely to be long remembered and not readily forgiven, which will affect the public acceptability of future recycled water activities. An outbreak of illness caused by mismanagement of a dual water supply scheme in Netherlands in 2001 could be a good illustration. The lower quality of river water was supplied for non-drinking residential purposes, which has led to the abandonment of future water recycling schemes of this type (NRMMC-EPHC-NHMRC, 2006). Encouragingly, in a survey conducted by the Cooperative Research Centre for Water Quality and Treatment, 74% of 3000 respondents across five Australian capital cities expressed their willingness to drink recycled water if they could be assured of its safety (Lampard et al., 2010). As a result, Australia has been active in developing new guidelines and approaches such as the Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 1, 2A, 2B and 2C), to provide an stable framework for investment in water recycling as well as further guidance for quantifying, regulating and managing the risk of recycled water (Page et al., 2010). According to these guidelines, pathogens (e.g., viruses, bacteria and protozoa) are prime concerns in human health studies whereas excessive chemicals (e.g., trace organics, heavy metals and pharmaceuticals) as well as hydraulic and nutrient loading rates are highly addressed in the environmental risk assessment.

To further investigate the pathogenic or chemical risk, the construction of an assessment model plays an important role for any water recycling scheme. However, the qualitative (or semi-quantitative) model where the consequences and likelihood of potential hazards in recycled water are judged from individual or group’s degree of belief can only be used as an initial screening. Besides, Hamilton et al. (2007) have introduced a deterministic recycled water irrigation risk analysis (RIRA) model for Australian irrigation schemes. Although it is able to calculate many risk levels in a short period of time with a wide variety of irrigation scenarios, it fails to account for uncertainty associated with the parameters owing to its end-point structure. A more pragmatic and reliable approach, which has been gaining favour in recent years, is the application of probabilistic models which take into account of stochastic variables in quantitative microbial and chemical risk assessment. As stochastic approaches involve complicated mathematical calculations, the existing models are mostly relied on commercial softwares such as @risk or Crystal Ball which are costly and may not be a practical option for common users. Consequently, after a snapshot of the current recycled water use in Australia, this paper proposes a risk assessment framework with an emphasis on the use of MATLAB in probabilistic assessment for existing and future water recycling schemes. A case study on the Water Reclamation and Management Scheme (WRAMS) of Sydney Olympic Park Authority is conducted afterwards.

2. REPRESENTATIVE WATER RECYCLING SCHEMES IN AUSTRALIA

Currently, there are more than 580 different water recycling schemes being operating in Australia with many more in the planning and construction stages, where large-scale projects (more than 5,000 litres per day) have important contributions to water recycling targets as well as low public controversy since they are subject to stringent environmental regulations and policy controls (Stenekes et al., 2006). Consequently, large recycling schemes constitute the focus of this paper. With respect to different end uses, the agricultural and landscape irrigation projects remain the largest user of recycled water in Australia, including the Hawkesbury Water Recycling Scheme in Sydney (500 megalitres per year (ML/yr) of treated wastewater plus 200 ML/yr of treated storm water), the Virginia Pipeline Scheme in Adelaide (18 gigalitres per year (GL/yr)) and the Eastern Irrigation Scheme in Melbourne (11 GL/yr). These large-scale irrigation schemes have been successfully operated with the application of class A recycled water which involves tertiary treatment and pathogen reduction processes, enabling to irrigate many fresh vegetables that can be eaten raw as well as playing fields and gardens with no detrimental human health issues and environmental impacts. Moreover, water authorities have also recognized the opportunity of substantial water saving from residential areas by constructing dual-reticulation pipe systems for supplying recycled water for garden watering, toilet flushing, car washing, etc. The representative demonstrations throughout Australia include the Rouse Hill Water Recycling Scheme and the WRAMS in Sydney (2.2 GL/yr and 850 ML/yr, respectively), Mawson Lakes (800 ML/yr) and New Haven Village in Adelaide, Marriott Waters in Melbourne and Pimpama Coomera Scheme in Gold Coast, saving 30-50% of the household's total water demand (Wang, 2011; Willis et al., 2011). As recycled water from these schemes generally has high risk exposure to customers and potential cross connection errors, current water quality is subject to class A or even higher water quality standard, which can be achieved through advanced treatment technologies (e.g., microfiltration (MF), reverse osmosis (RO), chlorination and UV disinfection).

Regarding the industry, because of the mandatory water restrictions caused by severe drought conditions since 2003 but the constant high water demand, industrial recycling schemes have been expanded to about 80 together with the acceleration of the reuse rate by 25% in most industrial sectors (Stevens et al., 2008). Taking the state of New South Wales for example, the Eraring Power Station (4 ML/d) and the BlueScope Steel Corporation (20 ML/d) have used high-purity recycled water as cooling or boiler feed make up water which undergoes MF, RO, UV disinfection and demineralization processes. The BlueScope Steel has also conducted interdepartmental water reuse schemes (300 KL/d) to provide secondary treated water for internal quench basins. Similarly, the Mars Food Water Recycling Project has also adopted UF and RO to treat both food manufacturing wastewater and onsite stormwater for non-product utility purposes, saving 355 ML/yr of drinking water. Overall, although most of the existing recycling schemes in mining, refinery, fibre cement, commercial laundry and food processing industries have received wide public acceptance, recycled water in the industrial sectors with frequent exposure to workers should comply with the same health standards as for residential recycling schemes (ATSE, 2004). Additionally, other end uses such as environmental flow (e.g., river, lake, wetland and lake) recharge and groundwater recharge are also being explored, including the St Marys recycled water plant replacement flow project (18 GL/yr), the Bolivar recycled water aquifer storage and recharge (ASR) project (250 ML/yr), the Alice Springs soil aquifer treatment (SAT) project (600 ML/yr), etc. (Dillon et al., 2006). Despite the limited exposure to the public, some of the schemes (e.g., the Bolivar and the Alice Springs ASR projects) still receive environmental concerns in terms of salinity, nutrients, pathogens as well as trace organics thereby requiring risk controls based on relevant guidelines (Page, 2010). Furthermore, there have been a number of indirect potable reuse (IPR) projects (e.g., the Toowoomba in Queensland and the Quaker's Hill in Sydney) proposed in Australia during the last two decade, which have been faltered due to public misgiving. Nevertheless, by 2007, major IPR schemes such as the Western Corridor Recycled Water Project (WCRWP) in South East Queensland (232 ML/day) and the three-year trial of the Leederville aquifer replenishment for IPR in Western Australia (25-35 GL/yr) have been partially developed but their full implementation is yet to be realised (Khan, 2011). Considering the health risks associated with IPR schemes, chronic effects are of greater importance and need to be carefully considered. Till now, as the above two projects undertake the combination of MF, RO and advanced oxidation (or UV disinfection) for wastewater treatment and purification, they are successfully operated without the detection of risk problems. Comparatively, planned direct potable reuse (DPR) is not currently practiced and there are no known guidelines for DPR at present.

3. PROBABILISTIC RISK ASSESSMENT FRAMEWORK AND METHODOLOGY

Although the use of risk assessment framework from Australian water recycling guidelines was proved to be efficient in some of the above-mentioned schemes, it only describes the risk assessment execution steps without mention of any possible combination with other assessment tools. To establish a more comprehensive evaluation system in terms of health and environmental protection, this paper proposes a new framework in Figure 1 based on the risk assessment steps which have been successfully applied to nine Managed Aquifer Recharge projects in Australia. As can be seen, it outlines four stages of risk assessments and control measures with the integration of other environmental assessment tools to arrive at a sustainable water cycle development (NRMMC-EPHC-AHMC, 2009; Page et al., 2011).

According to the above framework, full assessment procedures in each stage related to water recycling schemes can be developed which are summarised below:

(1) Stage 1. The first thing is to conduct a desktop study by collecting all available information (e.g., the major type, location of the scheme and its ambient environment and involved residents, the capacity and treatment processes of the water recycling plant as well as the estimated environmental benefits against economic cost and energy consumption) for an entry level assessment. During this initial stage, the viability of the recycling project can be identified.

(2) Stage 2. In quantitative risk assessment stage, identifying hazards that are likely to present significant detrimental impacts on health and the environment is essential. As specified in Australian Guidelines for Water Recycling, for most of large-scale recycling schemes, campylobacter, rotavirus and cryptosporidium can be used as reference pathogens for bacteria, virus and protozoa respectively in microbiological risk studies whereas nine chemical hazards including boron, cadmium, chlorine disinfection residuals, hydraulic loading, nitrogen, phosphorus, salinity, chloride and sodium should be priorities in assessing environmental risks (NRMMC-EPHC-AHMC, 2006). To eventually describe the risk results as probability distribution functions (PDFs), it is prerequisite to generate stochastic input data. The selected hazards, together with the exposure characteristics (e.g., exposure pathways, magnitude, medium, frequency, extent, duration and the exposed environment or population) constitute the inputs of risk calculations. Regarding the hazard, the doses can be obtained by collecting and detecting a series of recycled water samples during a certain period of time. The next is to fit observed data to PDFs (e.g., normal, lognormal, uniform and Weibull curves). To simplify this procedure, a lognormal distribution is assumed as it has been previously recommended in many water quality studies (Khan and McDonald, 2010). This fitting process can be automatically achieved using the distribution fitting tool (dfittool) in MATLAB where the distribution parameters (mean and variance) are displayed in a dialogue window whilst the goodness of fit of the distribution versus known data is visualised in a graph window.

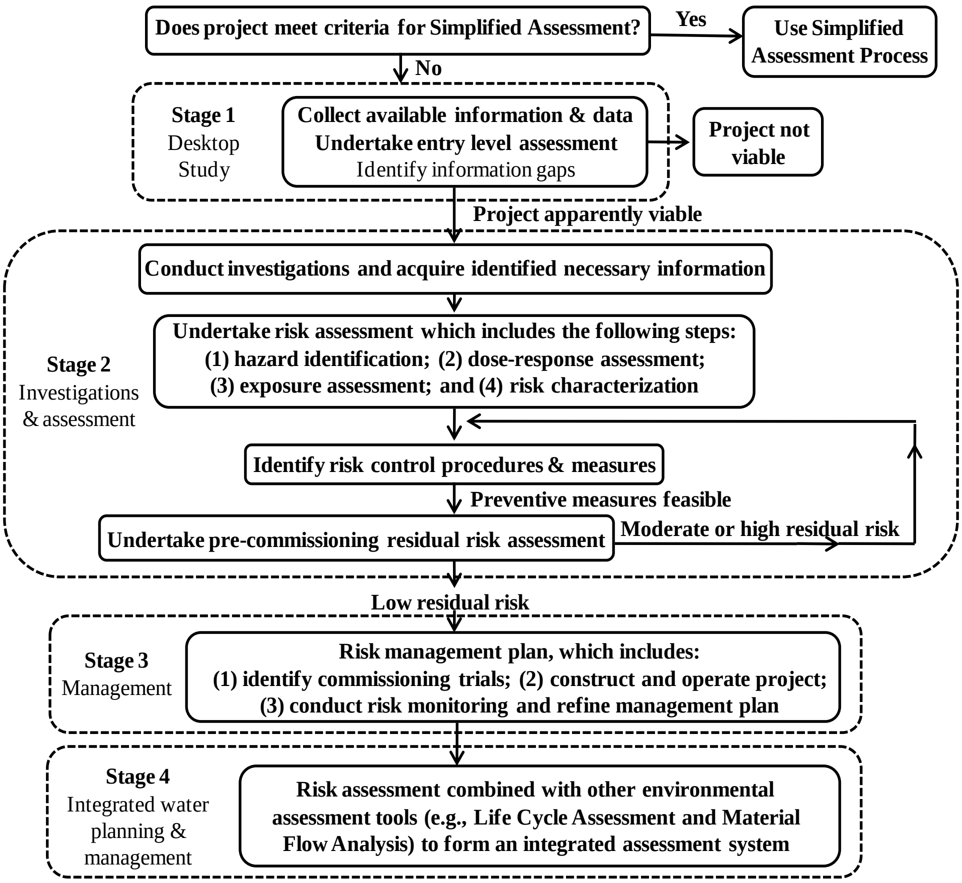


Figure 1 Outline of the risk assessment framework for water recycling schemes

Comparatively, the exposure volume and frequency of recycled water for exposed environment or population is normally considered as uniform or triangular PDF, of which the fitting process is the same as for hazard dose (NRMMC-EPHC-AHMC, 2006). Once the input PDFs are obtained, the Monte-Carlo simulation and Latin Hypercube sampling techniques (the lognrnd and lhsdesign functions in MATLAB) can be applied to randomly select data (e.g., 10,000 sampling trials for each PDF) for the following dose-response calculations where the model parameters can be obtained from available literature (Haas et al., 1999). Finally, the corresponding probabilistic risk results (e.g., 10,000 results) are displayed in MATLAB command window for further analysis.

If the results are greater than specified guideline values, which indicate moderate or high risks to human and the environment, the related risk control and management measures must be conducted so as to ensure the recycled water in a safe, acceptable and reliable state. Risk control measures such as source control, recycled water quality improvement, critical point control and exposure control are well practiced in Australia. Particularly, advanced treatment processes (e.g., MF, UF, NF, RO and MBR) contribute a significant reduction (one to six orders of magnitude) in microbial risk. If the concentrations of the particular hazard after unit treatment processes can be described as lognormal PDFs, the entire treatment train performance can be estimated by a simple mathematical equation (Equation 1). In the case that the end-point samples consistently yield non-detectable results, it is necessary to undertake challenge tests (hazards are intentionally added to feedwaters at elevated concentrations in order to demonstrate high levels of removal) as well as theoretical considerations to develop PDFs for treatment performance of treatment processes so as to estimate the PDFs of final effluents (Khan, 2010). For these situations, MATLAB is also capable of assigning and calculating the PDFs.

$$PDF_{Removal} = \frac{PDF_{Influent} - PDF_{Effluent}}{PDF_{Influent}} \times 100 \quad (1)$$

The risk control procedures should be iterated unless the treatment performance is highly satisfactory or the risk final effluent has been reduced to the guideline level.

(3) Stage 3. When the residual risks are deemed to be acceptable, the project can move into operation with a risk management plan and regular operational monitoring. The management plan should continue to be modified according to monitoring results.

(4) Stage 4. The full risk assessment and management plan should be further coupled with other environmental assessment tools such as Life Cycle Assessment (LCA), Material Flux Analysis (MFA) and Life Cycle Cost (LCC) to form a holistic evaluation system for the integrated water planning and management.

4. CASE STUDY ON THE WATER RECLAMATION AND MANAGEMENT SCHEME (WRAMS)

The Water Reclamation and Management Scheme (WRAMS) at Sydney Olympic Park is Australia's first large scale urban water recycling scheme which was commissioned in the year 2000 and has extended the urban water recycling concepts to integrated water management by incorporating both storm water and recycled water in recycled water delivery systems. More specifically, raw sewage firstly undergoes secondary treatment at the water reclamation plant (WRP) by sequence batch reactor (SBR) and UV disinfection and then mixed with storm water at the subsequent water treatment plant (WTP) where mixed water processed by MF, RO and cope with large events. In addition to serve 2,000 houses in neighbouring residential suburb of Newington, WRAMS also supplies recycled water to all commercial premises and sporting venues at Sydney Olympic Park, saving approximately 850 ML/yr of drinking water (SOPA, 2011). To ensure the water quality, WRAMS tests the important chemical and microbiological parameters such as ammonia, BOD, pH, total nitrogen, total phosphorus, colour, total coliform and faecal coliform bacteria in the laboratory on a weekly basis. The turbidity, chlorine and conductivity are also measured onsite every week whereas heavy metals such as aluminium, arsenic, manganese lead and zinc as well as pathogens (e.g., rotavirus, adenovirus, reovirus, enterovirus, Cryptosporidium and Giardia) are subjected to a bi-annual detection. Table 1 lists some recycled water quality data during 2010 and 2011. As can be seen, the accurate microbiological data of the total coliform and faecal coliform concentrations at chlorination can be operated at any rate to WRP, WTP and Newington are not available due to instrumental limitations. Besides, the bi-annually tested heavy metal and pathogen concentrations are not sufficiently enough for stochastic risk assessment. For these reasons, to illustrate the probabilistic risk assessment processes, this paper conducted simplified analyses on nutrient loadings (total nitrogen and total phosphorus) which are also important chemical parameters in water quality monitoring, especially for environmental risk assessment.

Regarding the modelling input data, in the absence of the raw sewage data between 2010 and 2011, the model generated 100 random numbers for TN and TP influents respectively based on Table 2 (Chapman, 2006). The input data were then fitted to a lognormal distribution using the distribution fitting tool in MATLAB. As a result, the parameters (mean and variance) of the two fitted curves are shown in Table 3.

Table 1 Water quality data at WRAMS

Test	**Guideline**	**Date**			
		07.2010	09.2010	03.2011	05.2011
Ammonia, mg/L	2	0.333	0.468	0.798	0.044
Total phosphorus, mg/L	1	0.418	0.525	0.508	0.240
Total nitrogen, mg/L	12	1.23	2.75	2.42	1.88
pH	6.5-8.0	7.56	7.3	7.42	7.44
Free chlorine, mg/L	0.5	0.38	0.27	0.34	–
True colour, Pt-Co	<15 TCU	3	6	3.6	7.2
Conductivity, μs/cm	<1000	567	660	678.8	–
Total coliform at WRP, units/100 mL	<10	<1	<1	<1	<1
Faecal coliform at WRP, units/100 mL	<1	<1	<1	<1	<1
Total coliform at WTP, units/100 mL	<10	<1	<1	<1	<1
Faecal coliform at WTP, units/100 mL	<1	<1	<1	<1	<1
Total coliform at Newington, units/100 mL	<10	<1	<1	<1	<1
Faecal coliform at Newington, units/100 mL	<1	<1	<1	<1	<1

Table 2 WRAMS raw sewage characteristics in 2003/2004[a]

Test	Influent range
Ammonia, mg/L	20-44
Total phosphorus, mg/L	5-9
Total nitrogen, mg/L	29-58
BOD, mg/L	80-210
Suspended solids, mg/L	100-360
pH	7-8
Dissolved solids, mg/L	300-500
COD, mg/L	250-600

[a]Adapted from Chapman, (2006).

Table 3 Parameters of fitted curves

Sampling place	**Analytical compounds**	**Parameters**	
		Mean	Variance
Influent	Total nitrogen	44.34	81.87
	Total phosphorus	6.65	2.81
Effluent	Total nitrogen	2.15	0.15
	Total phosphorus	0.40	0.0051

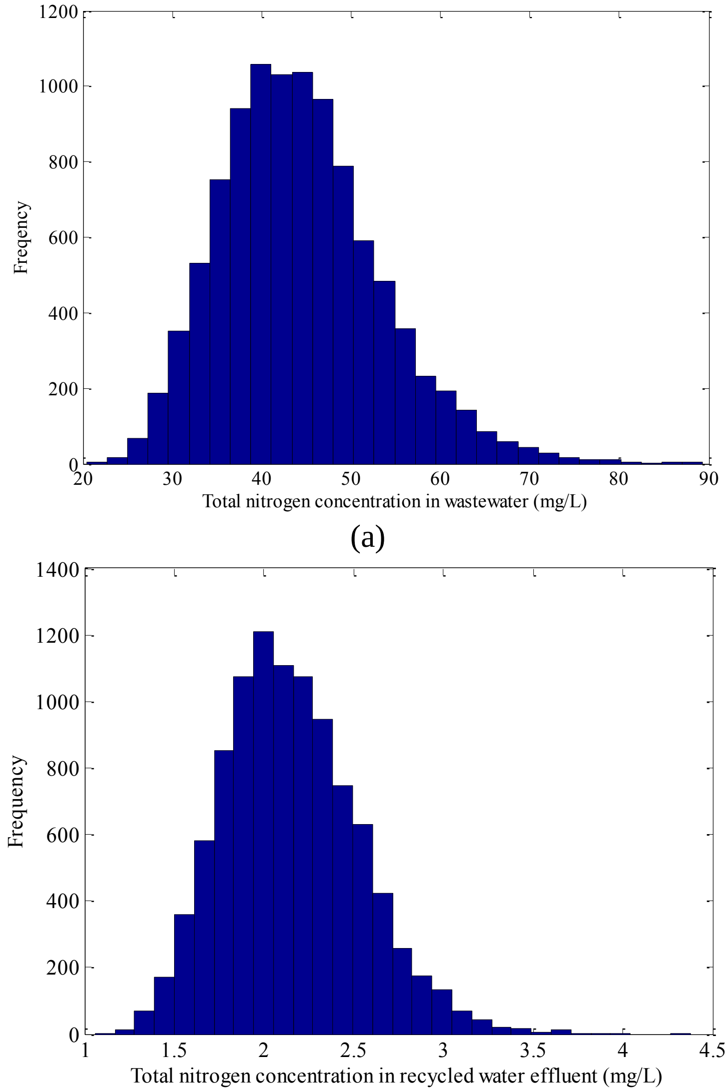
The obtained parameters were then used to generate PDFs corresponding to the TN and TP at WRAMS influent and effluent (Figures 2 and 3). This step is able to smooth out the spikes of the real data and turn discrete data into continuous forms. However, cares must be taken when using lognrnd function in MATLAB. Owing to the inherent properties, the parameters should be subjected to related conversions (Equations 1 and 2).

$$\mu = \log(\frac{m^2}{\sqrt{v+m^2}}) \quad (2)$$

$$\sigma = \sqrt{\log(\frac{v}{m^2+1})} \quad (3)$$

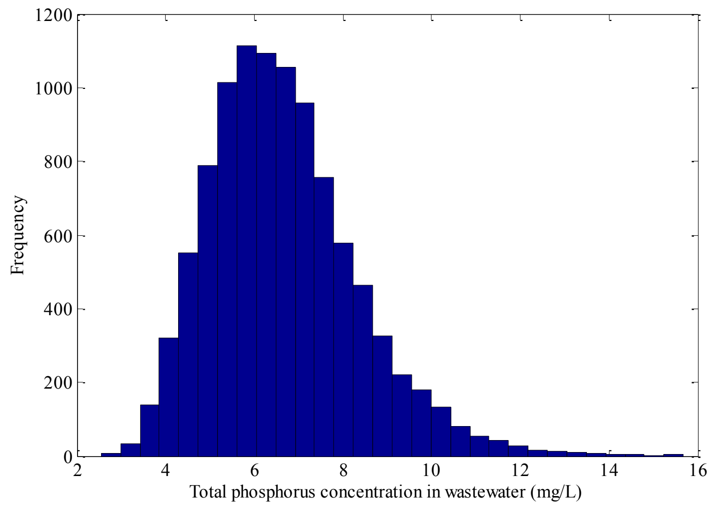
where m and v are mean and variance respectively. μ and σ are input parameters for the lognrnd function which finally results in a PDF with mean m and variance v (MATLAB manual, 2011).

The next step is to undertake mathematical manipulations to calculate the TN and TP removal through the wastewater treatment processes. To achieve this, the idea is to take 1,000 samples from each PDF and then apply Equation 1 for calculating the PDF of percent removal. The lhsdesign function was adopted to ensure that each sample was randomly taken from each interval (0, 1/1000), (1/1000, 2/1000), (1-1/1000, 1) rather than from the areas that have higher probabilities of occurrence (Khan, 2010). Figure 4 shows the total nitrogen removal results which indicated that nitrogen was highly removed with 5^{th} and 95^{th} percentile values of 94.92 and 95.35 respectively. When similar assessment procedures were conducted for total phosphorus, an average 94% removal rate was reached with 5^{th} and 95^{th} percentile values of 93.07 and 94.54 respectively (Figure 5). The treatment performances are highly satisfactory so that additional risk controls may not be required.

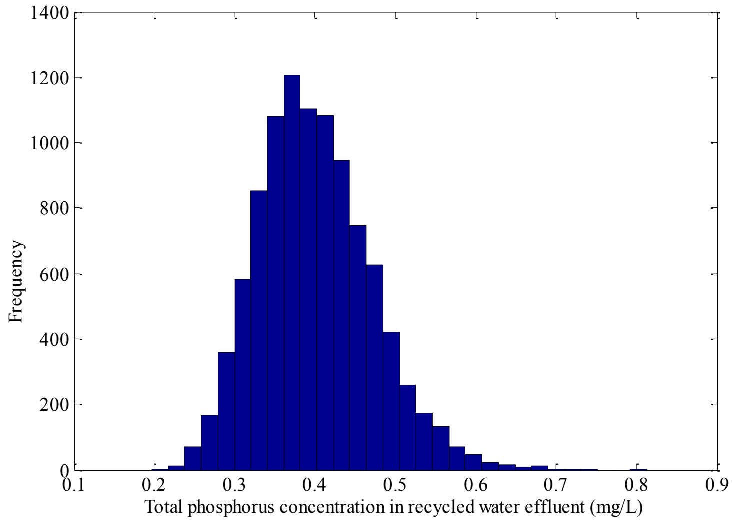


(b)

Figure 2 Simulated PDFs of TN concentrations at WRAMS influent (a) and effluent (b)



(a)



(b)

Figure 3 Simulated PDFs of TP concentrations at WRAMS influent (a) and effluent (b)

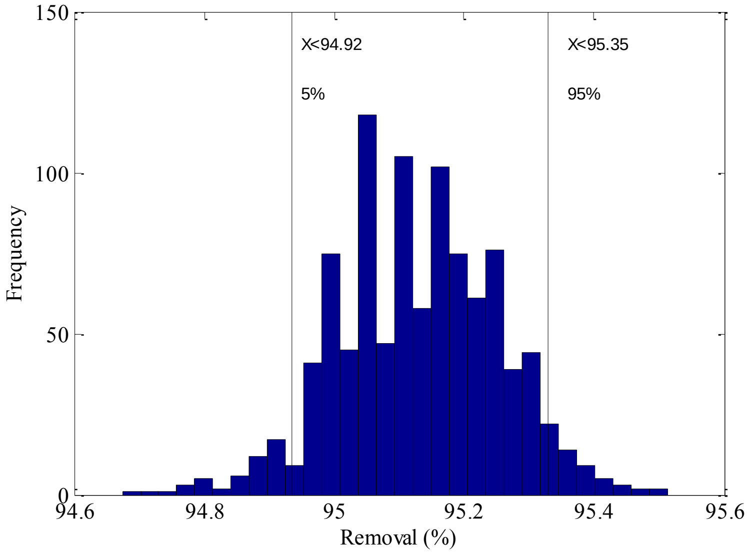


Figure 4 Simulated PDF of TN removal (%) from influent to effluent at WRAMS

CONCLUSIONS

As quantitative risk assessment models are still lacking, this study proposed a probabilistic risk assessment framework for detailed evaluation of the recycled water schemes and conducted a simplified case study on total nitrogen and phosphorus at WRAMS in Sydney Olympic Park using MATLAB. The simulated PDFs of nutrient removal not only indicated the average removal rates but also pointed out the confidence intervals which are (94.92, 95.35) and (93.07, 94.54) for total nitrogen and phosphorus respectively. With more accurate data regarding trace chemicals and pathogen are available in future investigation, more detailed human or environmental risk assessment can be performed to achieve more realistic and reliable outcomes. While the case study focuses on one residential recycling scheme, the assessment methodology can be applied to other existing schemes or future projects nationwide or can be incorporated with other assessment tools to form a holistic evaluation system.

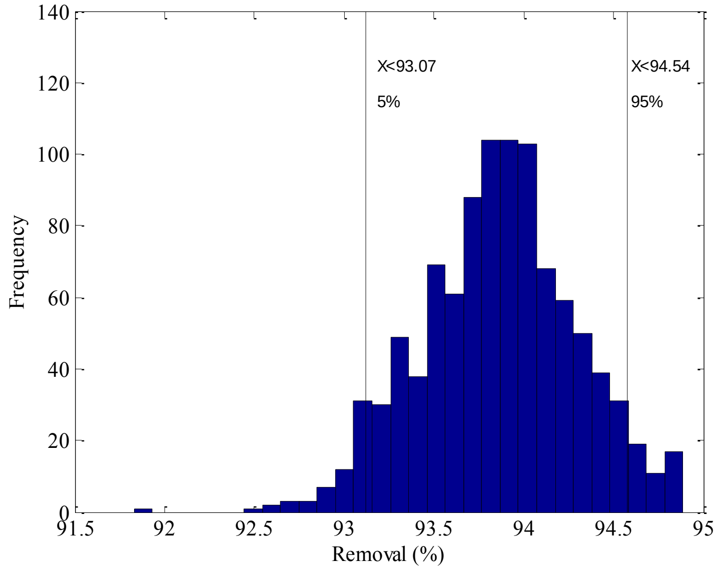


Figure 5 Simulated PDF of TP removal (%) from influent to effluent at WRAMS

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