Water-reuse risk assessment program (WRAP): a refinery case study

Maria Dian Kurnia Sari, Gert Holm Kristensen, Martin Andersen, Alain Andre Maria Ducheyne and Wan Aik Lee

ABSTRACT

The key approach to manage and prevent potential hazards arising from specific contaminants in water networks is to consider water as the main product delivered. This new concept, addressed as water-reuse risk assessment program (WRAP), has been further developed from hazard analysis of critical control points (HACCP) to illustrate the potential hazards which are the roots of hindering intra-facility water reuse strategies. For industrial sectors applying water reclamation and reuse schemes, it is paramount that the reclaimed water quality stays within the desired quality. The objective of WRAP is to establish a new methodology and knowledge, which will contribute to the sustainable development of industrial water management, and demonstrate its capabilities in identifying and addressing any potential hazards in the selected schemes adoption by the industries. A 'what-if' scenario was simulated using a refinery as a case study to show strategies on how to benefit reclaimed or reuse water based on reliable, applied and scientific research within the process integration area. In conclusion, the WRAP model will facilitate operators, consultants and decision makers to reuse water on a fit-for-use basis whilst avoiding contaminant accumulation in the overall system and production of sub-quality products from inadequate processes after several reuses.

Key words | HACCP, quality control, refinery, risk assessment, water reuse, WRAP

Maria Dian Kurnia Sari (corresponding author)
Alain Andre Maria Ducheyne
Wan Aik Lee
DHI Water & Environment (S) Pte Ltd,
1 Cleantech Loop, CleanTech One, #03-05,
637141,
Singapore
E-mail: *mds@dhigroup.com*

Gert Holm Kristensen
Martin Andersen
DHI Hørsholm,
Agern Allé 5 DK-2970,
Hørsholm,
Denmark

INTRODUCTION

The global water crisis is becoming one of the most serious natural resource issues facing the world nowadays. Water is a vital element and it is directly related to environment, economy, health and safety aspects (AquaFit4Use). In general, due to tradition and focus on the manufacturing process and the quality of the manufactured products, industries tend to use too high water quality (i.e. applying fresh water for all water consuming units within the facility). However, population growth, increasing water scarcity (e.g. urbanization and industrialization), rising costs for water and wastewater treatment, as well as increasing environmental concern regarding wastewater discharge, have forced industries to start looking into possibilities for water savings and water reuse to reduce the water footprint of their activities. For large freshwater consuming industries, such as the refinery industry, water is no longer regarded as a consumable or utility, instead it has become a highly valuable asset (AquaFit4Use 2009).

Industrial water efficiency management should be implemented to address freshwater demand (e.g. catchment, imported, reclaimed, and desalinated water) by applying reclamation and reuse schemes. Minimizing the consumption of freshwater can be typically achieved by increasing

doi: 10.2166/wrd.2016.175

internal recycling and reuse of wastewater to replace the intake of fresh resources and utilities. Wastewater can be treated differently depending upon the source, the use of the water, and how it gets delivered to specific unit processes. Some of the process units in industrial process plants may require high quality of pure water, while other process units can use lower quality of water or even contaminated water sources. Depending on the process water quality requirement, wastewater from a process unit can be partially treated and reused within the plant (Sharma & Rangaiah 2016; El-Halwagi 2012). EPA (2009) states that the quality and quantity of wastewater produced from a treatment unit are highly variable depending upon a range of factors, such as:

- the raw process material and the characteristics of the products;
- the industrial process that generates the water, e.g. wash water, process filtrates, process backwashes, boiler and cooling tower blowdowns;
- reactions and additives required in the processes, e.g. pH adjusters, biocides, surfactants;
- temperature of the waters.

In the current situation, knowledge on the effect of water quality on process, product quality and health issues are mostly not available. This makes industries often (and still) choose far better water qualities than needed, mostly potable water or better. The industries should start to consider the use of water in the right quality or 'fit-for-use' to achieve higher sustainability (AquaFit4Use; Grüttner *et al.* 2010). Water requirement for different process units depends on flowrate, temperature and contaminant concentration. The mixing of wastewater from different process units with fresh water stream must comply with the water quality requirements of the given process (Bogataj & Bagajewicz 2008; Sharma & Rangaiah 2016). With appropriate technology management and quality controls, wastewater can be reused for a wide range of purposes including material washing, process wash water, in-production line, boiler or cooling tower make-up, non-industrial domestic uses, etc.

The concept outlined by water-reuse risk assessment program (WRAP) in this paper shares similarity with the general application of hazard analysis of critical control points (HACCP). HACCP is 'a management system in which food safety is addressed through the analysis and control of biological, chemical, and physical hazards from raw material production, procurement and handling, to manufacturing, distribution and consumption of the finished product' (FDA 2014). The principle of HACCP can also be applied on the water network to improve operation efficacy, product quality, and safety. By considering water as the main product delivered, potential hazards arising from specific contaminants in water networks can be managed and prevented.

Application of the HACCP concept for water reuse in food industry was discussed by Casani *et al.* (2005), focusing on challenges and limitations associated with microbiologically safe reuse of water. Later, Grüttner *et al.* (2010) implemented HACCP into an industrial water reuse quality control methodology under a European research project called AquaFit4Use. However, there are a number of deviations for direct application into the water network, such as how to define which water streams can be reused and how to ensure the reclaimed water quality to stay within the required quality criteria of the process in question. The methodology developed in WRAP has successfully addressed these deviations by implementing water quality characterization and compatibility assessments. Using a petroleum refinery company (Nabi Bidhendi *et al.* 2010) as a case and illustration study, the objective of WRAP is to demonstrate its capabilities in identifying and addressing any potential hazards which are the roots of hindering intra-facility water reclamation and reuse scheme adoption by the industries.

METHODS

The WRAP methodology developed for this paper is based on the principles of HACCP and AquaFit4Use (NACMCF 1992; NFPA 1993; USDA 1999; Casani *et al.* 2005) and AquaFit4Use (Grüttner *et al.* 2010; AquaFit4Use), with particular focus on the water quality criteria (WQC) assessment, hazard identification, and description of critical control points (CCPs). A complete decision making process flow in WRAP methodology can be found in Figure 1.

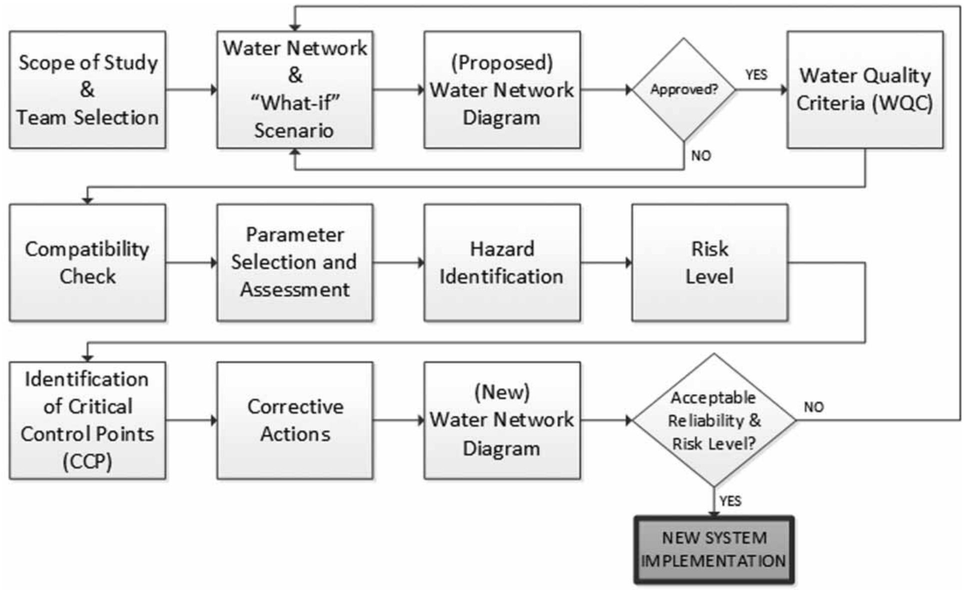


Figure 1 | Decision making process flow in WRAP.

Define scope of study and selection of the WRAP team

The project investigator has the responsibility to provide the team members with a clear description of what has to be studied or accomplished and which parts of the plant will be the focus of the study, as industrial plants are not a static asset in general. When a plant undergoes any changes (e.g. renewal, regeneration, retrofitting, expansion), the concept of process integration and optimization which are affiliated with water should be re-evaluated to ensure the relevance of changes and optimal design. The project team members should ensure a continued and reliable new system in water reclamation and reuse scheme that is in line with the facility. The project team members should include a minimum representative from top management, process engineers, quality control, and Health Safety and Environment.

Developing water network and 'what-if' scenario for optimization strategies

Process flow diagrams and/or piping and instrumentation diagrams of the selected water network should be provided and gathered before the quality assessment takes place. A verification of the developed diagrams (i.e. site survey along the areas included in the scope of study) must be carried out as the basis in developing the water network diagram.

A flow diagram of water network with bottom-up approach is recommended to be developed to show inflow and outflow streams of the individual processes; including other products and any chemicals involved, if required. In complex systems, it is advised to categorize the purposes of water and define its requirements within a process.

A simplified diagram of water (and steam) network for the demonstration of WRAP model can be found in Figure 2 (Nabi Bidhendi *et al.* 2010). The refinery utilized about 505 m^3/hr water. Table 1 illustrates flowrate and stream constraints in the existing water network. Based on these constraints, limiting water flowrates are determined for optional operations. Water flowrate is needed to achieve mass transfer of contaminants required for water minimization and environmental regulations. It is also important to select processes which have major water consumptions. In this case study, there are three processes which use vast amounts of water (up to 340 m^3/hr or 67.4% of total water utility in the refinery), such as (a) desalter, (b) cooling towers, as well as (c) plant, domestic, and fire water.

For a given process where an outlet stream is identified for possible reuse and needs to be recovered, the outlet

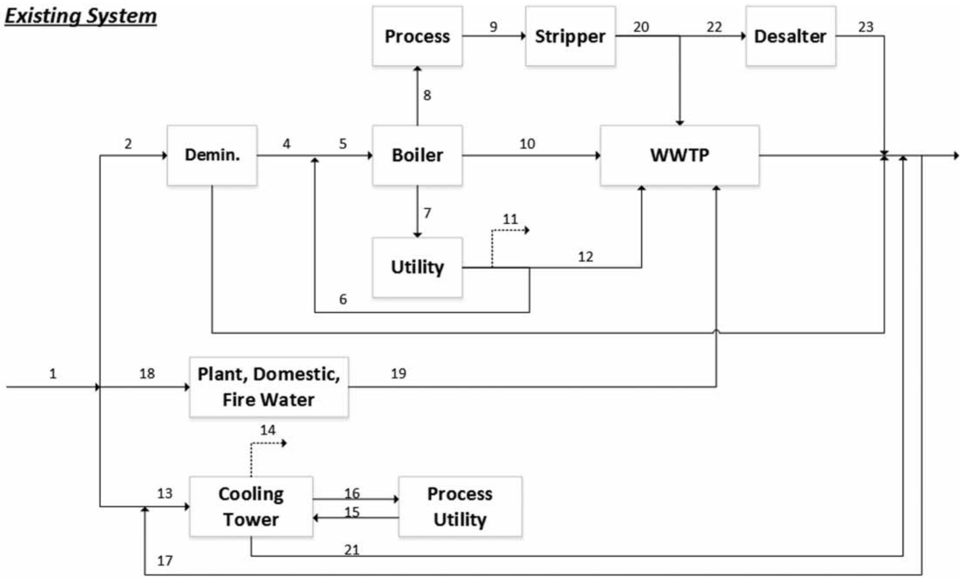


Figure 2 | Simplified water (and steam) allocation network of a refinery plant (Nabi Bidhendi *et al.* 2010).

Table 1 | Flowrates and stream constraints of the water network (Nabi Bidhendi *et al.* 2010)

			Contaminants (ppm)											
Stream code	**Flowrates (m^3/hr)**	**pH**	**Cond.**	**Hard.**	**Alk.**	**SiO_2**	**SS**	**TSS**	**Fe**	**Cl**	**COD**	**PO_4**	**H_2S**	**NH_3**
1	505	7.9	360	150	140	9.3	1	2.15	<0.05	<0.05	0			
10	20	9.8	90	0					<0.05		0	20		
13	113	7.9	360	150	140	9.3	1	2.15	<0.05	<0.05	0			
15	37	7.1	4,350	1,250	30	48.9	1	2.95	0.35	2.5				
17	104	7.6	1,400	270	66	9.87	2	2.66	<0.05	<0.05				
18	168	7.9	360	150	140	9.3	1	2.15	<0.05	<0.05	0			
19	160	7.3	930	241	23		22				4			
21	17	5.5	850	12	44	6.6	13	24.3	0.83	<0.05	10		3.4	46
22	59	5.5	850	12	44	6.6	13	24.3	0.83	<0.05	2		3.4	46
23	59	6.5	1,600	160	40	1.4	20	25	3.12	<0.05	5			

stream is termed as a *process source*. On the other hand, a *process sink* refers to a unit where a source is consumed (Foo 2013). In the WRAP model, matching of process sources and sinks need to be conducted for process optimization in the proposed water network.

Nabi Bidhendi *et al.* (2010) have proposed a 'what-if' scenario to find an appropriate way to minimize freshwater demand in the refinery industry (Figure 3). The refinery industry was chosen to analyse feasibilities of regeneration, reuse and recycling in the water network. Plant, domestic, and fire water demand can be supplied by reusing the wastewater from a desalter. In addition, the demand can be supplied by treating the cooling tower blowdown using a regeneration unit (RU). For the WRAP model demonstration, *Cooling Tower Blowdown* and *Desalter Wash Water (from outlet utility and boiler blowdown)* are the *water sources*. Thus, *Plant, Domestic, Fire Water* is the *water sink*.

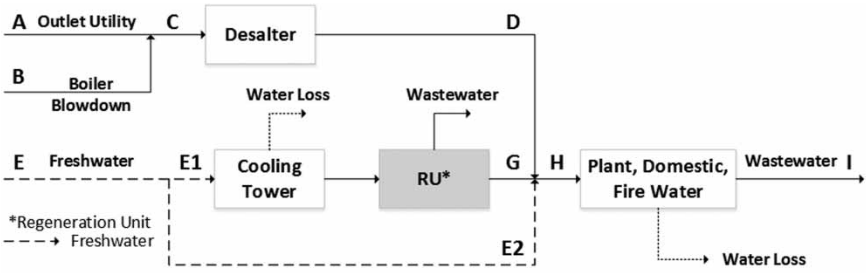


Figure 3 | Proposed 'what-if' scenario to minimize freshwater demand in the refinery industry.

Different techniques and methods have been developed to design a water allocation network so that freshwater demand can be minimized at an acceptable level (Bagajewicz 2000). Water pinch technology is a systematic technique for analysing water networks and reducing consumption related to different water-using processes within a plant (Mohammadnejad *et al.* 2010). Most of the methods used in water pinch analysis are based on the mass exchange of one or several contaminants. If the mass exchange is based on one contaminant, the problem will be solved as a single contaminant. If it includes two or more key contaminants, the problem will be solved as multiple contaminants. Graphical methods, mathematical and computer-based method may be used for both cases (Nabi Bidhendi *et al.* 2010; Mohammadnejad *et al.* 2011).

Data extraction: defining WQC for potential reuse streams

After developing the water network, there are some data which should be gathered before the WQC assessment takes place. The data must be based on actual operational data; however, assumptions and literature data may be used should available data be insufficient in quality or not available for aspects such as:

- water process functions;
- water quality or process components of individual processes, e.g. temperature (T), pH, conductivity (cond.), hardness (hard.), alkalinity (alk.), silica (SiO_2), total suspended solids (TSS), chemical oxygen demand (COD), phosphate (PO_4), hydrogen sulphide (H_2S), ammonia (NH_3), oil & grease (O&G), phenol, mercury (Hg) and other heavy metals, benzene, etc.;
- input and output flowrates for each unit process in the proposed network (water quality data are affected by the flowrate, especially for mixing);
- standard units of flowrate and process components (to avoid any miscalculation);
- mass and concentration balances of inflow and outflow water streams; and
- equipment and instrumentation specification, if applicable.

The assessment of the process components has to be performed under four groups of compounds found in the water:

1. physical properties, e.g. temperature;
2. chemical properties, e.g. pH, dissolved salts, organic matters;
3. micro-pollutant, e.g. heavy metals, specific organics;
4. microbiology components, e.g. *Legionella* spp., if applicable.

Desalter Wash Water, and *Plant, Domestic, Fire Water* are listed as the WQC with the associated process components for the proposed 'what-if' scenario in Figure 3. In complex wastewater reuse applications, the wastewater streams can contain more than two process components. The level of detail used in the WRAP model can be based on the investigator's judgement, taking into account water sensitivity for the specific industry, water flowrate and quality demands by a given reuse application, as well as an allowable limit for wastewater discharge (environmental regulations).

The WQC can be used as the basic requirements to be followed by the reuse streams. For more accurate optimization and quality assessment, each WQC should be provided in minimum and maximum value of quality (acceptable range in lower and upper bound limit). The water quality data of each potential reuse stream should also be provided in minimum and maximum range to illustrate any fluctuations occurring during operation or unexpected process upsets. In this case study, Table 1 only shows the flowrates and stream constraints of the water network at the maximum limit (no available data for minimum allowable limit).

Compatibility check

Using the available operational data, compatibility assessment of the proposed scenario in Figure 3 can be performed to determine whether the reuse streams are 'fit-for-use' for a given process. The assessment will compare the process components quality of the alternative water source with the associated WQC of the given process sink. For example, the quality data of stream A, B and C (outlet utility, boiler blowdown and the mixed streams, respectively) will be compared with the quality requirement of *Desalter Wash Water* WQC. The quality data of stream E2, D, G, H (freshwater, wastewater from desalter, treated water from RU and the mixed streams, respectively) will be compared with the quality requirement of *Plant, Domestic, and Fire Water* WQC (freshwater replacement). Each process component of a certain reuse stream has to be within the acceptable range of WQC quality.

Nabi Bidhendi *et al.* (2010) have selected hardness and COD as key contaminants based on the industry and its water requirement. The maximum allowable limit of hardness for Plant, Domestic, and Fire Water WQC is 150 mg/L, COD is 0 mg/L, and the required input flowrate is 168 m^3/hr (based on Table 1 for stream 18). The quality of stream H should be within the hardness and COD limit to be considered as Freshwater Replacement (other process components may also be compared, if applicable). If a process component is within the range, it can be identified as *compatible* (v), or else as *incompatible* (x). The illustration can be found in Table 2.

In the event of mixing reused water to top up a feed water intake, it is recommended to investigate the chemical interactions, which may occur when mixing two or more different water types. The investigation is recommended to be carried out by actual laboratory experiments and analyses of the mixture. In the absence of actual waters to sample, the use of water quality modelling (e.g. PHREEQC by USGS) can provide early information.

Hazard analysis and parameter classification

Parameter classification assessment of the chosen stream must be performed to determine any potential hazard in a given process. A hazard is the potential consequence of exceeding a process component limit, in particular with respects to these five key concerns:

1. product safety;
2. product quality;
3. process water function;
4. equipment; and
5. health and safety (i.e. working condition).

The quality aspect in reclamation and reuse scheme can be identified by addressing the above five key concerns to control potential hazards and unforeseen disturbances for the application of intra-facility water reuse. Each of the five key concerns must be sequentially screened for each of the four groups of compounds found in water (i.e. physical properties, chemical properties, and micro-pollutant, microbiological) with respect to the acceptable range of the relevant process components.

Table 2 | Compatibility assessment for desalter wash water and freshwater replacement

		Stream quality[a]		WQC[a]		Compatibility	
Process water function	**Input stream**	**Hard.**	**COD**	**Hard.**	**COD**	**Hard.**	**COD**
Desalter Wash Water	C	0	0	12	2	v	v
Freshwater Replacement (Plant, Domestic, Fire Water)	H	185.24	1.15	150	0	x	x

[a]In ppm.

Risk level

Risk is an estimate of the likelihood of an adverse effect (hazards) on products, production, equipment, or employees. To reuse industrial water in a safe and sustainable way, it is important to identify, assess and appropriately manage the risks. The risk assessment should be undertaken on the proposed scenario to identify potential hazards and understand the likelihood and severity of these occurring. The risk assessment can help to determine any appropriate management controls needed to reduce and avoid the risks.

Risk level can be calculated by using a combined approach of the two main factors, namely *Severity* and *Likelihood*, with coding as illustrated in Figure 4. The 5×5 matrix (Equation (1)) is preferable to give a more reliable range for assessing a certain risk:

$$\textit{Risk Level}\ (1-25) = \textit{Likelihood}\ (1-5) \times\ \textit{Severity}\ (1-5) \tag{1}$$

Likelihood can be represented on a scale of 1–5:

1: Rare, 2: Unlikely, 3: Possible, 4: Likely, 5: Almost certain

Severity is also represented on a scale of 1–5:

1: Very low, 2: Low, 3: Medium, 4: High, 5: Very high

Larger matrices (i.e. 8×8) can be used for increased resolution should the quantification of severity and likelihood be distinctly reliable. In the experience of the authors, reliable quantification of the parameters is often a problem.

Identification of CCPs

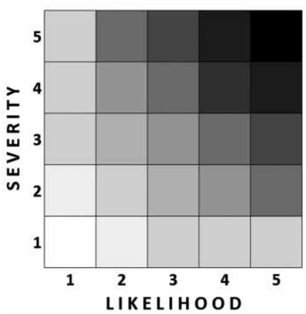
The CCP is a point in the water network that needs routine control in order to manage the identified risks and be in control of unforeseen disturbances. This assessment can be used to identify and describe any points in the process which have a reasonable probability of creating unacceptable risks. There are four quality control considerations that need to be assessed under the four groups of compounds:

- impacted by;
- adjusted or controlled by;
- generally recommended point of process control;
- alternative indirect points of control.

After this set of relevant mitigation measures has been defined, corrective actions for each CCP will be identified and used as preventive measures, procedures or actions implemented to reduce the severity and likelihood of the potential hazards. The corrective actions should achieve acceptable reliability level for the scenario in question to be implemented.

Acceptance of new risk level and new system implementation

The corrective actions for each CCP that are suitable and effective to control and manage any potential risk in a given process will be updated in the proposed 'what-if' scenario and the associated water network. A new risk level will be measured again after the corrective actions have taken place in the water network. Once the desired new system is determined with acceptable risk level, it can be tested



Legend	Guidelines for Risk Level
1-5	Control system preferred
6-10	Control systems are needed to some extent
11-15	Significantly reliable control measurement should be put in place
16-20	Highly reliable and acurate control systems or mitigation are required (other options should be considered)
21-25	Not advised. Excessive risk exists and should be avoided through elimination of the risk (i.e. not considering reuse of this stream)

Figure 4 | A conceptual diagram of combined likelihood and severity for a certain risk with its guidelines.

out in a laboratory scale and/or a pilot study prior to the actual implementation in the plant. For '*incompatible and not advisable*' results with medium to high risk level (≥11), improvement in the water network and 'what-if' scenario can be arranged and planned again for a better system in the reclamation and reuse scheme.

The required treatment technology and its economic justification (including '*True Cost of Water*'), limitation in plant areas (e.g. piping, space, and location), efficiency in process integration and environmental benefits, can also be further assessed if the chosen scenario is considered to be implemented in the existing system. Andersen *et al.* (2014) described the '*True Cost of Water*' concept and it would be more important to have an accurate economic indicator for cost. The actual or the 'true' cost of utilities (freshwater, process water, steam, etc.) should take into account the energy cost, in-plant treatment processes, maintenance, chemicals, discharge fees, and valuable products that are associated with it.

RESULTS AND DISCUSSION

Water reuse involves using 'used' water as new resources for a process that does not really require freshwater to reduce freshwater consumption and wastewater discharge. The quality and quantity of industrial water produced is highly variable depending upon a range of factors. This water reuse approach can be considered if the eventual contaminant level of the wastewater meets the standard quality of the process sink (i.e. the new water source is of the same quality or cleaner than the process sink requirement). Water can also be reused by mixing wastewater of different concentrations with freshwater to obtain the acceptable contaminant level as well as flowrate of the given process sink (Klemeš *et al.* 2014).

The WRAP model has been developed for the industries to analyse the effectiveness and efficacy of the overall water quality network using 'what-if' scenarios in reclamation and reuse schemes. A refinery industry (Nabi Bidhendi *et al.* 2010) was used as a case study. Reusing 'used' water was simulated to show strategies on how to benefit from different types of water quality, as well as to minimize freshwater consumption. The minimum required flowrate was deducted from the most polluted stream and the cleanest stream remained as the last alternative for treatment. Hardness and COD were analysed simultaneously based on their mass transfer. The final water network can be found in Figure 5. These alternative water resources can highly support the freshwater demand and the freshwater consumption can be reduced from 340 to 197.12 m^3/hr (about 42%), if implemented.

As seen in the final water network, the flowrate of Plant, Domestic, and Fire Water and Cooling Tower (168 m^3/hr and 113 m^3/hr, respectively) followed the flowrate constraint in Table 1. However, to achieve the acceptable level of mass transfer and contaminant concentration in the whole water network, the required flowrate of the desalter became 54.28 m^3/hr after the calculation carried out by Nabi Bidhendi *et al.* (2010). The outlet utility and boiler blowdown streams supplied the desalter wash water demand (45 m^3/hr and 9.28 m^3/hr, respectively).

Cooling Tower Blowdown and *Desalter Wash Water (from outlet utility and boiler blowdown)* are the *water sources*. *Plant, Domestic, Fire Water* is the *water sink*. Regeneration reuse and regeneration recycling processes were placed in the water network assuming that only 80%

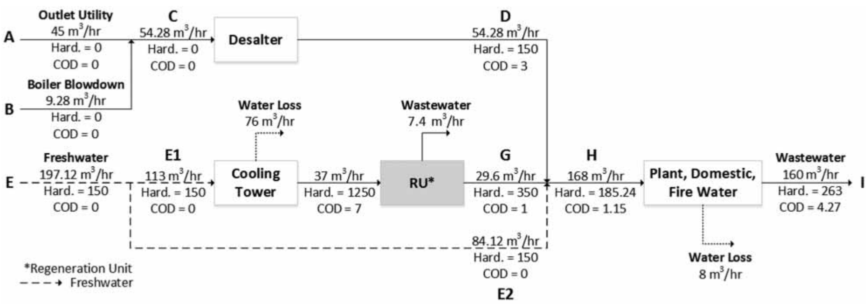


Figure 5 | Final water network with key contaminants (Nabi Bidhendi *et al.* 2010).

of treated wastewater from the RU may be reused or recycled. The RU received 37 m^3/hr of blowdown water from the cooling tower and produced 29.6 m^3/hr of treated wastewater. The rejected wastewater of 7.4 m^3/hr from the RU was then sent to the wastewater treatment plant. The removal ratio of RU was 78% for hardness and 89% for COD. The feed water quality was 1,250 ppm of hardness and 7 ppm of COD. After the regeneration process, the RU produced treated water with 350 ppm of hardness and 1 ppm of COD.

Another approach can also be applied in the assessment, such as *Outlet Utility* and *Boiler Blowdown* are the *water sources*, and *Desalter* is the *water sink*. Basically, the desalter does not require freshwater and can just reuse wastewater from the outlet utility and boiler blowdown. In terms of quality, outlet utility and boiler blowdown contained 0 ppm of hardness and 0 ppm of COD. Thus, the mixture of these two streams will contain the same quality of hardness and COD. The quality of this 'used' water is suitable for the desalter wash water. After the desalting process, the desalter unit produced wastewater containing 150 ppm of hardness and 3 ppm of COD. The wastewater from the desalter was then mixed with the treated wastewater from the RU and some portion of the freshwater to achieve the desired quality for Plant, Domestic, and Fire Water demands. By using a simple mass balance equation, it was found that the mixture stream (stream H) contained 185.24 ppm of hardness and 1.15 ppm of COD.

Optimization using a compatibility assessment has been carried out by simply aligning the water quality of reuse streams with the associated WQC. Based on the compatibility check in terms of hardness and COD (Table 2), stream C has better quality than the desalter wash water requirement (hard. = 12 ppm, COD = 2 ppm; other stream constraints can be found in Table 1 for stream 22). As for stream H, this stream is not compatible to be used as a freshwater replacement (for plant, domestic and fire water). The hardness and COD value in stream H exceeded the associated WQC (hard. = 150 ppm, COD = 0 ppm; other stream constraints can be found in Table 1 for stream 18). Further treatment is required if the proposed 'what-if' scenario is considered to be implemented. The value of hardness and COD (185.24 ppm and 1.15 ppm, respectively) will not be suitable to be used as process plant water and/or domestic usages (especially for potable water). When applying an optimization strategy it is also recommended to provide minimum and maximum allowable limits to illustrate real operating conditions in the industry. A more complete operational data of process components in the refinery industry should also be provided to avoid any interference from specific contaminants or process constraints that can impact the whole water network (e.g. temperatures, pH, heavy metals, O&G, phenol, benzene, etc.). However, to demonstrate how the WRAP model works, the two streams had been selected to be further assessed for any potential hazard in the water network.

Hazard identification and risk management play important roles in water network management. Theoretical hazard identification has been performed with a focus on the water network together with the acceptable concentration levels of the relevant process components. The potential hazards for each group of compound can be varied with respect to the possible chain of hazards. Such an assessment of the potential hazards will depend on the nature of the production and can be hard to generalize. A company will have to carry out the assessment themselves and determine policies for the acceptable level of risk or safety required for the identified hazards. A few key concerns have been found during the hazard identification that relate to the process water sources, regeneration system, and the proposed water network. More process components have been considered for this hazard identification (Table 1 was used as the operational basis). The assessment was based on literature data and the details can be seen in Tables 3 and 4.

After undertaking hazard identification, it is also important to identify, assess and appropriately determine the risk level under the five key concerns (Table 5). Based on the assessment in this WRAP model, stream C (mixture of outlet utility and boiler blowdown) might have medium risk level in terms of Process Water Function and Health & Safety. Typically, boiler blowdown will have a base level of pH (around 11–12). The pH of desalter wash water should be maintained between 6 and 8. Crude oils in the refinery industry may contain emulsion-stabilizing compounds and contaminants that may affect desalting operation and end product quality. Thus, a higher pH level will stabilize this emulsion. The desalter operating

Table 3 | Hazard analysis and parameter classification for stream C (Desalter Wash Water WQC)

Groups of compounds	Parameter selection and classification				
	Product safety	Product quality	Process water function	Equipment	Health & safety
Physical properties			Too low water temperature might impact the ability of the water to wash specific organic matters or additives		
Chemical property	Certain chemicals might be toxic in higher concentrations	Boiler blowdown can contain PO_4 and it can affect the end product quality. The blowdown may also contains other contaminants, e.g. Alk., SiO_2, TDS, Na, Cl, etc. Deviating pH might also interfere the next processes	Adjusting pH of desalter wash water is needed (6–8). Higher pH will affect desalting operation and product quality, lower pH will cause corrosion in desalter	If water in emulsion contains calcium or magnesium carbonate, higher pH of wash water can cause operation problem in desalter and scale in effluent piping system (downstream water network will eventually be affected)	The accumulation of the suspected contaminants and process constraints might give adverse impact in the next processes. The wastewater quality will be affected as well
Micro-pollutants	*(Heavy metals should be further analysed)*				
Microbiology components	N.A.	N.A.	N.A.	N.A.	N.A.

temperature is usually around 90–150 °C (varying from crude to crude) and will produce high temperature wastewater as well. Too low feed water temperature of stream C might impact the ability of the water to wash specific contaminants and increase the viscosity (making settling of salts and water difficult). The above factors need to be further assessed by the industry as stream C might produce a risk level of 12 for Process Water Function. As for the Health & Safety concern, the accumulation of associated and unidentified contaminants may give an adverse impact for the next processes (and will eventually produce more polluted wastewater). Stream C might give a risk level of 12 for Health & Safety.

Stream H might also produce a medium to high risk level ($\geq$11) in terms of Product Quality and Health & Safety. Based on Table 1 for stream 21, cooling tower blowdown can contain H_2S and NH_3 (and other contaminants such as SiO_2, Fe, Cl, COD, etc.) and it can affect the freshwater replacement quality. Stream H is the mixture of wastewater stream from a desalter, cooling tower blowdown, and freshwater. For domestic usage, especially potable water, these contaminants are not safe for human consumption. This might give a risk level of 12 for Product Quality and a risk level of 16 for Health & Safety.

Based on Figure 4, if the industry is considering using the selected water stream for reusing application, control systems are needed to some extent and significantly reliable control measurements may be put in place to achieve higher process water and product quality. Additional treatment options should also be considered and mitigation is required.

As described earlier, reusing wastewater can present a wide range of risks to the environment, occupational health and safety, and economic aspect. To effectively manage risk, it is important to identify mitigation measures and management controls rather than rely on reactive measures. Any potential hazard has to be extended when all aspects of applying water reuse scheme or alternative water sources are considered. To identify CCP(s), Grüttner *et al.* (2010) recommended to track backwards (upstream) in the process flow from the associated process to the point where the water quality component is potentially

Table 4 | Hazard analysis and parameter classification for stream H (Freshwater Replacement WQC)

Groups of compounds	Parameter selection and classification				
	Product safety	**Product quality**	**Process water function**	**Equipment**	**Health & safety**
Physical properties			High temperature water from Desalter (typically 90–150 °C) might not be suitable for plant, domestic, and fire water		
Chemical property	Certain chemicals might be toxic in higher concentrations	Cooling tower blowdown can contain H_2S and NH_3, and it can affect the end product quality. The blowdown may also contains other contaminant, e.g. Alk., SiO_2, TDS, Fe, Cl, COD, scaling materials, etc. Deviating pH from previous processes might also interfere the next processes	Adjusting pH of the new water source for freshwater replacement is needed (pH should be within 7.7–8.5)		If the stream will be used for process plant water and/or domestic potable water, the accumulation of the suspected contaminants and process constraints will give adverse impact (e.g. product, equipment and health impact). The wastewater quality will be affected as well
Micro-pollutants	*(Heavy metals should be further analysed)*				
Microbiology components				Cooling tower water is an ideal environment for *Legionella* bacteria. Growth of biofilm on the wetted surfaces can create fouling, affect the performance of the equipment, and will lead to metal corrosion	*Legionella* infection (i.e. legionellosis or pneumonia, pontiac fever) can be acquired when an individual breathes in water droplets containing the bacteria

impacted (e.g. freshwater sources, utility units, process units, RU, and the contaminant accumulation in the whole system). For the selected streams of the proposed scenario in this WRAP model demonstration, the upstream processes supplying the water have contributed to the associated risk level (i.e. desalter feed water and wastewater, regeneration system). Higher efficiency in the regeneration system or additional pre-treatment can also be provided to achieve the desired water quality and remove other associated contaminants. Another approach is to modify the proposed 'what-if' scenario. The desalter wastewater can be directly mixed with the cooling tower blowdown. The mixture will be treated using RU and the treated water will be reused as a freshwater replacement. Currently, the proposed RU system is only to remove the selected key contaminants, i.e. hardness and COD. It is suggested to have a new RU that can remove more contaminants and have a higher removal ratio. pH control and online sensors for the specific contaminants also need to be installed to ensure certain quality levels are achieved (i.e. temperature, COD, PO_4,

Table 5 | Hazard identification and risk level of the proposed network

WQC	Reuse stream		Hazard identification	Likelihood (1–5)	Severity (1–5)	Risk level
Desalter Wash Water	C	Mixed stream from Outlet Utility and Boiler Blowdown	Product safety	3	2	6
			Product quality	3	3	9
			Process water function	4	3	12
			Equipment	3	2	6
			Health & safety	4	3	12
Freshwater Replacement (for Plant, Domestic, and Fire Water)	H	Mixed stream from Desalter, Regenerator and Freshwater	Product safety	3	2	6
			Product quality	3	4	12
			Process water function	3	3	9
			Equipment	2	3	6
			Health & safety	4	4	16

NH_3, H_2S, O&G, phenol, heavy metals, etc.). A heat exchanger will also be useful to achieve the desired temperatures for different types of water sources.

A multi-barrier approach should be able to address any problem in reclamation and reuse schemes. If there is a process upset in the system, a safe process water can still be produced and used. EPA (2009) suggested that it is also important to identify which contaminants and characteristics need to be monitored, at what point in the process, and how often they need to be monitored. For example, visual monitoring at process sources and/or process sinks may be sufficient if the key concern can be visually identified; while in other cases, laboratory analysis may be required at process sources and/or process sinks to ensure certain quality levels are reliable. Fluctuation of the feed water in the system also needs to be monitored in a real-time approach during operation. Operational conditions (e.g. process and control characteristics, available online sensors in place) should be provided to effectively manage risk controls and identify corrective actions required.

A development plan for sustainable water management should also be organized to ensure product quality, environment, and work safety. New system evaluation and audit of the reclamation and reuse schemes will also be needed to understand whether the preventive risk management and controls in place are effective and have been implemented properly. To achieve long term performance, annual review and continuous development has to be implemented to improve the effectiveness of the proposed scheme system.

CONCLUSIONS

The WRAP model can successfully analyse the effectiveness and efficacy of water quality in the proposed scenario of reusing 'used' water for freshwater replacement by implementing the principles of HACCP (NACMCF 1992; NFPA 1993; USDA 1999; Casani *et al.* 2005) and AquaFit4Use (Grüttner *et al.* 2010; AquaFit4Use). The model is capable of identifying and addressing the potential hazards by applying the WQC assessment, hazard identification, description of CCP, and corrective action through multi-barriers. The WRAP model can facilitate operators, consultants and decision makers during water efficiency management planning to mitigate and avoid risks associated with water reuse when applied correctly.

In conclusion, there are some quality control considerations to be taken into account when applying reuse, recycling, or reclamation schemes:

- Multiple water streams with different water quality (e.g. contaminant concentrations).
- Change in contaminant load due to mixing and/or component splitting (e.g. mass and concentration balances, chemical reaction, etc.).
- When treated water is to be reused as a direct source, engineers must be cautious to monitor higher concentrations of specific organic chemicals or any unknown contaminants in the upstream to downstream system.

Minimum and maximum allowable limits should be provided for the selected process water WQC.

- The number of times the water has been reused that potentially increases the concentration levels of process contaminants in the overall system.
- Quality standard monitoring system with technology that can alert operators in real-time if the quality of the process water exceeds the acceptable standard. This monitoring system should also be coupled in the multi-barrier approach to reduce the risk level.
- Change in environmental regulations (local and/or international regulations).

ACKNOWLEDGEMENTS

This research grant was supported by the Singapore National Research Foundation under its Environmental & Water Technologies Strategic Research Programme and administered by the Environment & Water Industry Programme Office (EWI) of the PUB.

REFERENCES

Andersen, M., Lau, H. H., Xu, S. C., Li, G. & Eikaas, H. S. 2014 Six Rs of industrial water conservation techniques and true cost of water. In: *Conference Paper Presented at the Singapore International Water Week 2014 (SIWW 2014)*. Singapore, 1–5 June 2014.

AquaFit4Use The Project for Sustainable Water Use in Industry. www.aquafit4use.eu.

AquaFit4Use 2009 AquaFit4Use: Sustainable Water Use in Industry. *Water21*, December 2009, 49–50. Available from: www.aquafit4use.eu/userdata/file/Articles/2009-12%20Water21%20magazine.pdf.

Bagajewicz, M. 2000 A review of recent design procedures for water networks in refineries and process plants. *Comput. Chem. Eng.* **24**, 2093–2113.

Bogataj, M. & Bagajewicz, M. J. 2008 Synthesis of non-isothermal heat integrated water networks in chemical process. *Comput. Chem. Eng.* **32** (12), 3130–3142.

Casani, S., Rouhany, M. & Knøchel, S. 2005 A discussion paper on challenges and limitations to water reuse and hygiene in the food industry. *Water Res.* **39**, 1134–1146.

El-Halwagi, M. M. 2012 *Sustainable Design through Process Integration*. Butterworth-Heinemann Ltd/Elsevier, Oxford, UK.

EPA 2009 Industrial Waste Resource Guidelines: Industrial Water Reuse (EPA publication IWRG632). www.epa.vic.gov.au/our-work/publications/publication/2009/june/iwrg632.

FDA 2014 Hazard Analysis & Critical Control Points (HACCP). www.fda.gov/Food/GuidanceRegulation/HACCP/.

Foo, D. 2013 *Process Integration for Resource Conservation*. CRC Press, USA.

Grüttner, H., Frank, W., Kristensen, G. H., Feenstra, L. & van Tongeren, W. G. J. M. 2010 Methodology Water Quality Control – Identification and Management of Water Quality Aspects in an Optimised Water Network based on HACCP Methodology and Principles. AquaFit4Use. www.aquafit4use.eu/userdata/file/Public%20results/AquaFit4Use%20-%20Methodology%20Water%20Quality%20Control.pdf.

Klemeš, J. J., Varbanov, P. S., Wan Alwi, S. R. & Manan, Z. A. 2014 *Process Integration and Intensification*. Walter de Gruyter GmbH, Berlin.

Mohammadnejad, S., Nabi Bidhendi, G. R. & Mehrdadi, N. 2010 A new algorithm for water and wastewater optimization in multiple contaminants network using water pinch technology. *Res. J. Environ. Sci.* **4**, 193–208.

Mohammadnejad, S., Nabi Bidhendi, G. R. & Mehrdadi, N. 2011 Water and wastewater minimization in petroleum refinery through water pinch analysis-single and double contaminants approach. *Res. J. Environ. Sci.* **5** (1), 88–104.

Nabi Bidhendi, Gh. R., Mehrdadi, N. & Mohammadnejad, S. 2010 Water and wastewater minimization in Tehran oil refinery using water pinch analysis. *Int. J. Environ. Res.* **4** (4), 583–594.

NACMCF (National Advisory Committee on Microbiological Criteria for Foods) 1992 Hazards Analysis and Critical Control Point System. *Int. J. Food Microbiol.* **16**, 1–23.

NFPA (Microbiology and Food Safety Committee of the National Food Processors Association) 1993 HACCP implementation: A generic model for chilled foods. *J. Food Protect.* **56** (12), 1077–1084.

Sharma, S. & Rangaiah, G. P. 2016 Design, Retrofit and revamp of industrial water networks using multi-objective optimization approach. G. P. Rangaiah, ed. *Chemical Process Retrofitting and Revamping: Techniques and Applications*. John Wiley, New York.

USDA (United States Department of Agriculture) 1999 Guidebook for the preparation of HACCP plans. Available from: www.fsis.usda.gov/wps/wcm/connect/3ec95930-e7fe-4e61-90ad-675e6b483591/HACCP-1.pdf?MOD=AJPERES.

First received 30 September 2015; accepted in revised form 9 February 2016. Available online 18 March 2016