SYSTEMATIC DESIGN OF A MAXIMUM WATER RECOVERY NETWORK FOR AN URBAN SYSTEM BASED ON PINCH ANALYSIS

S. R. Wan Alwi, Z. A. Manan and Z. Ujang
Department of Chemical Engineering, Universiti Teknologi Malaysia 81310 UTM, Skudai, Johor
E-mail: zain@fkkksa.utm.my

ABSTRACT

Pinch Analysis has been an established systematic technique for optimal design and retrofit of heat, mass and water recovery networks in industry to achieve maximum energy as well as mass efficiency. Until today, the application of Pinch Analysis is perceived to exclusively belong to the domain of process industry. This work represents a shift in the current process engineering paradigm to allow Pinch Analysis application to be extended beyond the frontiers of process industry. Two key developments related to the extension of Pinch Analysis technique to the urban sector has been presented. One is as per the establishment of the minimum water targets using the new water cascade analysis technique; and two, the adaptation of the source-sink mapping technique for the design of a maximum water recovery network to an urban system to achieve the water targets.

Application of these techniques on Sultan Ismail Mosque in Universiti Teknologi Malaysia yields potential maximum reductions of 85.5% fresh water and 67.7% wastewater.

Keywords: *Pinch Analysis, Regeneration, Urban Systems, Water Cascade Analysis*

1.0 INTRODUCTION

Water demands are growing every year as the result of the booming world population. A population report on environment and water issues had estimated that more than 2.8 billion people in 48 countries will lack access to adequate water supplies by 2025 [1]. The Middle-Eastern countries have long relied on non-conventional water supplies due to water scarcity. For example, four Gulf states; Bahrain, Kuwait, Saudi Arabia, and the United Arab Emirates have so little fresh water available that they resort to desalination, a costly process of converting sea water into fresh water. Saudi Arabia now must mine fossil groundwater to fulfill three-quarters of its water needs. Jordan and Yemen withdraw 30% more water from groundwater aquifers every year than the replenishment rate, Israel's annual water usage already exceeds 15% of its renewable supply [2].

Huge investments have been spent to expand water supply to increasing number of consumers in industry and housing estates world-wide. Rapid increase in water tariff has spurred water conservation efforts particularly in industrial sector. It has been reported that industrial water used in some developed countries has been falling as a result of greater water efficiency through reuse, recycling or regeneration of water. For example, industrial water use in England and Wales has fallen by 900 million m^3 since year 1998 [3]. While industries and commercial enterprises have made significant progress in water efficiency, the reduction of water usage among the general public have been extremely poor, thereby resulting in a steady increase of urban water demand [4]. This discrepancy can be attributed to the low water-tariff and wide availability of potable water in urban areas. Consequently, the general public, particularly the urban population, has little consciousness on water savings and hence, the energy savings associated with water used.

The urban sector contributes a significant percentage of water consumption particularly in developed countries with warmer climates. In Malaysia for example, the domestic sector contributes 68% of the total water consumption compared to other sectors [5]. The need for efficient water management in urban sector is getting more crucial as a result of the sharp increment of fresh water price. This trend is likely to continue in the near future due to the predicted shortage of fresh water, and hence, the possibilities of resorting to wastewater treatment, desalination, groundwater extraction and, interstate water purchase as well as water transfer. Compared to the extensive amount of work conducted on water minimisation in industry, there has been much less efforts towards water conservation in urban sector.

The majority of works on urban water conservation have focussed on reuse of greywater with and without treatment and rainwater harvesting. Apart from the conventional approaches of water recycling/reuse and rainwater harvesting for lower grade water usages such as for toilet flushing and irrigation, there has been noteworthy efforts towards maximising water recovery through the design of closed-loop water system as well as water cascading.

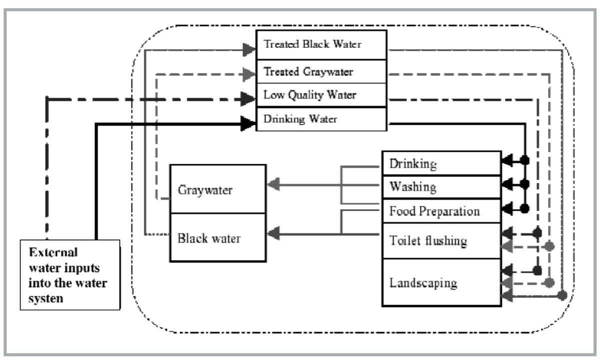

Figure 1: A closed water loop for a residential building [6]

Closed loop water system aims towards a total re-use of all components in the wastewater. Bakir [6] has documented the concept of closed loop in water demand management for a residential building. The main idea is to match water quality with the appropriate water usage as shown in Figure 1. This closed-loop method can also be applied for household, neighbourhood, community, industry, or institution scale. After water is used, the generated wastewater is segregated into greywater and blackwater streams. The wastewater streams are treated accordingly before being reused or recycled for other applications.

Table 1: Water Quality Cascade with End Uses [7]

Increasing perception of risk (↓)	Source	End Use	Increasing quality requirement (↑)
	Scheme water OR Treated and disinfected rainwater	Drinking Kitchen Showers Basins	
	Treated and disinfected greywater	Cleaning Cooling tower make up Toilet flushing	
	Treated and disinfected cooling tower blowdown	Cleaning Toilet flushing	
	Treated and disinfected blackwater and blackwater blowdown	Roof garden irrigation	

The basic principle of water cascading system is water quality cascade where water sources are matched with end uses in terms of the required water quality as shown in Table 1. According to [7], water conservation can be maximised through integration of the whole suite of water conservation measures such as rainwater capture, installation of water efficient fixtures, effluent reuse and evaporation as well as productive reuse of treated effluent in roof gardens. Two case studies, a 4-storey commercial green building in Melbourne and a typical commercial high-rise building have shown a reduction up to approximately 80% of freshwater consumption and 80% of wastewater discharge achievable via this technique.

Toilet flushing contributes between 30 to 60 percent of water uses in urban areas [8]. As toilet flushing activity is one of the highest water demands in urban system and it does not involve human contacts, hence the reuse of greywater after treatment or rainwater for toilet flushing is a viable option with minimum health risk [8, 9, 10, 11, 12]. Several researchers have reported significant savings in reusing greywater and rainwater for toilet flushing. For example, [13] had stated that theoretically rain or greywater can replace all drinking water for toilet flushing. This can constitute up to 34% of the total water consumption. Burkhard *et al.*[13] has also reported that [14] study has managed to achieve a savings of 39% and sayers [15] has reported a reduction between 5.2 to 30.6%. Aside from water reuse or recycle for toilet flushing, its use for irrigation is also an alternative. CSBE [16] reported that greywater from ablution in the King Abdullah Mosque in Jordan was collected, filtered and reused for irrigation. The system has resulted in significant savings on the mosque's water bills such that the capital cost for installation of the system was recovered within the first year of operation.

In a water distribution system, it is possible to determine the maximum water reuse/recycle flowrate through appropriate water cascading. Note that the maximum water reuse and recycling corresponds to the minimum fresh water consumption. The first key step towards maximising water recovery and minimising fresh water consumption as well as wastewater generation is to establish the baseline minimum water targets prior to the design of a water recovery network to achieve the minimum water targets, or the maximum water recovery (MWR) network.

The available works on water targeting and MWR network design are almost exclusively focused on industrial applications, in line with the advent of Water Pinch Analysis (WPA) technique [17, 18, 19, 21, 22, 23, 24]. Water pinch analysis is a systematic technique for implementing strategies to maximise water reuse and recycling through integration of water-using activities or processes. Typical WPA solution comprises of two steps, i.e., setting the baseline water targets followed by network design to achieve the baseline targets. Wan Alwi et al. [25] had recently made the first attempt to establish the baseline water targets for an urban water system using a new technique known as Water Cascade Analysis (WCA).

From the preceding review, it can be concluded that even though water conservation techniques involving reuse, recycling and regeneration have been implemented for urban system, the concepts of baseline minimum water targets, maximum water recovery design, stream mixing and process modifications to achieve the minimum water targets are unknown for urban sector. The objective of this study is to extend the WPA methodology beyond the frontiers of process industry for sustainability of water resources. In this work, the WPA technique will be used to design a maximum water recovery network for the urban sector. Breakthrough of WPA technique into the urban sector will significantly contribute towards the global effort for efficient conservation of water resources.

2.0 METHODOLOGY

Water management hierarchy consists of five levels, namely (1) source elimination, (2) source reduction, (3) direct reuse/outsourcing of external water, (4) regeneration, and (5) use of fresh water [26]. Water Pinch Analysis (WPA) is concerned with maximising water reuse and regeneration-reuse/recycling down the third and fourth level of the water management hierarchy. This will minimise fresh water consumption as well as wastewater generation. In section 4.1 to 4.5, this study presents the implementation of WPA into the urban system in five key steps. The first step is to

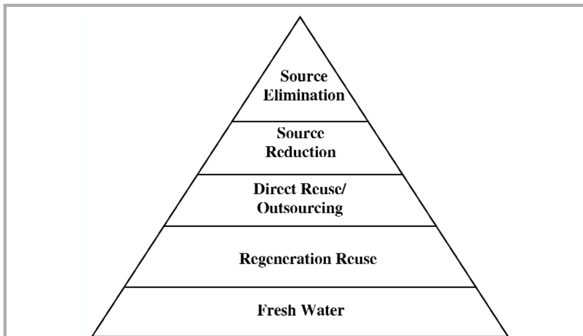

Figure 2: ZM Hierarchy of Water Management (Priority)

audit the existing or the base case water network in terms of quantity (flowrate) as well as quality (contaminant concentration). The second step is to identify and isolate the relevant water sources and water demands having potential for integration. The third step is to establish the minimum water and wastewater targets using the water cascade analysis technique (WCA). The fourth step is to design a water recovery network to realise the minimum water targets. The final step is to consider process changes like regeneration and to evaluate the economics of the newly designed or retrofitted network. A case study involving Sultan Ismail Mosque in Universiti Teknologi Malaysia (UTM) was used to illustrate the procedure for implementing Water Pinch Analysis on an urban system.

3.0 RESULTS AND DISCUSSION

3.1 Audit of the existing Sultan Ismail Mosque (SIM) water network

Sultan Ismail Mosque (SIM) located in Universiti Teknologi Malaysia (UTM) was chosen as the case study for this work to illustrate the MWR network design method for urban system. The four-storey mosque is mainly used by 3500 Muslim UTM community for prayer and educational activities. The estimated total fresh water consumption for SIM is 11550 m^3/yr [27]. Of this value, 9178 m^3/yr is used for ablution and the rest is for toilet flushing, irrigation, mosque cleaning, wash-basin and toilet pipes [27]. The total water consumption varies throughout the year during semesters and holidays. During the semester, the amount of water consumed for ablution is about 60 m^3/day on Friday but only 25 m^3/day on other days. For this study, daily water consumption calculations will be based on normal semester days [27]. Figure 3 shows the water using processes in terms of total flowrate and limiting maximum contaminant data. The initial freshwater consumption for the mosque is 29.10 te/day.

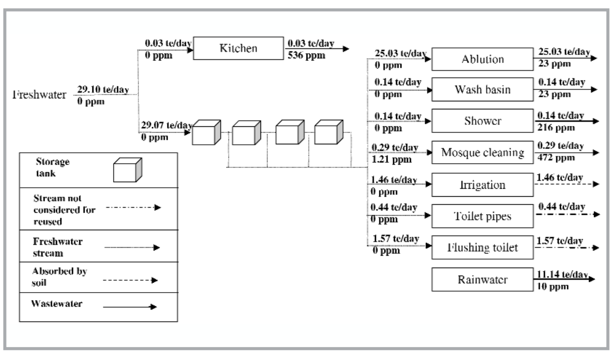

Figure 3: Water distribution network for Sultan Ismail Mosque

3.2 Data extraction

The maximum limiting contaminant concentration data for water demands for SIM was based on USA-EPA standards for water reuse [28]. USA-EPA specifies for the BOD level to be reduced to at least 10 ppm for non-potable domestic water recycle. Non-potable water refers to water that is not used for human consumption, such as for drinking. Since all the water usages after the distribution tank in SIM was non-potable, a maximum BOD limit of 10 ppm was set for the water demands. A BOD value of 0 ppm was set for kitchen water demand. Fresh water, greywater, rainwater, snow and treated wastewater are all potential water sources. The limiting contaminant concentration for these water sources can be obtained via water quality test or from literature data. "Blackwater" from toilet flushing and toilet pipes were not considered as water source since it was highly contaminated with urine and faeces while water from irrigation was assumed to be completely absorbed by soil.

The limiting data for water sources were based on the data provided [16] as well as from [8]. CSBE [16] performed quality tests on ablution greywater collected from King Abdullah Mosque. In this work, it was assumed that wash basin greywater and ablution greywater were of similar quality, i.e. 23 ppm. Surendran and Wheatley [8] conducted research on the average pollutant concentration in greywater from a hall residence. The BOD data for sources like showering, kitchen and mosque cleaning for SIM were based on these data. The BOD for mosque cleaning was assumed to be similar to that of a washing machine since they both contained detergent. The limiting data for the water demands and sources are summarised in Table 2 and 3 respectively.

Table 2: Summary of the water demands for Sultan Ismail Mosque

Stream	Demands Description	Flowrate (te/day)	Biological Oxygen Demand (BOD) concentration, (ppm)
D1	Kitchen	0.03	0
D2	Ablution	25.03	10
D3	Wash basin	0.14	10
D4	Showering	0.14	10
D5	Mosque cleaning	0.29	10
D6	Irrigation	1.46	10
D7	Toilet pipes	0.44	10
D8	Flushing toilet	1.57	10

Table 3: Summary of the water sources available in Sultan Ismail Mosque

Stream	Sources Description	Flowrate (te/day)	Biological Oxygen Demand (BOD) concentration, (ppm)
S1	Rainwater	11.14	10
S2	Ablution	25.03	23
S3	Wash basin	0.14	23
S4	Showering	0.14	216
S5	Mosque cleaning	0.29	472
S6	Kitchen	0.03	536

3.3 Targeting the minimum utility using Water Cascade Analysis technique (WCA)

One of the latest and widely used water targeting techniques known as water surplus diagram [22] is limited in its ability to estimate the minimum water targets as it implements a graphical approach that involves time-consuming trial-an-error steps. This limitation has inspired the development of a numerical technique known as Water Cascade Analysis (WCA) that eliminates the trial-an-error approach [29]. The main objective of the WCA is to establish the minimum water targets, i.e. the overall fresh water requirement and wastewater generation for a process after looking at the possibility of using the available water sources within a process to meet its water demands.

Manan *et al*. [29] provides a detailed description of how WCA was used to established the baseline water targets for the

Table 4: Water Cascade Table (WCT) for Sultan Ismail Mosque case study

Interval n	Concentration C_n (ppm)	Purity, P_n	ΣF_D (te/day)	ΣF_S (te/day)	$\Sigma F_D + \Sigma F_S$ (te/day)	F_C, (te/day)	Pure water surplus (te/day)	Cumulative pure water surplus (te/day)
						F_{FW} =10.16		
	0	1.000000	-0.03		-0.03			
1						10.13	0.000101	
	10	0.999990	-29.07	11.14	-17.93			0.000101
2						-7.80	-0.000101	
	23	0.999977		25.17	25.17			**0 (Pinch)**
3						17.37	0.003353	
	216	0.999784		0.14	0.14			0.003353
4						17.51	0.004484	
	472	0.999528		0.29	0.29			0.007837
5						17.80	0.001139	
	536	0.999464		0.03	0.03			0.008976
6						**F_{WW} =17.83**	17.824789	
	1000000	0						17.833765

Sultan Ismail Mosque. The targets generated via WCA predict a significant potential reduction in terms of fresh water and wastewater, far beyond the water network revamp proposed earlier. Table 4 shows the WCA targets for fresh water consumption and wastewater generation for the mosque at 10.16 te/day and 17.83 te/day respectively. These targets represent 65.1% fresh water savings and 51.5% of wastewater reduction. Note that the pinch point for the mosque water network exists at the third purity level (P = 0.999977) where there is zero cumulative pure water surplus.

Results of the study show that setting the minimum fresh water and wastewater targets prior to design allow a designer to rapidly pinpoint the options for water recovery network design that satisfy the minimum water targets, thereby saving considerable amount of resources in detailed evaluation and screening of numerous inferior design options. Next, a systematic procedure for the design of a maximum water recovery (MWR) network is carried out to achieve the baseline water targets established.

3.4 Design of a maximum water recovery network

3.4.1 Network design

The network that achieved maximum water recovery, and hence, the minimum water targets without regeneration was generated using the source-sink mapping diagram (Figure 4) which were based on three key design heuristics presented in this section. Table 4 shows the minimum fresh water target for SIM at 10.16 te/day and the pinch concentration at 23 ppm. In order to achieve the water targets, it was necessary to observe the pinch division by designing the water networks above and below the pinch separately according to heuristic 1:

Heuristic 1: Do not feed water sources above the pinch (including fresh water) to demands below the pinch and vice versa [22].

Heuristic 1 forbids water sources above the pinch (including fresh water) from being mixed with demands below the pinch concentration. On the other hand, it also disallows mixing of demands above the pinch with sources below the pinch. For the SIM case study, source S1 (10 ppm) above the pinch should not be fed to any demand below the pinch concentration. However, since all demands in this case were above the pinch, all water sources above the pinch could be matched with any of the demands. Sources S4 (216 ppm), S5 (472 ppm) and S6 (536 ppm), which existed below the pinch should not be fed to demands above the pinch according to heuristic 1. Since there were only sources and no demands below the pinch, all sources there could not be reused and was discharged as wastewater.

Note that the source at the pinch concentration partly belongs to the region above the pinch and partly below the pinch. The exact distribution of the source stream at the pinch concentration is shown in column F_c of the water cascade table. Table 4 shows that 7.8 te/day of water source at 23 ppm belongs to the region above the pinch while 17.37 te/day belongs to the region below the pinch.

Heuristic 2 serves as a guide in finding the right match between the various source and demand streams that exist in the region above as well as below the pinch. Following heuristic 2, the demand at the lowest contaminant concentration was first matched with the source at the lowest contaminant concentration.

Heuristic 2: Start the source-demand matching process with the demand at the lowest contaminant concentration [31].

For the SIM case study, demands D2 to D8 existed at the same concentration of 10 ppm. Thus, the source at the lowest concentration could be matched with any of these demands. Table 4 shows that two sources can be selected to satisfy D2. Source S1 at 10 ppm had the lowest contaminant concentration and was first selected to be matched with demand D2 according to heuristic 2.

This study have proposed heuristic 3 as a corollary to heuristic 2 for the systematic mapping of the available source streams as well as fresh water to the individual demands. Heuristic 3 and Equation (1) were used to determine the exact contaminant load and flowrate of sources S1 and S2 to satisfy demand D2.

Heuristic 3: Map the available sources one after another, and fresh water as required, to each demand according to heuristic 2 until all demands have been satisfied in terms of both quality (contaminant load) and quantity (flowrate) .

The contaminant load of a source S or a demand D, ($\Delta m_{S/D}$) was calculated using Equation (1).

$$\Delta m_{S,\,i\,/\,D,\,j} = \frac{F_{S/D} x \Delta C_{S/D}}{1000} \tag{1}$$

Hence, the contaminant load of D2 (Δm_{D2}) was obtained using Equation (1) by multiplying its flowrate (F_{D2}) by its contaminant concentration (ΔC_{D2}).

$$\Delta m_{D2} = \frac{F_{D2} x \Delta C_{D2}}{1000}$$

$$\Delta m_{D2} = \frac{25.03 te/day x 10 ppm}{1000} = 0.25 kg/day$$

Recall that S1 was selected to satisfy D2 according to heuristic 2. The contaminant load of S1 was 0.11 kg/day. This was less than the contaminant load required by D2. Hence, all 11.14 te/day of S1 flowrate was used to satisfy D2.

$$\Delta m_{S1} = \frac{F_{S1} x \Delta C_{S1}}{1000}$$

$$\Delta m_{S1} = \frac{11.14 te/day x 10 ppm}{1000} = 0.11 kg/day$$

The balance of D2 contaminant mass load was found to be 0.14 kg/day

$$\Delta m_{D2} = \Delta m_{S1} + \Delta m_{S2} + \Delta m_{FW}$$

$$\Delta m_{S2} = 0.25kg\ /\ day - 0.11kg\ /\ day - 0kg\ /\ day = 0.14kg\ /\ day$$

The remaining contaminant load of 0.14 kg/day for D2 was satisfied using source S2 at the next highest contaminant concentration. The required flowrate of S2, determined using Equation (2), was 6.04 te/day.

$$F_{S2} = \frac{\Delta m_{S2}}{\Delta C_{S2}}\ x1000 \qquad (2)$$

$$F_{S2} = \frac{0.14kg.day}{23ppm}\ x1000 = 6.04te/\text{day}$$

However, Equation (3) shows that the total quantity required by D2 was still short by 7.85 te/day even though its contaminant load had been satisfied. The deficit of 7.85 te/day was satisfied using fresh water according to heuristic 3.

$$F_{D2} = F_{S1} + F_{S2} + F_{FW}$$

$$F_{FW} = 25.03te/day - 11.14te/day - 6.04te/day = 7.85te/day \qquad (3)$$

The remaining quantity of 18.99 te/day from the total flow of 25.03 te/day for source S2 was used to satisfy the demand at the next highest contaminant concentration.

$$\sum F_{S2} = F_{S2,\ D2} + F_{S2,\ left}$$

$$F_{S2,\ left} = 25.03te/day - 60.4te/day = 18.99te/day \qquad (4)$$

3.4.2 Network Modifications

It is emphasised that Figure 4 is only one of the possible network designs for this case study. Other possible matches, including mixing of streams, may also yield the maximum water savings. Even though WPA had proposed a guideline for design to achieve the maximum water savings, the decision to strictly implement the design ultimately rests with the designer. For safety or layout reasons, a designer may influence the

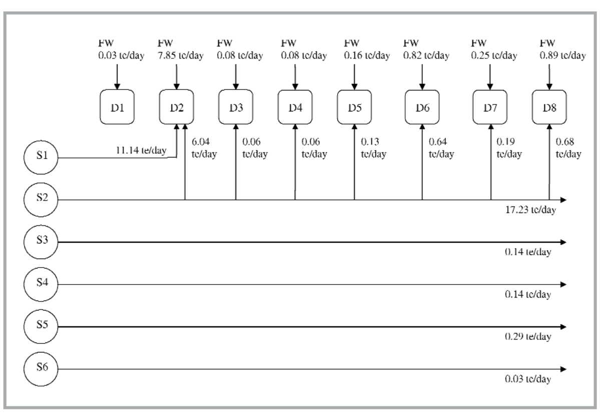

Figure 4: One possible water network design that achieved the targets for SIM case (without regeneration)

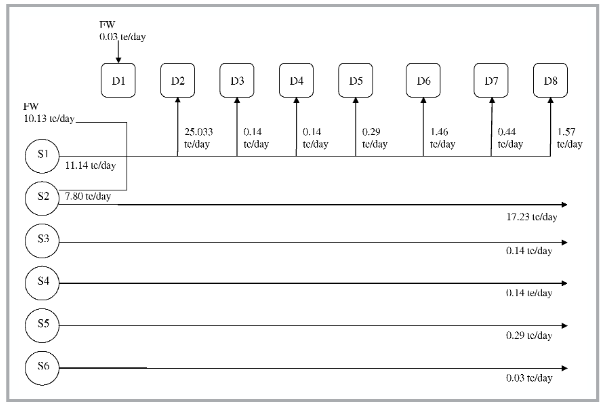

Figure 5: Water network design that achieved the targets for SIM case without regeneration (after modifications)

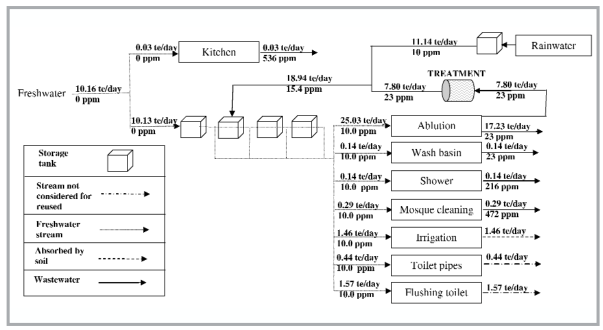

Figure 6: Final water network for SIM without regeneration (freshwater savings: 65.1% and wastewater reductions: 51.5%)

network design by imposing forbidden or forced connections [22]. Adhering to these constraints may however incur penalty in terms of the fresh water flowrate.

In the case of SIM, accepting the proposed network in Figure 4 will require rather extensive modifications to the original network in terms of new pipeworks, storage tanks and control system. The inconsistent ablution water flowrate would have to be supplied to seven water demands. For each demand, different freshwater flowrate needed to be added in order to satisfy the contaminant balance. This may be uneconomical and difficult to implement. Alternatively, instead of piping fresh water to all these demands, the rainwater (S1) and ablution wastewater (S2) may be mixed with freshwater in a distribution tank to produce a new water source at 10 ppm as required. With this modification, SIM was still able to achieve maximum water savings. The source and sink diagram for this modified design and the flow diagram for the final water network is shown in Figures 5 and 6 respectively. Note that the water demands (D1 to D8) are ordered at the top according to increasing contaminant concentration from left to right while the water sources (S1 to S6) are aligned vertically on the left hand side according to increasing contaminant concentration from top to bottom.

3.4.3 Water Regeneration Network Design

Making appropriate changes to a process has been widely accepted as an effective measure to further reduce utility targets in heat and mass integration [18, 32]. The same principle applies to WPA. Two possible scopes for process changes to further reduce the water targets, and hence, water consumption, include water regeneration and equipment (hardware) modifications. Water regeneration involves the partial or total upgrading of water purity using purification techniques such as wastewater treatment like microfiltration, greenhouse filter, sand filter with reeds, multi media filter and biofilter. The regenerated water can either be reused in other water-using processes or recycled to the same process to further reduce water consumption and wastewater generation.

The main problem of dealing with process changes is that, assessment of the impact of changes involves repetitive calculations to revise the utility targets and relocate the pinch. Such tasks can be quite cumbersome in the absence of an efficient targeting tool. The WCA has managed to overcome this problem through the introduction of the Water Cascade Table (WCT) that is very amenable to computer programming.

Recall that the pinch concentration for SIM case study was 23 ppm (before regeneration). One possible option of regenerating the water source is to treat the ablution water to a concentration above the pinch. It was suggested that 7.27 ton/day of ablution water at 23 ppm be regenerated to 10 ppm using sand filter with activated carbon. Table 5 from the WCT shows the new pinch purity at 0.999977 (23 ppm), and the fresh water and wastewater flowrates reduced to 6.06 ton/day and 13.73 ton/day respectively. This contributed to 79.2% freshwater savings and 62.7% wastewater reduction. The network design technique described previously also applies to the case involving water regeneration. The final flow diagram for water network with regeneration that achieves the new water targets is shown in Figure 7.

Table 5: WCT for process involving partial regeneration of ablution water

Interval n	Concentration C_n (ppm)	Purity, P_n	ΣF_D (te/day)	ΣF_S (te/day)	$\Sigma F_D + \Sigma F_S$ (te/day)	F_C (te/day)	Pure water surplus (te/day)	Cumulative pure water surplus (te/day)
						F_{FW} = 4.22		
	0	1.000000	-0.03		-0.03			
1						4.19	0.000018	
	4.2	0.999996		7.27	7.27			0.000018
2						11.46	0.000066	
	10	0.999990	29.07	11.14	17.93			0.000084
3						6.47	-0.000084	
	23	0.999977		17.90	17.90			**0 (PINCH)**
4						11.43	0.002206	
	216	0.999784		0.14	0.14			0.002206
5						11.57	0.002962	
	472	0.999528		0.29	0.29			0.005169
6						11.86	0.000759	
	536	0.999464		0.03	0.03			0.005928
7						**F_{WW} = 11.89**	11.885539	
	1000000	0						11.891467

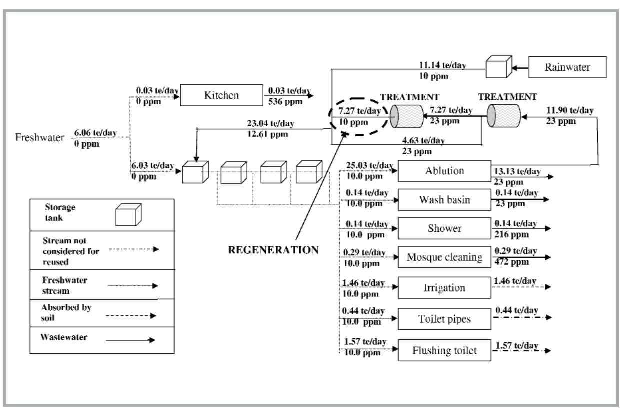

Figure 7: Final water network for SIM after partial regeneration (freshwater savings: 79.2% and wastewater reductions: 62.7%)

3.4.4 Water Network Scheme for Sultan Ismail Mosque Proposed by IEWRM

The Institute of Environmental and Water Resource Management (IEWRM), UTM, had proposed a water-recycling scheme aimed at minimising fresh water consumption for SIM. The retrofitted network design proposed by IEWRM is shown in Figure 8. IEWRM proposed the idea of reusing treated ablution water and rainwater for the entire mosque except for kitchen services. The ablution water or rainwater were to be filtered for solid particles like hair, stones and dirt's before going through a series of treatment using activated carbon and sand filter processes. The treatment process was to ensure that water being recycled to the distribution tank was at an acceptable purity for uses which involve body contact.

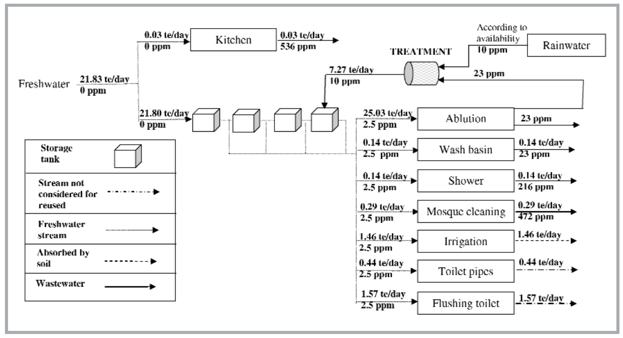

Figure 8: Retrofitted water network for SIM proposed by IWERM

The amount of ablution water reclaimed and rainwater collected was limited by the existing distribution tank. Treated ablution water will only be sent to the last distribution tank. Since the water output was approximately 29.07 ton/day for the four distribution tanks, only 7.27 ton/day of treated water can be fed into the last distribution tank. The flowrate of 7.27 ton/day represented the limiting point or bottleneck for this system. During the rainy season, rainwater was collected instead and the spent ablution water was diverted to the sewer. This design allowed an estimated fresh water savings and wastewater reductions up to 25% and 20%, respectively.

3.5 Economic Analysis

The system proposed by IEWRM predicted fresh water savings of 25% and wastewater reductions of 19.8% (Figure 8). The system suggested by WPA predicted savings of 79.2% freshwater and 62.7% of wastewater reduction after regeneration (Figure 7).

Table 6 provides a preliminary comparison of the economics between the solution proposed by IEWRM and WPA involving partial water regeneration. Both IEWRM and water pinch method used a UV disinfection unit and sand filter with activated carbon treatment to regenerate about the same amount of wastewater. Sand filter equipped with activated carbon that has a maximum flow rate flow of 7.27 m^3/day costs RM1170 per unit [33] and a UV system with 11 m^3/day flow rate cost RM1900 per unit [34]. The UV system has an operating cost of RM483 per year [34] for 10 hours in operation per day per unit. IEWRM uses one unit of sand filter and UV system for their new water network solution while the WPA solution uses one unit of sand filter for regeneration (secondary treatment) purposes and two unit of UV system for primary treatment purposes. The freshwater tariff in Johor for the year 2004 is RM2.13 per m^3 (SAJ water bill, [35]). This gives the treatment investment cost and annual freshwater savings as stated in Table 6.

Table 6: Economic comparison between the water network schemes proposed by IEWRM and WPA (with regeneration)

	FW savings	WW reductions	Treatment Investment			Annual FW Savings, RM/ yr	Payback Period, Months
			UV cost, RM	Sand filter cost, RM	Electrical cost, RM/yr		
IEWRM	25%	20%	1, 900	1, 170	483	5, 700	7.4
WPA	79.2%	62.7%	3, 800	1, 170	970	17, 900	4.0

Preliminary economic evaluation on these schemes indicated the payback period for IEWRM and WPA at 7.4 months and 4 months, respectively. The payback period using WPA was shorter due to much higher potential fresh water savings as compared to the IEWRM solution. Note however, that the current analysis, which considered only the cost of regeneration units was adequate as a preliminary economic comparison and design screening. To implement the selected design, a more detailed economic evaluation, which also considers pipework and storage tank costs should be performed.

4.0 CONCLUSION

A systematic procedure for design of a maximum water recovery network for an urban system based on WPA has been proposed. Sultan Ismail Mosque was selected as a case study to demonstrate the impact of the technique. The conventional solution proposed by IEWRM predicted fresh water savings of 25% and wastewater reductions of 19.8%. However, WPA method predicted savings of 65.1% fresh water savings and 51.5% of wastewater reduction for SIM without regeneration and 79.2% fresh water and 62.7% of wastewater reduction for SIM with regeneration. WPA enabled the minimum utility targets to be established prior to network design and provided systematic guidelines for the design of an MWR network to achieve the established utility targets. ■

REFERENCES

[1] Hinrichsen D., Robey B., A. M., and Upadhyay U. D., 1998, Population Reports (Volume XXVI, Number 1), Center for Communication Programs, The Johns Hopkins School of Public Health, USA.

[2] McCarthy, M., 2003, Water Scarcity Could Affect Billions: Is This the Biggest Crisis of All?, lndependent UK.

[3] Graham, N. J. D., 2001, Improving sustainability and quality in urban drinking water supplies, URBAN WATER, International Conference on Sustainable Development and Green Entrerprises, MACAU G. E

[4] Cheng, C., 2002, Study of the inter-relationship between water use and energy conservation for a building, *Energy and Building*, 34: 261-266, Elsevier.

[5] The Malaysian Water Association, 2003, *Malaysia Water Industry Guide*, 2003, Pg 74.

[6] Bakir, H., 1999, Water demand management and pollution control: Key to securing and safeguarding the water supplies of MENA in the 21st Century, http://www.emro.who.int [AssesedAssessed Februray 2004].

[7] Chanan, V., White, S., Howe, C., Jha, M., 2003, Sustainable water management in commercial office buildings, http://www.isf.uts.edu.au [Assessed February 2004].

[8] Surendran, S. and Wheatley, A. D., 1998, Grey-water reclamation for non-potable re-use, *Journal of Chartered Instituition of Water and Environment Management*,12 (6): 406-413.

[9] Hall, M. J., Hooper, B. D. and Postle, S. M., 1988, Domestic per capita water consumption in South West England, *Journal Institution Water & Environment Management*, 2 (6): 626.

[10] Butler, D., 1996, How much water do we use? *In Proc. Of Conf. on Water Recycling – Technical and Social Implications*, The Instituition of Chemical Engineers, London.

[11] Edwards, K. and Martin, L. A., 1995, A methodology for surveying domestic water consumption, *Journal Institution Water & Environment Management*, 9 (5): 477.

[12] Kresig, D., 1991, Greywater recycling: Treatment techniques and cost savings, *Worlds Water and Environment Engineering*, 19 (2): 17.

[13] Burkhard, R., Deletic, A. and Craig, A., 2000, Techniques for water and wastewater management: a review of techniques and their integration in planning, *Urban Water, 2*: 197-221, Elsevier.

[14] Sims, B., 1998, Liquid asset - services for housing grey water recycling, *Building Services Journal*, p. 30.

[15] Sayers, D., 1998, *A study of domestic greywater recycling*, Interim Report. National Water Demand Management Centre, Environment Agency. Worthing, West Sussex.

[16] Center for the Study of the Build Environment (CSBE), 2003, A Report on Graywater Reuse in Jordan, http://www.csbe.org [Assessed January 2004].

[17] Wang, Y. P. and Smith, R., 1994, Wastewater Minimisation, *Chem. Eng. Sci.*, 49, 981–1006.

[18] Linnhoff, B., Townsend, D. W., Boland, D., Hewitt, G. F., Thomas, B. E. A., Guy, A. R., & Marshall, R. H., 1982, A user guide on process integration for the efficient use of energy, Rugby: IChemE.

[19] Dhole, V. R., Ramchandani, N., Tainsh, R. A., Wasilewski, M., 1996, Make Your Process Water Pay For Itself,Chemical Engineering 103, 100-103.

[20] Sorin, M., & Bédard, S., 1999, The global pinch point in water reuse networks, *Transactions of IChemE*, Part B. 77: 305-308.

[22] Hallale, N., 2002, A new graphical targeting method for water minimization, *Advances in Environmental Research*, 6 (3): 377–390.

[23] El-Halwagi, M. M., Gabriel, F., & Harell, D., 2003, Rigorous graphical targeting for resource conservation via material recycle/ reuse networks, *Ind. Eng. Chem*. Res., 42: 4319-4328.

[24] Manan, Z. A., Ooi, B. L., Lim, F. Y., and Foo, C. Y., 2003, Heat-MATRIX - A Computer Software for the Reduction of Energy and Water in Process Plants, 31st Int. Exhibition of Invention, New Techniques and Products of Geneva, Switzerland.

[25] Wan Alwi, S. R., Manan, Z. A., and Ujang, Z., 2004, Systematic technique for water minimisation in urban water system using water pinch analysis, *Proceedings of ASIA WATER 2004*, Kuala Lumpur, Malaysia.

[26] Manan, Z. A. and Wan Alwi, 2005, A Holistic Framework for Design of Minimum Water Utilisation Networks for Industry and Urban Systems, *AiChE Journal*, Under review.

[27] Ujang, Z., and Larsen M., 2000, Development of Mass Balance and Quantitative Inventory of Water Management in UTM Skudai Campus for Reclamation and Reuse Program, Research VOT 71498, Institute of Environmental and Water Resource Management Universiti Teknologi Malaysia, pg 33-35.

[28] Al-Jayousi, O. R., 2003, Greywater reuse: towards sustainable water management, *Desalination*, 156: 181-192, Elsevier.

[29] Manan, Z. A., Foo, C. Y. and Tan, Y. L., 2004a, Targeting the Minimum Water and Wastewater Flowrates using the New Water Cascade Analysis Technique, *AiChE Journal* , Vol 50, No. 12, December 2004.

[30] Manan, Z. A., Wan Alwi, S. R. and Ujang, Z., 2004b, Water Pinch Analysis for Urban Systems: Setting the Minimum Water Targets. *Desalination* (Ref: DES 3270)

[31] Polley, G. T., and Polley, H. L., 2000, Design better water networks, *Chemical Engineering Progress*, 96 (2): 47-52.

[32] El-Halwagi, M. M., 1997, *Pollution prevention through process integration: systematic design tools*. San Diego: Academic Press.

[33] Delcol United Marketing (M) Sdn Bhd, 2004, e-catalogue, www.delcolunited.com/ [Assessed February 2004].

[34] PuriTec, 2004, Advanced Air and Water Treatment Technologies, www.puritec.com [Assessed Febuary 2004].

[35] Syarikat Air Johor (SAJ) water bill, December 2004.

NOMENCLATURE

Symbols

C = contaminant concentration, ppm
F = flowrate of water demand or source, kg/s or t/hr
n = number of purity intervals
N = number of water demands or sources
P = purity
Δ = difference
Σ = summation
m = contaminant load

Subscripts

C = cumulative
D = water demands
FW = fresh water
S = water sources
WW = wastewater

PROFILES

Zainuddin bin Abdul Manan
Chemical Engineering Department,
Universiti Teknologi Malaysia,
81310 Skudai, Johor, Malaysia.