AN OPTIMAL WATER RECOVERY NETWORK MODEL FOR A MOSQUE

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ABSTRACT

This work presents a mixed integer nonlinear programming (MINLP) model for cost-effective retrofit of a minimum water network involving a multiple contaminants. This optimization problem was performed on a water network superstructure to achieve the minimum water targets for global water operations. The model simultaneously considers all levels of water management hierarchy and cost constraints to select the best water minimization schemes that can achieve the minimum water networks within a desired payback period. In this model, a centralized regeneration and reuse system is considered to reduce freshwater consumption as well as capital investment. The approach has been successfully implemented on a mosque case study and yielded significant savings within a designers' payback period criterion.

Keywords: Optimization; Minimum water targets, Water management hierarchy; Water minimization; Water network.

1.0 INTRODUCTION

Water is an indispensable resource. Islam teaches human being to conserve resources and to avoid wastage. The Holy Quran says (Al-Araf, 31), *"But waste not by excess: for Allah loveth not the wasters"*. A *fatwa* issued by the Council of Leading Islamic Scholars (CLIS) in Saudi Arabia [1] postulated that *"Impure waste water can be considered as pure water and similar to the original pure water, if its treatment using advanced technical procedures is capable of removing impurities with regard to taste, colour and smell, as witnessed by honest, specialized and knowledgeable experts. Then it can be used to remove body impurities and for purifying, even for drinking"*.

Rising cost of raw water and effluent treatment, stringent environmental regulations and shortage of quality raw water have encouraged widespread water conservation efforts through design of maximum water recovery (MWR) networks. Typically, graphical water pinch analysis and mathematical programming approaches have been used to generate MWR design and maximize opportunities for water reuse and recycling for industrial and urban facilities through integration of water-using operations.

Water system integration research using graphical method for targeting maximum water reuse was pioneered by Wang and Smith [2]. Thereafter, various techniques on targeting, design and improvement of maximum water recovery networks for single contaminant system applicable for mass transfer-based (MTB) and non-mass transfer-based (NMTB) [3-9] operations have been developed using graphical water pinch analysis technique.

Mathematical programming technique, on the other hand, is more suitable for designing complex water networks involving multiple contaminants even though it is less popular among industrial practitioners due to the difficulty in mastering the technique. Implementation of mathematical programming techniques in solving water or wastewater minimisation problems has been reported in the literature since 1980s. Takama et al. [10] solved a water allocation problem in a petroleum refinery by using mathematical programming technique where the water recovery network problem was first presented by a superstructure that generates every possible connections for the water system. Then, mathematical model is formulated based on the superstructure that can be applied for a single contaminant system. In order to obtain a MWR network for an industrial plant, Bagajewicz and Savelski [11] proposed a linear program (LP) model to target freshwater usage while obtaining the maximum water recovery for a system involving single contaminant. The authors also developed a series of MILP problems to design different network alternatives. According to Savelski and Bagajewicz [12], the outlet concentrations must be set at their maximum allowable values in order to obtain an optimal water network system.

Dunn et al. [13] reported the results for the first published NMTB problem found thus far. They used an NLP model to target minimum wastewater generation by maximizing wastewater recovery. Even though the approach was said to have managed to reduce wastewater generation, it failed to consider fresh water usage as source. No methodology for solving the problem was presented in the paper.

Later, Wang et al. [14] described the application of the water networks with single internal water main for multiple contaminants. Water networks with just one internal water main determined by the presented method can obviously reduce water consumption, approaching the minimum water consumption target. The authors tried to solve the problem by presenting a related design methodology for water network that is easy to design, operate and control. Although the authors used single water main to reduce fresh water consumption, it cannot guarantee global solution. Zheng et al. [15], in their paper, proposed an optimal design procedure for water networks with multiple internal water mains. The methodology permitted experimentation with the number of internal water mains and the number of outlet streams from each process unit.

More recently, Teles et al. [16] proposed two initialisation procedures that provide multiple starting points to design optimal water network for MTB and NMTB operations by reducing NLP to LP during initialisation procedures using global optimisation methods [17]. However, the method also has its drawback since it requires highly computational effort due to the large number of problems that needs to be solved which may lead to an unreasonable computation time for problem involving more than six operations.

Most of the mathematical programming approaches based on NLP or MINLP involving multiple contaminants are focused on mass transfer-based operations. NLP and MINLP are very dependent on starting point and do not guarantee global optimum. Therefore, many authors then solved it using a two-stage optimisation to approximate the optimal solution [16, 18-21]. In contrast, Castro et al. [22] claimed that their heuristic procedure was able to generate good starting point and find global optimal solutions up to three orders magnitude faster than when using the global optimisation solver GAMS/BARON to solve NLP problem.

It is worth noting that freshwater consumption in a building or a plant can be further reduced by implementing regeneration system. Feng et al. [23] employed sequential optimisation and optimised regeneration recycling water networks at grassroots design stage using NLP and MINLP models. The mathematical models are solved step by step to obtain minimum fresh water consumption, minimum regenerated water flow rate and minimum contaminant regeneration load. Moreover, this method can be applied for both single and multiple contaminants regeneration recycling water networks. Meanwhile, Ng et al. [24] introduced partitioning regenerators where the contaminated water are purified by splitting it into a lean regenerated stream and contaminant-rich reject stream This work was further improved by Tan et al. [25] by introducing a superstructure-based model in order to design the water networks with centralised partitioning regenerators. Enhancement of water recovery via interplant water integration (IPWI) has been proposed by Chew et al. [26]. The method enhances water recovery via interplant water integration (IPWI) by using two different schemes for IPWI synthesis, which is direct and indirect integration. In the indirect integration scheme, water networks from different plants are interconnected via a centralised regeneration unit that is more practical in handling a large number of water networks. Lovelady and El-Halwagi [27] later implemented the centralised regeneration system in eco-industrial park in order to obtain maximum water recovery through IPWI.

All the above-mentioned methods have mainly focused on MWR concept which is related to maximum water reuse, recycle and regeneration. Nevertheless, it does not lead to the minimum water targets as widely claimed by researchers over the years. Earlier work on the use of water minimisation strategy beyond recycling had been done by El-Halwagi [28], who proposed targeting technique involving water elimination, segregation, recycle, interception and source/sink manipulation. Hallale [29] gave clear guidelines for process modifications and regenerations through pinch approach and how water surplus diagram can offers this insight to the designers. In other work, Feng et al. [30] proposed appropriate process changes for concentration and mass load using graphical approach by employing a set of heuristic rules. Nevertheless, the rules is only can applicable for MTB problem.

Remarkably however, it is important to note that the minimum water targets can only be achieved when all feasible methods are implemented to holistically reduce freshwater consumption through elimination, reduction, reuse/outsourcing and regeneration. Wan Alwi and Manan [31] introduced a water management hierarchy (WMH) to give new insight in process modification. The minimum water network (MWN) design not only considers reuse and recycling but all conceivable methods to holistically reduce fresh water consumption through elimination, reduction, reuse/outsourcing and regeneration based on the WMH. All this process changes are systematically implemented in terms of priority through a clear guidance.To date, Handani et al. [32] presented a generic MILP model to minimize freshwater consumption and wastewater generation for system involving multiple contaminants. The proposed model holistically considers process changes via all levels of water management hierarchy including elimination, reduction, reuse, outsourcing, and regeneration in order to select the best water minimization schemes that can achieve the minimum water targets and ultimately lead to a minimum water utilization network. In addition, the model can be used to simultaneously generate the minimum water targets and design the minimum water network for global water-using operation for various types of buildings. Furthermore, the model also is able to holistically determine water source to be eliminated or reduced, the amount of external water source needed, which wastewater source should be reused/recycled, regenerated or discharged. However, the main aim of the work by Handani et al. [32] is to reduce freshwater consumption and wastewater generation without considering any cost constraints.

Even though the aforementioned tendency is focused on fresh water minimisation, there are several works done on minimising cost objective for water system design. The idea of Cost-Effective Minimum Water Network (CEMWN) design with consideration of process changes guided by water management hierarchy (WMH) was first initiated by Wan Alwi and Manan [30] to give new insight in process modification and and its application was further

demonstrated in Wan Alwi et al. [33] All these process changes are systematically implemented in terms of priority through a clear guidance. In addition, the authors also introduced a cost screening technique known as *Systematic Hierarchical Approach for Resilient Process Screening Approach (*SHARPS) to screen inferior process changes based on investment and savings subjected to the desired payback period set by a plant owner. However, the graphical method and heuristics steps are quite cumbersome and tedious.
Later, Handani [34] expanded her work by introducing a Model for Optimal Design of Water Networks (MODWN) using two-stage optimization for a water system that containing multiple contaminants. In this approach, all the WMH options are considered simultaneously in order to obtain minimum water targets. The objective of the first stage is to minimise fresh water target which leads to minimum wastewater generation without considering any economic constraints and the problem is formulated as MILP model in order to provide initial values for the second stage. In the second stage, the optimiser determines the maximum net annual savings (NAS) of water networks while satisfying the minimum possible fresh water and wastewater targets and achieving the desired payback period for retrofit design. The solution available from the first stage is refined in the second stage to obtain a final solution in a general MINLP. The author also considered all water minimization options simultaneously and the model applied decentralized reuse system in order to avoid a complexity in designing a water network system.

This paper extends the CEMWN strategy to a mixed integer non linear programming (MINLP) model to achieve a cost-effective minimum water network for urban sector, particularly for mosque water distribution network. This model also considers centralized regeneration and reuse systems in order to reduce cost as well as freshwater consumption. Since the water flowrate is intermittent and there are no engineers or technician to maintain a complex system, a centralize reuse/recycle and regeneration system are prefered for easy maintenance and cheaper cost. The centralize system is also better for retrofit system as it requires minor renovation compared to decentralize system. It is important to note that, this method can be applied for both single and multiple contaminants problems.

2.0 PROBLEM STATEMENT

Given a set of global water operations for various water sources and water demands containing multiple contaminants, it is desired to design a cost effective minimum water network considering centralized reuse and regeneration using mathematical programming technique that considers all water management hierarchy that can achieve the maximum net annual savings at a desired payback period for retrofit design.

3.0 ASSUMPTIONS AND LIMITATIONS

Following are assumptions and limitations used in this model:

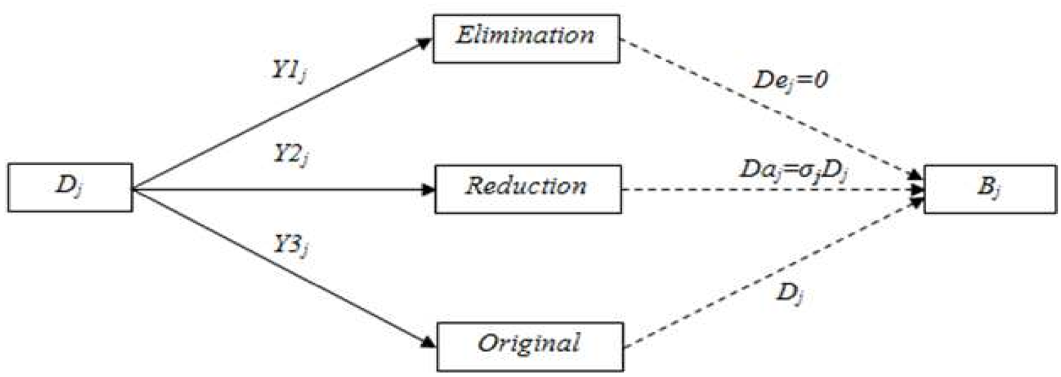
a) All contaminants concentrations for each demand and source are fixed to their maximum values.
b) There are no flow rate losses or gains, and hence, no changes in water flow rates in the water operations.
c) The water system is assumed to be operating continuously.
d) The system operates isothermally.

4.0 SYNTHESIS OF WATER NETWORKS

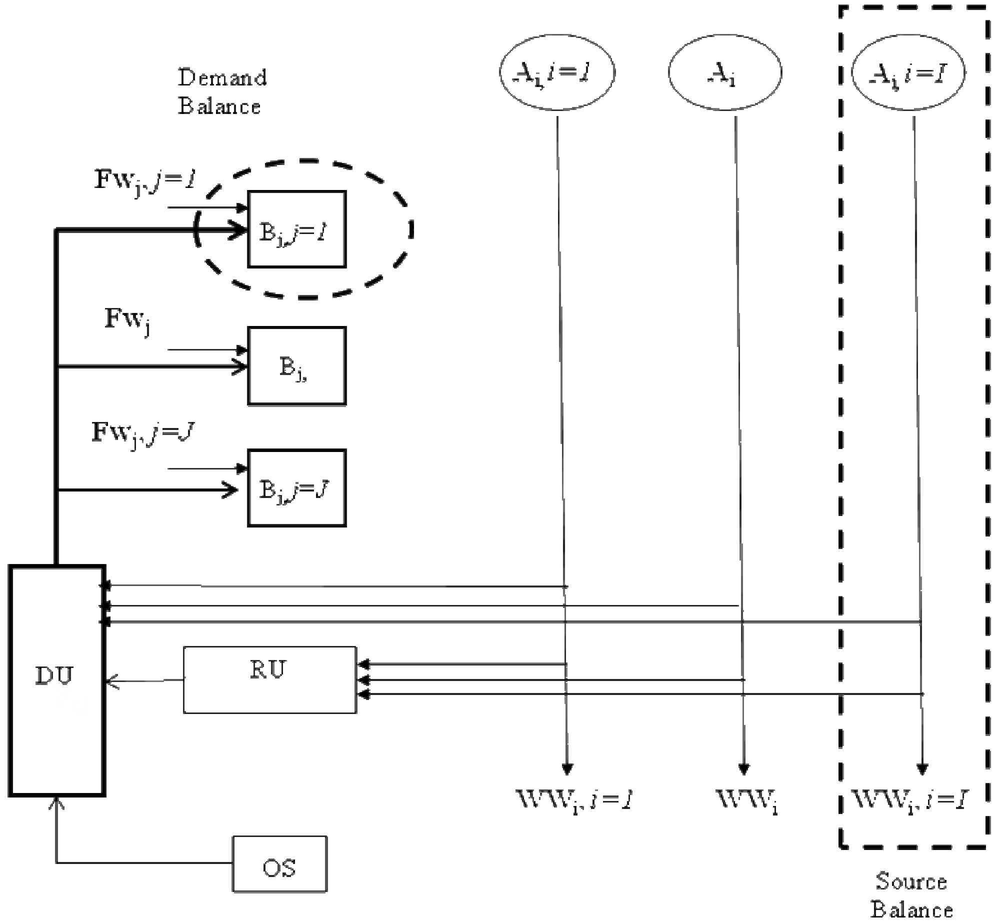
In this case, the objective function is to minimize total freshwater flow rate by considering all levels of water management hierarchy (WMH) subject to a desired payback period. By minimizing freshwater flow rate, it will also lead to maximum annual savings. The minimum water targets establishment consists of the overall freshwater requirement and wastewater generation for a process after considering the possibility of elimination and reduction of demand flow, and reuse or regeneration of source flow. The main data specifications are limiting contaminant data and flow rate for all available water sources and demands available in the system. The water sources data are obtained by identifying the maximum concentration limit and the minimum flow rate limit of the wastewater source from each process.

4.1 Superstructure Representation

The representative superstructure is based on water minimisation options using the WMH as a guide. The superstructure generates every possible connection between all water minimisation options and water using operation as well as wastewater discharges. In this case, superstructure of every possible configuration of a water-using network is allowed. The following notation is adopted throughout the paper: S_i, D_j, FW and WW represent water flow rate of source i, demand j, freshwater and wastewater respectively. **Figure 1(a)** shows the superstructure on path or choice to obtain the adjusted demand flow rate, B_j in case of source elimination and reduction are considered. Binary variables, $Y1_j$, $Y2_j$ and $Y3_j$ are introduced to represent the possible water elimination or reduction equipment. De_j, Da_j and D_j denote the flow rate for elimination, reduction or original water demand. **Figure 1(b)** represents all possible connections among water sources, water demands and wastewater discharges with inclusion of outsourcing and regeneration options. For each water-using operation, the adjusted water demand flow rate, B_j can be supplied by freshwater, FW_j and disinfected water from disinfection unit, DU which is Fdu_j. While at the water source, A_i, the generated wastewater may be directly discharged to the end of pipe treatment, WW_i, or send directly to disinfection unit, DU or partially treated in the centralized regeneration unit, RU. Then, the centralized reused and regenerated water as well as outsourced resources, OS (e.g. rainwater, river and snow) will be further treated in disinfection unit before being supplied to water demand. The combination of **Figure 1(a)** and **Figure 1(b)** gives the generalized superstructure for the minimum water utilisation network considering all water minimisation options.



(a) Water network superstructure to obtain the adjusted demand flow rate, B_j when possible source elimination and reduction are considered.



(b) Water network superstructure for maximum water recovery that includes outsourcing and regeneration options.

Figure 1. Generalized superstructure for a minimum water utilization network with WMH options that is applicable for global water operations.

4.2 Mathematical Formulation

The optimisation problem is formulated as a mixed integer nonlinear program (MINLP) and is implemented in Generalized Algebraic Modeling System (GAMS). The nonlinear term is due to the presence of power term that represents the capital cost functions that exist in the capital cost formula in payback period constraint. The objective function of this model is to determine the minimum freshwater target for a multiple contaminants in water system within the desired payback period set by a plant owner. The entire mathematical formulation of the superstructure model is as follows:

<u>Objective Function:</u>
The objective function is to minimise the total amount of freshwater demand, FW_j.

$$Min \sum_j FW_j \tag{1}$$

The minimisation of the objective function represented by Eq. (1) is subjected to the following constraints:

1) Water balance for each demand

The water supplied for each adjusted demand flow rate, B_j is a combination of freshwater, FW_j and water from disinfection unit, Fdu_j. The water balance for each demand, B_j is given by:

$$FW_j + Fdu_j = B_j \qquad \forall j \in J \qquad (2)$$

2) Water balance for each source

The water generated from each source i, A_i is either discharged directly as effluent, WW_i, direct reuse/recycle water from source i to disinfection unit, F_i or partially treated in regeneration unit, Fr_i. Model reduction is done by initially checking the feasibility of reuse/regeneration for each source and setting a binary value for wastewater discharge, reuse and regeneration stream which respectively are $X1_i$, $X2_i$ and $X3_i$. The water balance for each source i is given by:

$$WW_i X1_i + F_i X2_i + Fr_i X3_i = A_i \qquad \forall i \in I \qquad (3)$$

3) Water balance for disinfection unit

The water supplied from disinfection unit, Fdu_j is a combination of other resources, Fos_{os} (e.g rainwater, river and snow), reuse water from wastewater source, F_i and regenerated water from regeneration unit, Fr_i. The water balance for disinfection unit is given by:

$$\sum_{os} Fos_{os} + \sum_i F_i + \sum_i Fr_i = \sum_j Fdu_j \qquad (4)$$

4) Water consumption unit balance

For each demand, flow elimination, reduction or original flow rate option will be chosen in order to minimize the water demand. The number of unit allocated for elimination, EU_j, reduction, RU_j or original, OU_j must be equal to total unit in each demand, TU_j.

$$EU_j + RU_j + OU_j = TU_j \qquad \forall j \in J \qquad (5)$$

5) Demand constraint

Adjusted demand flow rate, B_j must be equal to original demand flow rate, D_j or less than demand flow rate after implementation of elimination, De_j or reduction, Da_j options. Model reduction is done by introducing binary variables, $Y1_j$, $Y2_j$ and $Y3_j$ which has been set by checking the availability of the water elimination or reduction equipment. For reduction and original flow option, that portion is divided by total unit TU_j to obtain the flow rate supply by each unit, RU_j and OU_j.

$$De_j EU_j Y1_j + Da_j RU_j Y2_j / TU_j + OU_j D_j Y3_j / TU_j = B_j \qquad \forall j \in J \qquad (6)$$

6) Reduction option constraint

If reduction option is selected, flow rate for j^{th} demand, Da_j is reduced by certain percentage, σ_j.

$$Da_{j,} = \sigma_j D_j \qquad \forall j \in J \qquad (7)$$

Substituting Da_j in Eq. (7) with (6) to form a linear constraint (6'). This equation can be written as below.

$$De_j EU_j Y1_j + \sigma_j D_j RU_j Y2_j / TU_j + OU_j D_j Y3_j / TU_j = B_j \qquad \forall j \in J \qquad (6')$$

7) Disinfection unit contaminant load

Contaminant mass load for disinfection unit flow, $Fdu_j Cdu_{j,k}$ is supplied from a sum of contaminant mass load from different sources (e.g potential reused/recycle water, $F_i Cre_{i,k}$, outsources, $Fos_{os} Cos_{os,k}$ or/and regenerated water, $Fr_i Cro_{i,k}$). For simplicity, the performance of regeneration units are measured with fixed outlet concentration for all contaminants, $Cro_{i,k}$.

$$\sum_i F_{i,} Cre_{i,k} + \sum_{os} Fos_{os} Cos_{os,k} + \sum_i Fr_i Cro_{i,k} = \sum_j Fdu_j Cdu_{j,k} \qquad (8)$$

8) Demand contaminant load satisfaction

Contaminant mass load for adjusted demand j, $B_j Cd_{j,k}$ is supplied from a mixed of contaminant mass load from freshwater, $FW_j Cw_k$, and disinfection unit flow, $Fdu_j Cdu_{j,k}$. Thus, the contaminant load from all sources must satisfy the contaminant load for demand j.

$$FW_j Cw_k + Fdu_j Cdu_{j,k} \le B_j Cd_{j,k} \qquad \forall j \in J \qquad (9)$$

9) Mass Transfer-Based (MTB) constraint

For MTB operations, the adjusted flow rate of water demand, B_j is equal to the adjusted water source flow rate, A_i.

$$B_j = A_i \qquad \forall j \in J \qquad (10)$$

10) Non Mass Transfer-Based (NMTB) constraint

If source streams exist for NMTB operations, the adjusted flow rate of water source, A_i, is equal to water source flow rate before implementation of WMH options, S_i.

$$A_i = S_i \qquad \forall i \in I \qquad (11)$$

11) Payback period constraint

The total payback period must be set equal or less than investment payback limit set by a plant owner. The payback period is calculated using below equation:

$$Payback \quad period \quad (yrs) = \frac{Net \quad Capital \quad Investment \quad (RM)}{Net \quad Annual \quad Savings \quad (RM / yrs)} \le \gamma \qquad (12)$$

where γ is investment payback limit set by a plant owner, e.g. three years.

12) Net annual savings (NAS)

Net annual savings includes the operating cost savings of freshwater demand, wastewater regeneration system and electricity required for pumping activities. The formula is given by:

$$NAS = \begin{bmatrix} \sum_j (FW_j^{initial} - FW_j) CostFW \\ + \sum_i (Fr_i^{initial} - Fr_i)(CostTreat + CostElect) \\ + \sum_i (F_i^{initial} - F_i) CostElect \\ \sum_j (Fos_{os}^{initial} - Fos_{os})(CostElect + CostTreat) \end{bmatrix} * AOT \qquad (13)$$

13) <u>Net capital investment (NCI)</u>
The net capital investment (NCI) consists of elimination unit costs, $CostEu_jEU_j$, reduction unit costs, $CostRu_jRU_j$ and original unit costs, $CostOu_jOU_j$. The NCI calculation also includes capital cost of reuse, outsourcing unit as well as regeneration unit. The capital investment for reuse, outsourcing and regeneration unit is a function of water flow rate with including pipes and pumps costs. The NCI for retrofit design can be calculated as below.

$$NCI = \left(CostEu_jEU_j + CostRu_jRU_j + CostOu_jOU_j\right) + CCReuse + CCOs + CCTreat \qquad (14)$$

Note that, capital cost for reuse, regeneration and outsourcing system for retrofit case is adapted from Wan Alwi et al. [33] which is calculated using sixth-tenth factor [35] (Refer **Appendix A** and **B** for detailed cost calculations).

14) <u>Selection of water minimisation options</u>

This constraint is imposed to ensure that only one water minimisation options is chosen at one time. Binary variables $Y1_j$, $Y2_j$ and $Y3_j$ are introduced to represent the water minimisation schemes involving elimination, reduction or original operation respectively.

$$Y1_j + Y2_j + Y3_j = 1 \qquad \forall j \in J \qquad (15)$$

14) <u>Non-negativity constraints</u>
The freshwater supply, wastewater generation and reused/recycled water flow rate, must be greater than zero, therefore the freshwater supply, wastewater generation and reuse/recycle water flow rate is defined as positive/non-negativity variables.

$$FW_j,\ WW_i,\ F_i,\ Fr_i,\ Fdu_j,\ Fos_{os},\ A_i,\ B_j,\ Da_j,\ Cdu_{j,k} \geq 0 \qquad (16)$$
$$\forall i \in I,\quad \forall j \in J,\quad \forall os \in OS$$

5.0 CASE STUDY

The approach was applied to an urban case study involving a mosque to demonstrate the applicability of the proposed model. For the particular cases, the model takes on the form of a mixed integer nonlinear program. The effectiveness and feasibility of the methodology for designing optimal minimum water networks was demonstrated guided by objective function and the models were coded into GAMS 23.0. In order to obtain optimal solution, BARON solver was chosen to solve MINLP problems. The case study was performed using a Window Vista personal computer with 2.26 GHz Intel Core Duo Processor. The cost correlations used for SIM case study are given in **Appendix B**.

5.1 Urban Case Study - Sultan Ismail Mosque (SIM), UTM

Sultan Ismail Mosque (SIM) which is situated in Universiti Teknologi Malaysia (UTM), Skudai, Johor was chosen as the case study for this work. This mosque is mainly used by the Muslim students and staff of UTM for prayer and educational activities. Water distribution network for SIM is shown in **Figure 2**. The SIM limiting water data taken from Wan Alwi et al. [32] as shown in **Table 1**. In this case study, the biological oxygen demand (BOD) was the most significant water quality factor chosen for water quality analysis. There are seven water demands and four water sources. Water demands and water sources for kitchen are excluded as the kitchen demand needs 0 ppm contaminant concentration, where only freshwater can fulfill the water demand while the BOD concentration of water source is too high and not worth to be treated. Water demands represent the actual requirements for various water-using processes meanwhile water sources are water available for possible recycling or reuse.

The data for water demands is adapted from USEPA water quality standards for water reuse [36]. Water from irrigation is first assumed to be completed absorbed by the soil. Wastewater from toilet flushing and toilet pipes is referred to as black water and will not considered to be reused since it is highly contaminated with urine and faeces. The model for retrofit design is based on the payback period desired by plant owner which is 5 years. Note that, for urban system, in order to reuse water safely, a disinfection unit is needed to ensure that the reuse/recyle/regenerated water is free from bacteria or faecal coliform. Furthermore, since the water flowrate is intermittent and since there are no engineers or technician to maintain such a complex system, a centralize reuse/recycle and regeneration system are therefore preferred for easy maintenance and cheaper cost.

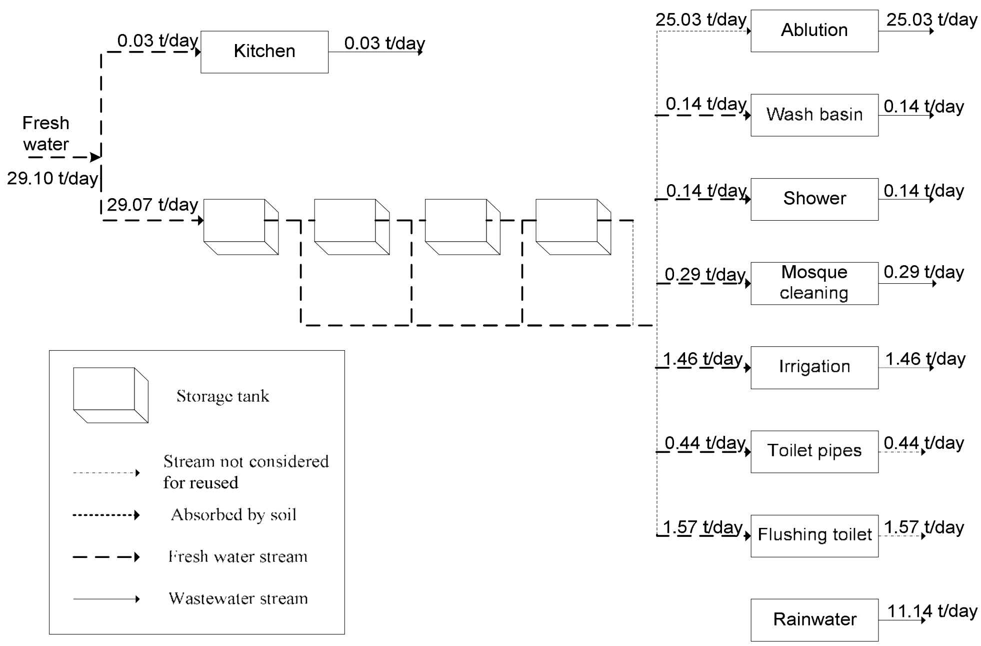


Table 1. Limiting Water Data for Sultan Ismail Mosque [31].

Stream	**Demands Description**	**Flow rate (t/day)**	**BOD Concentration (ppm)**	**Stream**	**Sources Description**	**Flow rate (t/day)**	**BOD Concentration (ppm)**
D1	Ablution	25.03		S1	Ablution	25.03	23
D2	Wash basin	0.14	10	S2	Wash basin	0.14	23
D3	Showering	0.14	10	S3	Showering	0.14	216
D4	Mosque cleaning	0.29	10	S4	Mosque cleaning	0.29	472
D5	Irrigation	1.46	10				
D6	Toilet pipes	0.44	10				
D7	Flushing toilet	1.57	10				

5.1.1 Water Management Hierarchy Implementation

All possible water minimization schemes to improve the SIM water system were considered according to the water minimization options. These options are listed in **Table 2** and described next.

Table 2. Various water minimization schemes for Sultan Ismail Mosque.

WMH	Strategy
Elimination	D_8: Change 12 liter flushing toilet to composting toilet
Reduction	D_1: Change normal ablution tap to laminar flow tap D_8: Change 12 liter flushing toilet to dual flush toilet
Reuse	Direct water reuse
External water sources	Rainwater harvesting (Fos_{os}^{max}= 11.14 t/day, $Cos_{os,BOD}$ = 10 ppm) [37]
Regeneration	Wastewater regeneration using a microfiltration, activated carbon and UV system ($Cro_{i,BOD}$ =4.2 ppm) [38]

5.1.1.1 Source Elimination

Source elimination concerns with possible complete removal of freshwater demand. In order to maximise fresh water savings, all possible means of process changes or to change existing equipment to new equipment in order to eliminate water demands were considered. In this case study, it is possible to eliminate D_7 (toilet flushing) by changing all 12 liter flushing toilet to composting toilet.

5.1.1.2 Source Reduction

After considering all the possible elimination for water demand, water reduction should be carried out. It is possible to reduce water demand at D_1 (ablution) by changing normal water tabs to laminar taps. This will also reduces source S_1. Another possibility to reduce fresh water demand at D_7 is by changing the 12 litre flushing to dual flush toilet. Dual-flush toilet technology allows the user to select a short flush (3 liter) or long flush (6 liter), hence become an average of 4.5 liter toilet flush.

5.1.1.3 External Water Sources

Rainwater harvesting is one of the possible external water sources to be used at SIM water system since the Skudai area, in which UTM is located, receives a high average annual rainfall of 2027.2 mm. Based on SIM available roof area and rain distribution, it is possible to harvest 11.14 t/day (maximum design limit, $F_{max\ design}$) of rainwater at concentration of BOD, Cos_{BOD} = 10 ppm [37].

5.1.1.4 Regeneration Reuse/Recycle

Regeneration is the final process change considered according to water management hierarchy. Regeneration here refers to treatment of wastewater or external water source to match the required quality of water for later reuse process. Regeneration can be used to remove contaminants on an intermediate basis. In this case, the regeneration process consists of three main steps. First of all, greywater is filtered for particles. After that, it is passed through an activated carbon to remove unpleasant odour and turbidity. Regeneration of wastewater using a microfiltration and activated carbon yielded 4.2 ppm from 23 ppm of BOD concentration ($Cro_{i,k}$) [38].

Finally, all reused water, regenerated water from regeneration unit and external water sources are mixed together into centralize disinfection unit. UV system is used to disinfect the greywater for storage purposes and make sure that the water is free from bacteria or faecal coliform.

5.1.2 Results and Discussion

The minimum water targets can be obtained by screening process changes using water minimization options. By solving Eq. (1) with constraints in Eqs. (2)-(15), the approach has successfully yield a minimum freshwater and wastewater flow rate targets at 2.10 t/day and 10.78 t/day, respectively. Note that, due to model reduction, the total freshwater required for the kitchen is excluded in the model since its contains high concentration of contaminants and uneconomical and safe to be treated. Therefore, the total freshwater and wastewater for the kitchen, about 0.03 t/day should also be included giving a total freshwater and wastewater targets of 2.13 t/day and 10.81 t/day, respectively with RM 5, 317/yr, net annual savings after implementing WMH options. The reduction of freshwater and wastewater are 92.7% and 57.9%, respectively with payback period of 5 years for retrofit case. In order to obtain the minimum freshwater consumption, the optimizer favored to reduce water flow rates at D_7 (toilet flushing) by changing all 12 liter flushing toilet to dual flush toilet. Besides, changing normal water taps to laminar taps at demand D_1 also led to reductions of freshwater consumption and less capital investment was needed. Water outsourcing through rainwater harvesting was employed to the maximum limit to take advantage of the high quality of rainwater as compared to quality of reuse and recycle water. Regenerating 0.50 t/day of wastewater also resulted in decreasing wastewater generation. **Figure 3** gives the corresponding optimal design of water network for retrofit case.

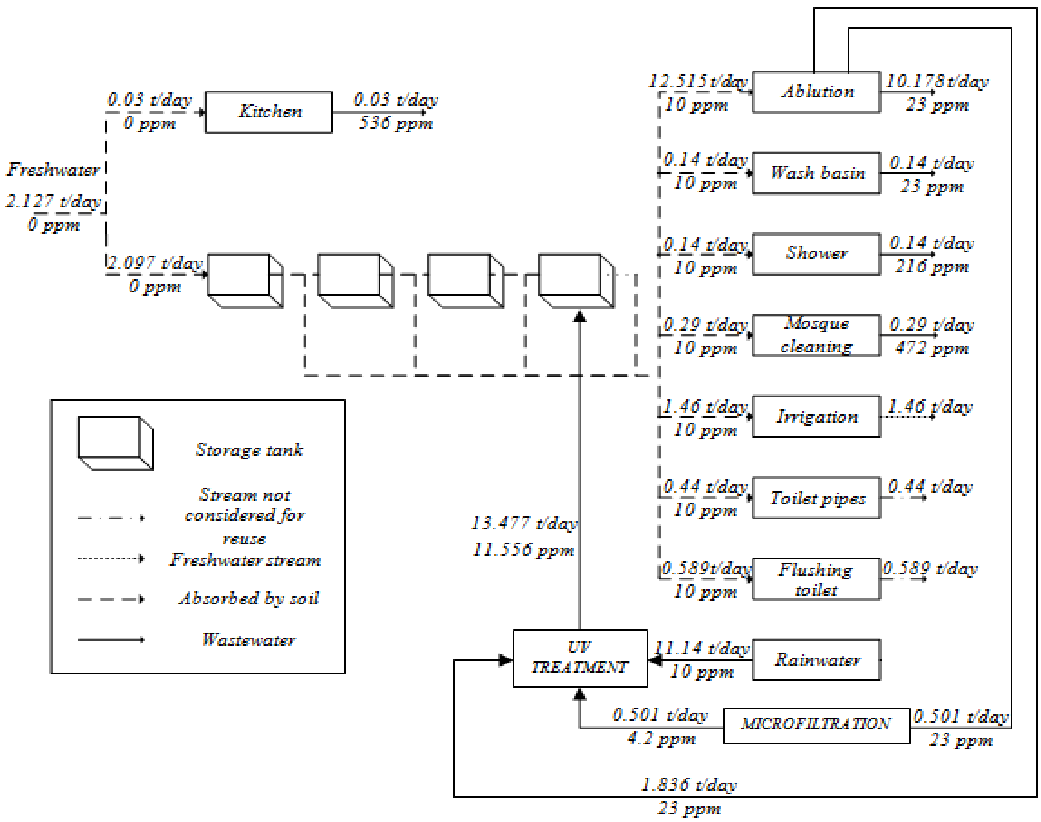


Figure 3. Optimal Design of Water Network for Sultan Ismail Mosque for retrofit design.

5.1.3 Results Comparison

Both CEMWN approach and GAMS modelling applied the same cost screening method by screen various water management options with water management hierarchy. **Table 3** compares the results of using CEMWN approach [33] and mathematical programming using GAMS for SIM case study. The overall GAMS modelling results are somewhat different from CEMWN in terms of fresh water and wastewater savings. The reason may be due to the fact CEMWN is just an estimation. It can be seen that the net annual savings (NAS) and net capital investment (NCI) obtained from the mathematical programming approach are slightly lower than obtained using CEMWN for retrofit design. Note that, CEMWN also follows heuristic approches while mathematical model considered all the water minimisation options simultenously. However, CEMWN is beneficial that it can help designers to interact with the process changes selection more interactively. Meanwhile, even though the freshwater target given by the optimizer is slightly higher than that obtained using CEMWN, the water utilization network designed is still able to achieve the desired payback period set by plant owner, and the freshwater target has also achieved a reduction of up to 93% which can still be considered as significant freshwater reduction. Although a few additional features can be solved simultaneously, the developed model is however disadvantaged in terms of providing good insights to designers during network synthesis. In addition, the MINLP is very dependent on good starting points and do not always guarantee a global optimum solution.

Table 3. Comparison of CEMWN and GAMS results for SIM case study.

Method	FW_{target}, t/day	WW_{target}, t/day	FW savings, %	WW savings, %	NAS, RM/yr	NCI, RM	Payback Period, yrs
Initial	29.10	25.63	-	-	-	-	-
CEMWN	0.73	8.4	97.5	67.2	5343	26757	5.01
GAMS	2.13	10.81	92.7	57.9	5317	26584	5.00

6.0 CONCLUSION

A new set of mathematical models algorithm has been developed based on water network superstructure to achieve the minimum water targets for centralize reuse and regeneration system. Water minimisations strategies for retrofit design of water network can now be quantitatively evaluated using mathematical modelling. The mathematical modeling approach proposed in this work can solve the water network design problem simultaneously by considering the minimum water targets, process changes based on water management hierarchy within specified payback period. The approach has been successfully implemented on Sultan Ismail Mosque in UTM. The results show a reduction of 92.7% freshwater and 57.9% wastewater respectively, within a payback period of 5 years.

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NOMENCLATURE

Indices

i	-	Index for water source
j	-	Index for water demand
os	-	Index for outsoursed resources

Parameters

AOT	-	Annual operating day
$CCReuse$	-	Capital cost for reuse system
$CCOs$	-	Capital cost for outsourcing unit
$CCTreat$	-	Capital cost for regeneration system
$Cos_{os,k}$	-	Outsource concentration of contaminant *k*
$CostEu_j$	-	Cost of elimination unit of demand j
$CostElect$	-	Cost of electricity
$CostF$	-	Cost of freshwater supply
$CostOu_j$	-	Cost of original unit of demand j
$CostRu_j$	-	Cost of reduction unit of demand j
$CostTreat$	-	Cost of treatment
$Cre_{i,k}$	-	Concentration of contaminant *k* in reused water
$Cro_{i,k}$	-	Outlet concentration of contaminant *k* from regeneration unit
Cw_k	-	Freshwater concentration of contaminant *k*
D_j	-	Flow rate of water demand *j*
$F_i^{initial}$	-	Initial water flow rate from source *i* to disinfection unit
$Fos_{os,j}^{initial}$	-	Initial outsource flow rate *os* to demand *j*
$Fr_i^{initial}$	-	Initial water flow rate from regeneration unit *to disinfection unit*
$FW_j^{initial}$	-	Initial freshwater flow rate to demand *j*
S_i	-	Flow rate of water source *i*
TU_j	-	Total water minimization unit for demand j
γ	-	Payback period limit
σ_j	-	Water reduction percentage

Continuous Variables

A_i	-	Adjusted flow rate of water source i
B_j	-	Adjusted flow rate of water demand *j*
$Cdu_{j,k}$	-	Concentration of contaminant *k* in disinfection flow to demand *j*
Da_j	-	Flow rate of reduction option for demand *j*
De_j	-	Flow rate of elimination option for demand *j*
EU_j	-	Number of unit allocated for elimination
Fdu_j	-	Water flow from disinfection unit to demand *j*
F_i	-	Water flow rate from source i to disinfection unit
Fos_{os}	-	Outsource flow rate *os* to demand *j*

Fr_i	-	Water flow rate from regeneration unit *to disinfection unit*
FW_j	-	Freshwater supplied to demand j
OU_j	-	Number of unit allocated for original,
RU_j	-	Number of unit allocated for reduction
WW_i	-	Unused portion of water source *i* (wastewater)

Binary Variables

$Y1_j$	-	existense or non existense of water elimination equipment
$Y2_j$	-	existense or non existense of water reduction equipment
$Y3_j$	-	existense or non existense of water original equipment
$X1_i$	-	existense or non existense of wastewater discharge stream
$X2_i$	-	existense or non existense of water reuse stream
$X3_i$	-	existense or non existense of water regeneration stream

Acronyms

BOD	-	Biological oxygen demand
C_{IC}	-	Instrumentation and controls cost investment
C_{PEI}	-	Equipment installation cost
C_{PE}	-	Total capital cost for the equipment
C_{piping}	-	Water reuse piping cost investment
C_C	-	Costs per unit time for chemicals used by water system
$CC_{base\ case}$	-	Capital cost for base case equipment
$CC_{new\ system}$	-	Capital cost associated with new equipment
C_{FW}	-	Costs per unit time for fresh water
C_{WW}	-	Costs per unit time for energy for water processing from water source
CEMWN	-	Cost Effective Minimum Water Network
GAMS	-	Generalized Algebraic Modeling System
IPWI	-	Interplant Water Integration
LP	-	Linear programming
MILP	-	Mixed integer linear programming
MINLP	-	Mixed integer nonlinear programming
MTB	-	Mass transfer-based
MODWN	-	Model for Optimal Design of Water Network
MWR	-	Maximum water recovery
NAS	-	Net annual savings
NCI	-	Net annual savings
NLP	-	Nonlinear programming
NMTB	-	Non-mass transfer-based
SHARPS	-	Systematic Hierarchical Approach for Resilient Process Screening Approach
SIM	-	Sultan Ismail Mosque
USEPA	-	United States Environmental Protection Agency
UV	-	Ultraviolet
WMH	-	Water management hierarchy

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APPENDIX A: OBTAINING PRE-DESIGN CAPITAL COST ESTIMATION [32]

An equipment capital cost is typically a function of the equipment capacity, and, in the context of SHARPS, is related to a flow rate increment or reduction associated with a water minimization options. The method to estimate the cost used in Eq. (14) for capital cost calculation is shown below.

A.1 Estimation for equipment purchased cost and installation cost (C_{PE} and C_{PEI})

The capital cost of and equipment of a given size can be predicted using the *six-tenth factor rule* [34]. According to this rule, if the cost of an equipment B at a given capacity is known, the cost of a similar equipment A at X times the capacity of B is $X^{0.6}$ times the cost of equipment b as given by Eq. (A.1) [35]. The 0.6 rule of thumb is only used when the actual cost exponent is unknown. The typical exponents for the equipment cost as a function of capacity can be obtained from most literatures on plant economics.

$$\text{Cost of equipment A} = (\text{Cost of equipment B})X^{0.6} \quad (A.1)$$

Eq. (A.2) is a capital cost correlation for a biological treatment unit [20]. The capital cost of a 30 t/hr wastewater treatment unit (F_{TU}) is RM136256.

$$CC_{T1}(RM) = 12600F_{TU}(t/h)^{0.7} \quad (A.2)$$

Note that, the capacity factor rule for equipment costing is applicable only for similar equipment type of up to 10 times the base-equipment capacity. The cost must also be updated as necessary using the Marshall and Swift equipment cost index or the *Chemical Engineering* cost index. The sum of individual equipment cost gives the total capital cost for the equipment, C_{PE}. The equipment installation cost (C_{PEI}) includes labor cost, foundations, supports, cost of construction, and other factors directly related to the erection of purchased equipment. The purchased equipment cost may vary between 20 to 90% of total installed cost depending on equipment complexity and type of plant with the equipment installed [35].

A.2 Estimation of piping and plumbing cost (C_{piping})

For piping cost, if the *base-case* plumbing and sanitation piping cost is available, Eq. (A.1) can also be used to estimate the reuse or outsource or regeneration piping cost using Eq. (A.3) as below:

Cost of piping and plumbing
= (Cost of *base case* plumbing and sanitation)x$[(F_{reuse/outsource/regen})/F_{demand\ initial}]^{0.6}$ (A.3)

A.3 Instrumentation and control, C_{IC}

In order to enable water reuse, pumps and control system must also be installed. This should include instrumentation cost, installation labour cost and operating cost for auxiliary equipment such pumps and motors. For preliminary design, the cost of instrumentation and control may range between 8 to 50% of the total delivered equipment cost depending on extent of control required [35].

APPENDIX B: SIM COST FORMULA[33]

For SIM retrofit case study, the formula for $OC_{base\ case}$, OC_{new}, $CC_{base\ case}$ and $CC_{new\ system}$ are listed in **Tables B.1 - B.4**.

Table B.1 $OC_{base\ case}$ formula for SIM case study.

Process	*Type of OC*	*Cost formula*	*Unit*
Freshwater cost, C_{FW}	Freshwater	$0.56F_{FW\ initial}$	RM/t

Table B.2 OC_{new} formula for SIM case study.

Process	*Type of OC*	*Cost formula*	*Unit*
Freshwater cost, C_{FW}	Freshwater	$0.56F_{FW\ initial}$	RM/t
UV lamp	Treatment	$0.03F_{reuse/outsource/reg}$	RM/t
Pumping	Electrical	$0.014F_{reuse/outsource/reg}$	RM/t

Table B.3 $OC_{base\ case}$ formula for individual equipment SIM case study.

Process	*Base case equipment*	*No of unit*	*Cost formula, RM*	*Unit*	*Cost/system (RM)*
Toilet	12 l toilet flush with installations	30	200	RM/unit	6000
Ablution tap	Tap 13.5 lpm with installations	126	20	RM/unit	2520
Plumbing and sanitation	Piping		8000	RM/ system	8000

Table B.4 $CC_{base\ case}$ formula for individual equipment SIM case study.

Process	**New equipment**	**No of unit**	**Cost formula, RM**	**Unit**	**Cost/ system (RM)**
Toilet	Option 1: Composting toilet with installations	30	1000	RM/unit	30000
	Option 2: Dual flush toilet with installations	30	300	RM/unit	9000
Ablution tap	Laminar tap with installations	126	25	RM/unit	3150
Total reuse	Reuse diversion system and pumps with installations (Retrofit)	-	$[(499*(F_{reuse}/22.71)^{0.6}) + (30*F_{reuse}) + 8000*(F_{reuse}/F_{demand\ initial})^{0.6}]*150\%$	RM/ system	
Rainwater harvesting (10ppm)	RW diversion system and pumps (Retrofit)	-	$[(499*(F_{RW}/22.71)^{0.6}) + (30*F_{RW}) + 8000*(F_{RW}/F_{demand\ initial})^{0.6}]*150\%$	RM/ system	
Treatment (Treat ablution WW to 4.2 ppm)	Treat all ablution WW by using microfiltration, activated carbon and UV. Need treatment system, installations, control and piping (Grassroots)	-	$[(100000*(F_{reg}/7.27)^{0.6})*150\%] + [(499*(F_{reg}/22.71)^{0.6}) + (30*F_{reg}) + 8000*(F_{reg}/F_{demand\ initial})^{0.6}]*150\%$	RM/ system	