A Holistic Approach for Benchmarking and Cost-Effective Water Minimisation

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Abstract

Water pinch analysis (WPA) is a well-established tool for the design of a maximum water recovery (MWR) network. MWR, which is primarily concerned with water recovery and regeneration, only partly addresses water minimisation problem. Strictly speaking, WPA can only lead to *maximum water recovery targets* as opposed to the *minimum water targets* as widely claimed by researchers over the years. The *minimum water targets* can be achieved when all water minimization options including elimination, reduction, reuse/recycling, outsourcing and regeneration have been holistically applied. This paper describes a new holistic approach for benchmarking and for designing a cost effective minimum water network (CEMWN) for industry and urban systems. The framework consists of five key steps, i.e. (1) Specify the limiting water data, (2) Determine MWR targets, (3) Screen process changes using water management hierarchy (WMH), (4) Apply *Systematic Hierarchical Approach for Resilient Process Screening* (*SHARPS)* strategy, and (5) Design water network. Three key contributions have emerged from this work. First is a hierarchical approach for systematic screening of process changes guided by the WMH. Second is a set of four new heuristics for implementing process changes that considers the interactions among process changes options as well as among equipment and the implications of applying each process change on utility targets. Third is the *SHARPS* cost-screening technique to generate a minimum water network that is cost-effective and affordable. The CEMWN holistic framework was successfully implemented on a mosque case study and yielded results within the designer payback period criterion.

Keywords: Minimum water network; water management hierarchy; water pinch analysis; maximum water recovery; SHARPS

Introduction

Facilities with large utility bills usually set annual targets for utility savings in order to continuously reduce operating costs. Many companies conduct a combination of *inter-company* and *intra-company* benchmarking as basis to set realistic utility savings targets. In the former, companies refer to achievements of other companies in the same business while in the latter, it refers to its own past performance. Inter-company and intra-company benchmarkings are usually part of a company's total quality management program that calls for the relevant department to set annual targets for continuous improvement. In order to meet the quality management requirements, a conservative utility savings target of, for example, 5% a year is usually randomly specified. This target is typically set quite separate from considerations of technical potentials and limitations, design and thermodynamic constraints of a plant. Hence, the true potential of a plant can be missed. Stricter environmental regulations, scarcity of quality industrial water and the rising cost of wastewater treatment have encouraged the conservation of water as a key utility in process plants. Concurrently, the development of systematic techniques for water reduction has seen extensive progress

The advent of water pinch analysis (WPA) as a tool for the design of a maximum water recovery (MWR) network enables a process plant to assess its inherent potential for saving utilities and benchmark its performance based on the structure, operating conditions, design and thermodynamic characteristics that are unique to the plant. Since its introduction by Wang and Smith [1], various noteworthy WPA developments on targeting, design, optimization and improvement of an MWR network have emerged. These include works on processes with fixed flowrate and fixed concentration [2, 3, 4, 5], regeneration targeting [6, 7], numerical water targeting [5], network design to achieve water targets [1, 9, 10, 7, 4, 11], mathematical modeling, network superstructure optimisation and problems with multiple contaminants [8, 12-19], water network retrofit [20], water targeting for batch systems [21-23] and capital cost targeting and optimization [24, 20]. Wan Alwi *et al.* [25] recently made the first attempt to implement WPA on urban system by using their *Water Cascade Analysis* (WCA) technique to establish water targets and design an MWR network for a mosque. Liu *et al.* [26] provide comprehensive practical steps to conduct an industrial water minimisation project focusing on maximising spent water reuse (MWR). Most authors claimed that their methods lead to the minimum fresh water and wastewater targets. MWR which relates to maximum reuse, recycling and regeneration has two limitations. Firstly, it only addresses water minimisation problem partly since crucial water minimisation options such as elimination and reduction are neglected. Secondly, since MWR focuses on water reuse and regeneration, strictly speaking, it does not lead to the *minimum water targets* as widely claimed by researchers over the years.

This work describes a new holistic framework for water benchmarking and cost effective water minimization applicable to industry and urban sectors. The procedure involves detailed analysis of a facility configuration and design, material and energy balances as well as thermodynamic constraints. The CEMWN technique strives to achieve maximum water reduction, and hence, maximum savings holistically after considering not only reuse and recycling, but all conceivable options to reduce water usage through elimination, reduction, reuse, outsourcing and regeneration. Two key features of the new framework are the water management hierarchy (WMH) as a guide to prioritise process changes and the *Systematic Hierarchical Approach for Resilient Process Screening* (*SHARPS*) strategies as a new cost-screening technique. We began by explaining WMH as a foundation for the holistic framework. This is followed by descriptions of a five-step methodology for designing a cost-effective minimum water utilization network (CEMWN). This is followed by the step-wise application of CEMWN methodology on a mosque. The paper concluded by comparing the outcomes of applying various approaches for water minimization.

Cemwn Methodology

The CEMWN procedure is a holistic framework for cost-effective water minimisation. A key feature of the holistic framework is the water management hierarchy (WMH) as a guide to prioritise process changes qualitatively as well as quantitatively. The WMH 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. The levels are arranged in order of preference, from the most preferred option at the top of the hierarchy (level 1) to the least preferred at the bottom (level 5) as in Figure 1 [29]. Water minimisation is concerned with the first to the fourth level of the hierarchy. The five key steps for cost-effective water minimisation are illustrated in Figure 2 and are described next.

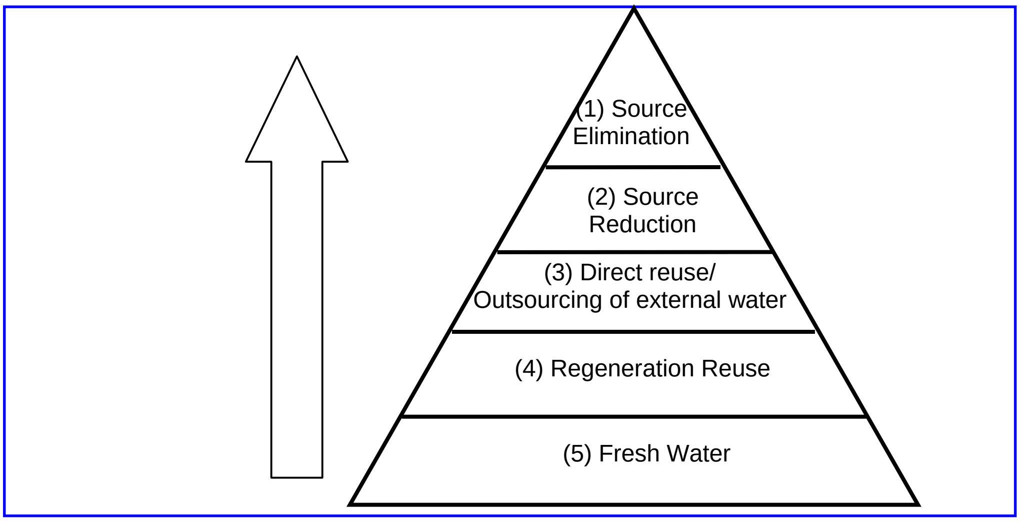

Figure 1. The water management hierarchy [29].

Step 1: Specify the limiting water data

The first step was to specify the limiting water data. This involved process line-tracing, establishing process material balances and isolating the appropriate water sources (outlet streams with potential to be recycled) and water "demands" (inlet streams representing process water requirements) having potential for integration. The water sources and demands were listed in terms of quantity (flowrate) and quality (contaminant concentration). In a water-intensive process plant, specifying the limiting data is a very tricky and time-consuming exercise and is typically the bottleneck, and more importantly, the critical success factor for a water minimization project. To isolate the relevant limiting data, readers are referred to Liu *et al.* [26]. Practical steps and rule-of-thumbs for selecting candidate process units for water-saving projects, extracting the right data, preparing a water balance diagram and isolating the candidate water sources and demands are discussed in detail.

Step 2: Determine the MWR targets

The second step was to establish the *base-case* MWR targets, i.e. the overall fresh water requirement and wastewater generation for the process. Note that the *base-case* MWR targets exclude other levels of WMH except re-use and recycling of available water sources and mixing of water sources with freshwater to satisfy water demands.

Established graphical and numerical techniques for setting the MWR targets are widely available. Some popular ones like the concentration composite curves (graphical approach [1, 26]), concentration interval table for mass exchange network (numerical approach [27]) and mass problem table (numerical approach [7]) however are only ideal for fixed flowrate cases where water-using processes are modelled as mass-transfer based operations involving water as a lean stream or a mass separating agent (MSA). For an industrial project where flowrate gains and losses are quite common, it may be necessary to analyze these streams separately and modify the stream data as done by Liu *et al.* [26] if the fixed-flowrate approach is used. A resilient tool should be able to handle not just mass-transfer based but also non-mass transfer-based water using-operations involving flowrate gain or losses which include water used as a solvent or withdrawn as a product or a byproduct in a chemical reaction, or utilized as heating or cooling media. The water cascade analysis (WCA) technique by Manan *et al.* [5] which fit the latter category was used in this work.

Step 3: Screen process changes using WMH

Changes can be made to the flowrates and concentrations of water sources and demands to reduce the MWR targets and ultimately achieve the MWN benchmark. This was done by observing the basic pinch rules for process changes and by prioritising as well as assessing all possible process changes options according to the WM hierarchy. The fundamental rules to change a process depend on the location of water sources and demands relative to the pinch point of a system.

It is vital to note that implementation of each process change option will yield new pinch points and MWR targets. In addition, interactions and “knock-on effects” between the process change options should also be carefully considered. It is therefore important that each process change be systematically prioritized and assessed with reference to the revised pinch points instead of the original pinch point so as to obey the fundamental rules for process changes listed previously and to guarantee that the MWN benchmark is attained. Bearing in mind these constraints, the core of step 3 was the level-wise hierarchical screening and prioritisation of process changes options using the water management hierarchy (WMH) and various option-screening heuristics which was sequentially applied to prioritise process changes [34].

The revised MWR targets as well as the option-screening heuristics were used as process selection criteria. The screening and selection procedure was hierarchically repeated down the WMH levels to establish the maximum scope for water savings. Systematic application of the MWN benchmarking procedure on a semiconductor plant is described in detail next.

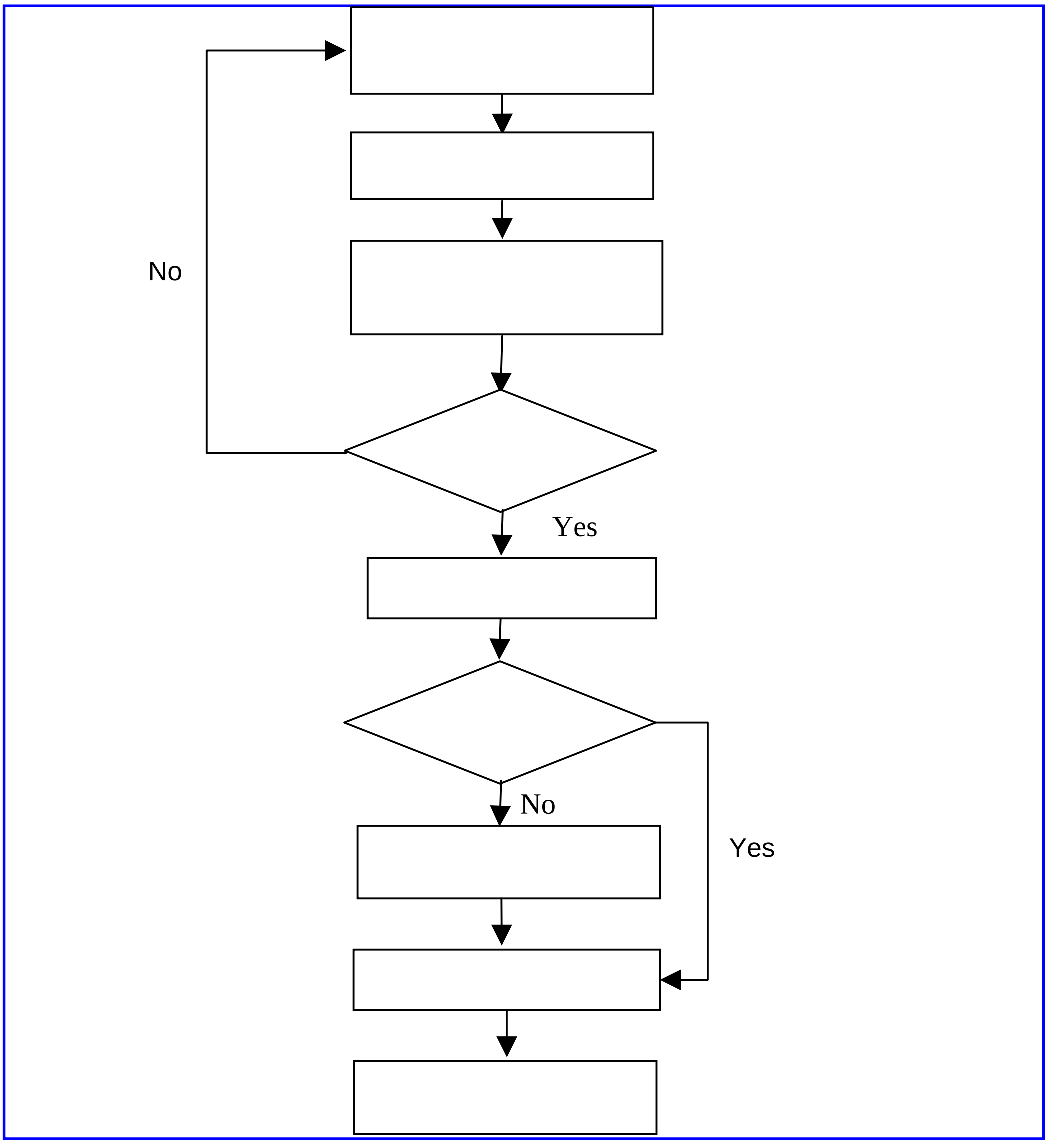

Figure 2. A holistic framework for cost-effective water minimisation

Step 4: Apply SHARPS strategy

Even though the minimum water network design technique could yield significant water reductions, however, some process changes may be costly and thus unattractive to plant owners. The *Systematic Hierarchical Approach for Resilient Process Screening* (*SHARPS*) is proposed as cost-screening tool for design and retrofit of minimum water network for urban and industrial sectors. *SHARPS* is used to screen various water management options before design based on the cost estimates for network investment and savings subject to a desired payback period set by a designer. SHARPS screening technique involves cost estimation associated with water management (WM) options prior to detailed design. It includes a profitability measure in terms of payback period; i.e. the duration for a capital investment to be fully recovered. The SHARPS technique has been described in detail elsewhere [35].

Step 5: Network design

Once the CEMWN targets have been established, the next step was to design a cost effective minimum water network (CEMWN) to achieve the CEMWN targets. The water network could be designed using one of the established techniques such as the one from Polley and Polley (1998), Hallale (2002) and Prakash and Shenoy (2005) or Wan Alwi and Manan (2008). The CEMWN in this work was designed using the technique from Polley and Polley (1998). Systematic application of the CEMWN framework on a mosque is demonstrated next.

Sultan Ismail Mosque Case Study

This case study compares the results of applying CEMWN framework and water pinch analysis (WPA) on Sultan Ismail Mosque (SIM) in Malaysia which is an urban building. Manan *et al.* (2006) uses WPA on the Sultan Ismail Mosque (SIM) case study which include maximum water recovery, regeneration and rainwater harvesting to achieve 85.5% freshwater and 67.7% wastewater reductions. The final Maximum Water Recover (MWR) network is shown in Figure 3. The limiting data for the study is shown in Table 1. Biological oxygen demand (BOD) is used as the key water quality factor. Figure 4 shows the base-case water distribution network for SIM before integration.

Table 1**.** Limiting water data for SIM.

	Demand	F, t/day	C, ppm		Source	F, t/day	C, ppm
D1	Kitchen	0.03	0	S1	Ablution	25.03	23
D2	Ablution	25.03	10	S2	Wash basin	0.14	23
D3	Wash basin	0.14	10	S3	Showering	0.14	216
D4	Showering	0.14	10	S4	Mosque cleaning	0.29	472
D5	Mosque cleaning	0.29	10	S5	Kitchen	0.03	536
D6	Irrigation	1.46	10	Total water sources		25.63	t/hr
D7	Toilet pipes	0.44	10				
D8	Flushing toilet	1.57	10				
Total water demands		29.10	t/hr				

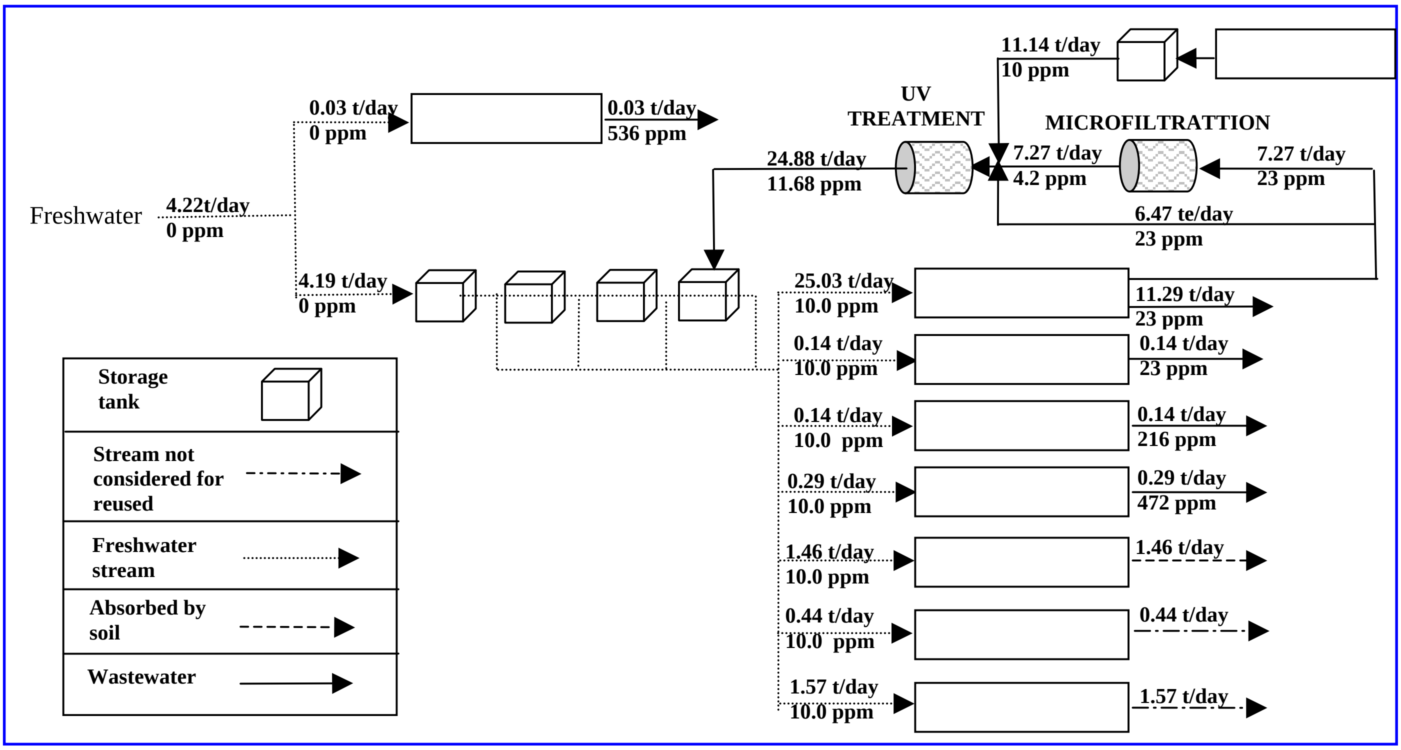

Figure 3. Final water distribution network for Sultan Ismail Mosque with regeneration and rainwater harvesting by Manan *et al.* (2006).

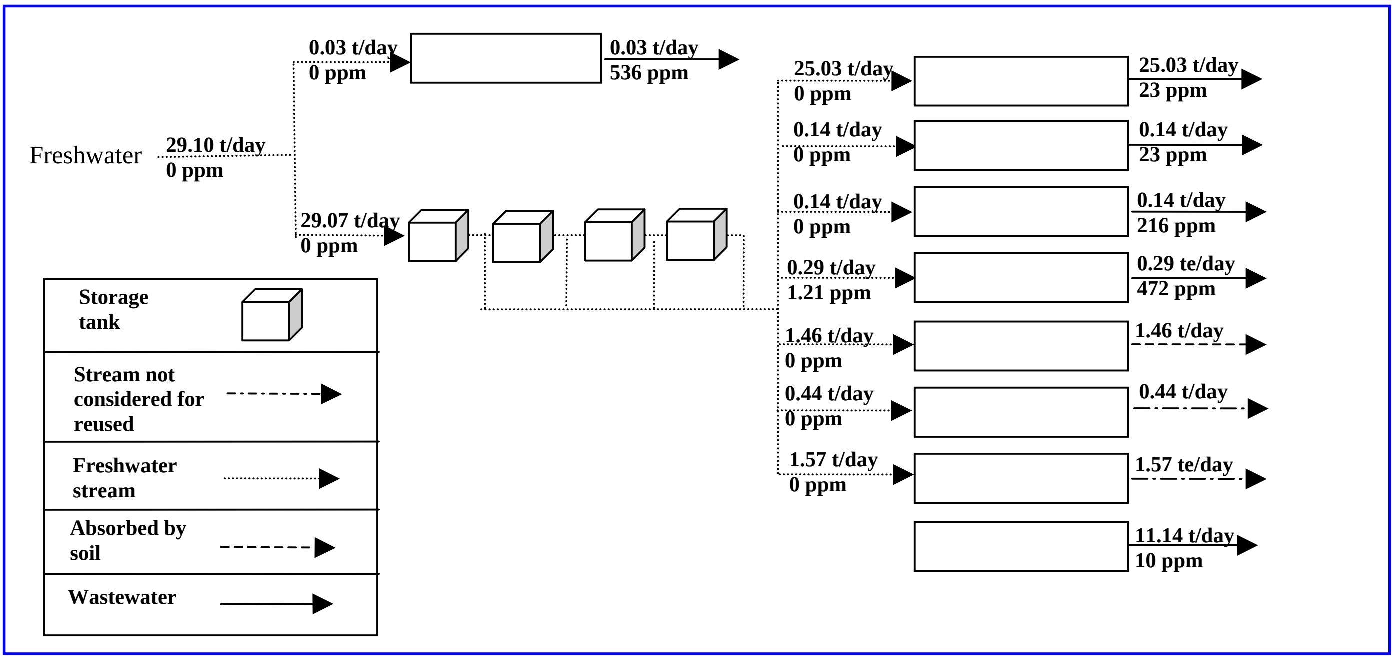

Figure 4. Base-case water distribution network for Sultan Ismail Mosque.

CEMWN framework was next applied to SIM to cost-effectively maximize water savings. Possible process changes options are listed in Table 2. The minimum water network targeted 99.9% freshwater and 63.8% wastewater savings after implementing WMH-guided process changes (see Figure 5**)**. Note that, in some cases, though the freshwater target decreased, the wastewater target increased. For example, when toilet demand was eliminated, some of the wastewater initially allocated for reuse in D8 had to be discharged.

Table 2. Various process changes options for SIM.

WMH	Strategy	Option selected based on MWN procedure
Elimination	Toilet option 1: Change 12 *l* flush toilet to composting toilet	✓
Reduction	Change normal ablution tap to laminar flow tap	✓
	Toilet option 2: Change 12 *l* flush toilet to dual flush toilet	X
Reuse	Total reuse	✓
Outsourcing	RW harvesting	✓
Regeneration	Treat ablution as required	✓

(✓) for selected option. (X) for eliminated option by SIM.

Figure 6 shows the initial IAS plot generated after MWN analysis for both grassroots and retrofit cases. The total payback period for grassroots design was 8.0 yrs and retrofit case 10.2 yrs. TPP_{set} were set at 3 and 5 years for grassroots and retrofit cases respectively for SIM. It is important to note that in the case of urban sector, a payback period of up to 10 years for retrofit cases are typically considered to be on the lower side due to the much cheaper urban freshwater tariff as compared to industrial tariff and the lack of economy of scale. Burkhard *et al.* (2000), Naisby (1997), Sayers (1998) and Mustow *et al.* (1997) estimate payback periods for domestic greywater and rainwater re-use systems in the range between 34 to 890 years in the UK. Thus, CEMWN implementation is encouraged for grassroots design more than for retrofit cases for urban sector.

WMH levels	Specific process changes considered	New FW target, t/day	New WW target, t/day	New pinch point concentration, ppm
Initial	None	29.1	25.6	
	Base case	16.5	13.0	23
+	Eliminate a demand at C = 10ppm by changing 12 *l* flushing toilet to composting toilet	15.6	13.7	23
+	Reduce by half the flowrate of demand at C = 10 ppm by changing the normal ablution water tap to low flowrate water tap.	8.5	6.6	23
+	Add a source* of C = 10 ppm by harvesting rainwater.	2.2	11.5	23
+	Regenerate to the maximum flowrate* for a source from C=23 ppm to C=4.2 ppm using a microfiltration, activated carbon and UV system.	0.03	9.27	4.2
= **Minimum water network (MWN) target**		**0.03**	**9.27**	**4.2**

Figure 5. The effects of WMH-guided process changes on MWR targets and pinch location.

Elimination of demand D8 by changing from a 12-l-flush toilet to a composting toilet (option 1) led to the steepest gradient on the IAS composite plot. SHARPS *Strategy 1* was then applied to remove the steepest gradient. Changing to a dual-flush toilet instead (option 2) yielded lower TPPs of 4.43 years for grassroots and 6.69 years for retrofit cases but the dual-flush toilet option then became the steepest gradient and the TPP_{set} was still exceeded (Figure 7.)

The base-case toilet option which gave a *TPP* of 4.01 years for grassroots and 5.19 years for retrofit was finally selected. Since TPP_{set} was not achieved by trimming the steepest gradient, hence, intensifying the regeneration option which formed the next steepest gradient was considered (SHARPS *Strategy 2*). Regenerating only 0.39 t/day of ablution for grassroots and 2.89 t/day for retrofit achieved the TPP_{set}.

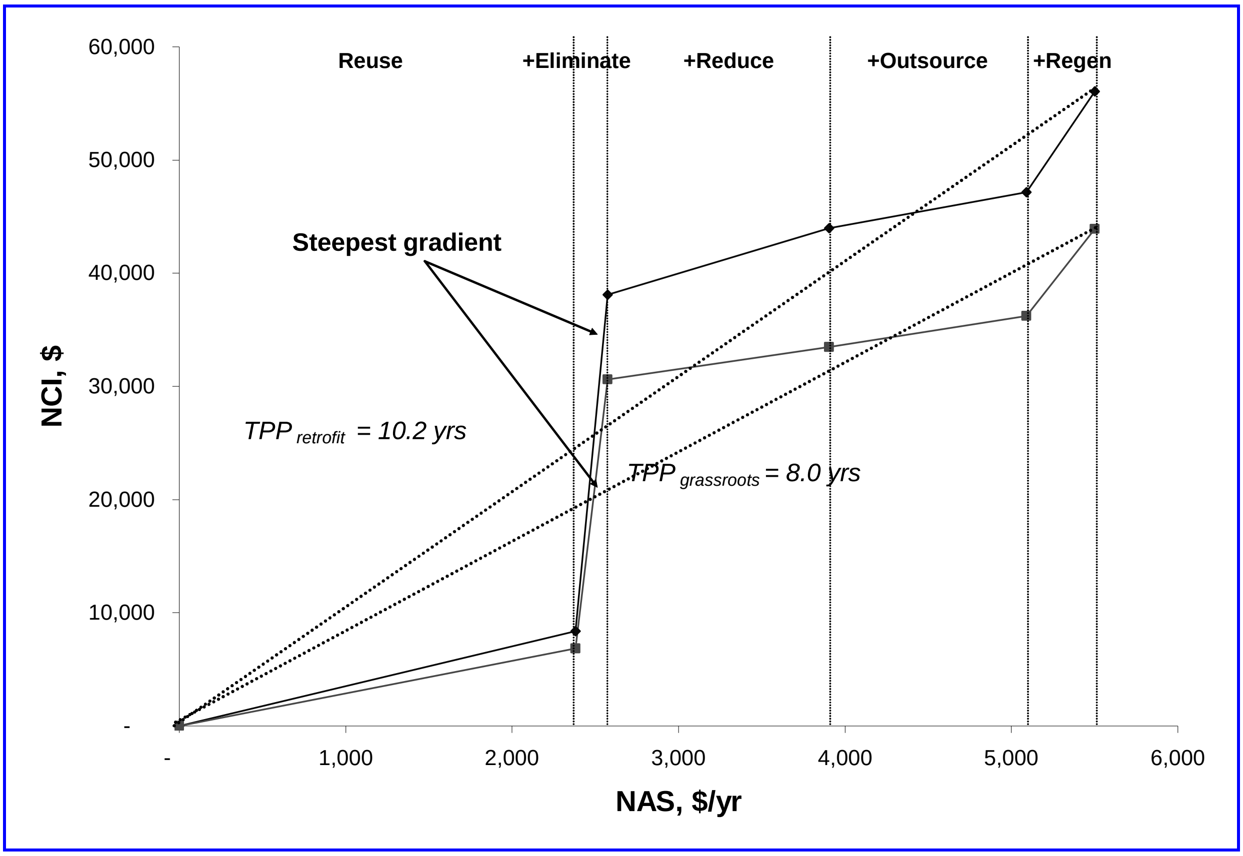

Figure 6. IAS plot for SIM.

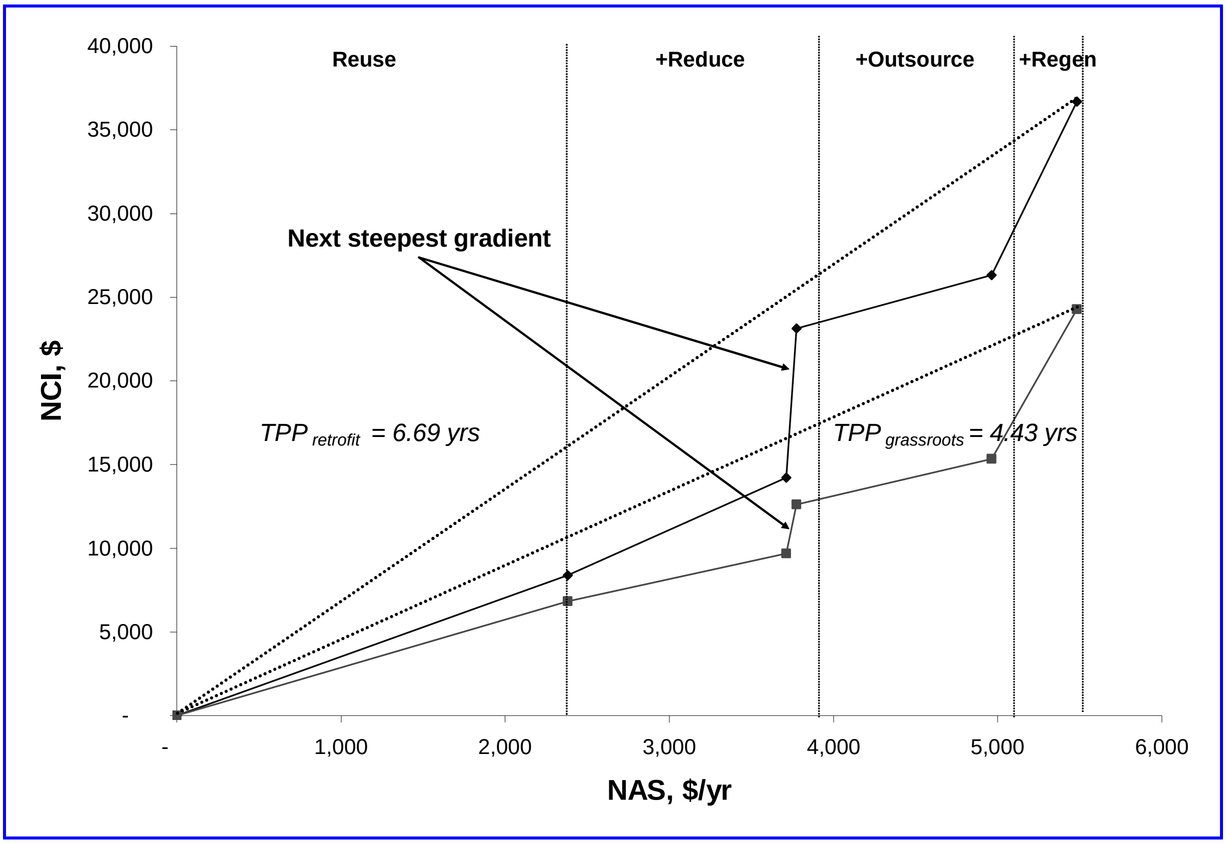

Figure 7. IAS plot after changing from composting toilet to dual-flush toilet for SIM.

This gave reductions of 90.5% freshwater and 59.3% wastewater for grassroots and 97.5% freshwater and 67.2% wastewater for retrofit. The final IAS plots that achieved the TPP_{set} are shown in Figure 8. The final network that achieved the CEMWN targets are shown in Figures 29(a) and 29(b).

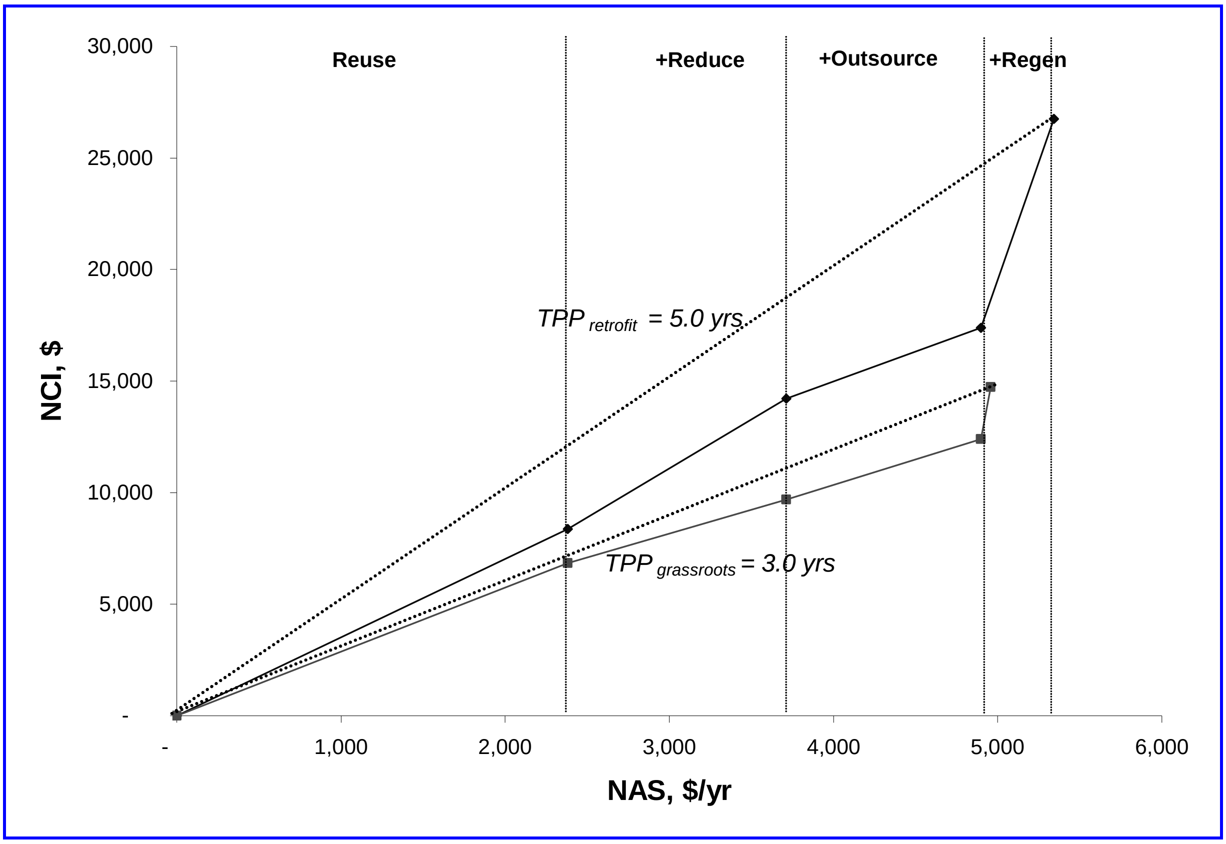

Figure 8. IAS plot after eliminating toilet flush process change and reducing regeneration for SIM.

Conclusion

The minimum water network (CEMWN) technique can help a company realize its' best achievable water savings target, assess its true potential for continuous improvement to fulfill its quality management requirement and ultimately minimize water through cost-effective design of water network. Application of CEMWN on a mosque building yileded savings of up to 90.5% freshwater and 59.3% wastewater achievable within a payback period of 3 years for grassroots case and 97.5% freshwater and 67.2% wastewater achievable within a payback period of 5 years for retrofit case. The proposed detailed improvement schemes and targets provided a useful guideline for short and long term water-saving programme that is generally applicable to any plant. Various approaches for benchmarking such as maximum water recovery (MWR) technique based on pinch analysis technique which considers plant design and thermodynamic constraints could also help a company realize its potential for conservation of resources beyond water, including material and utility heat, power and gases.

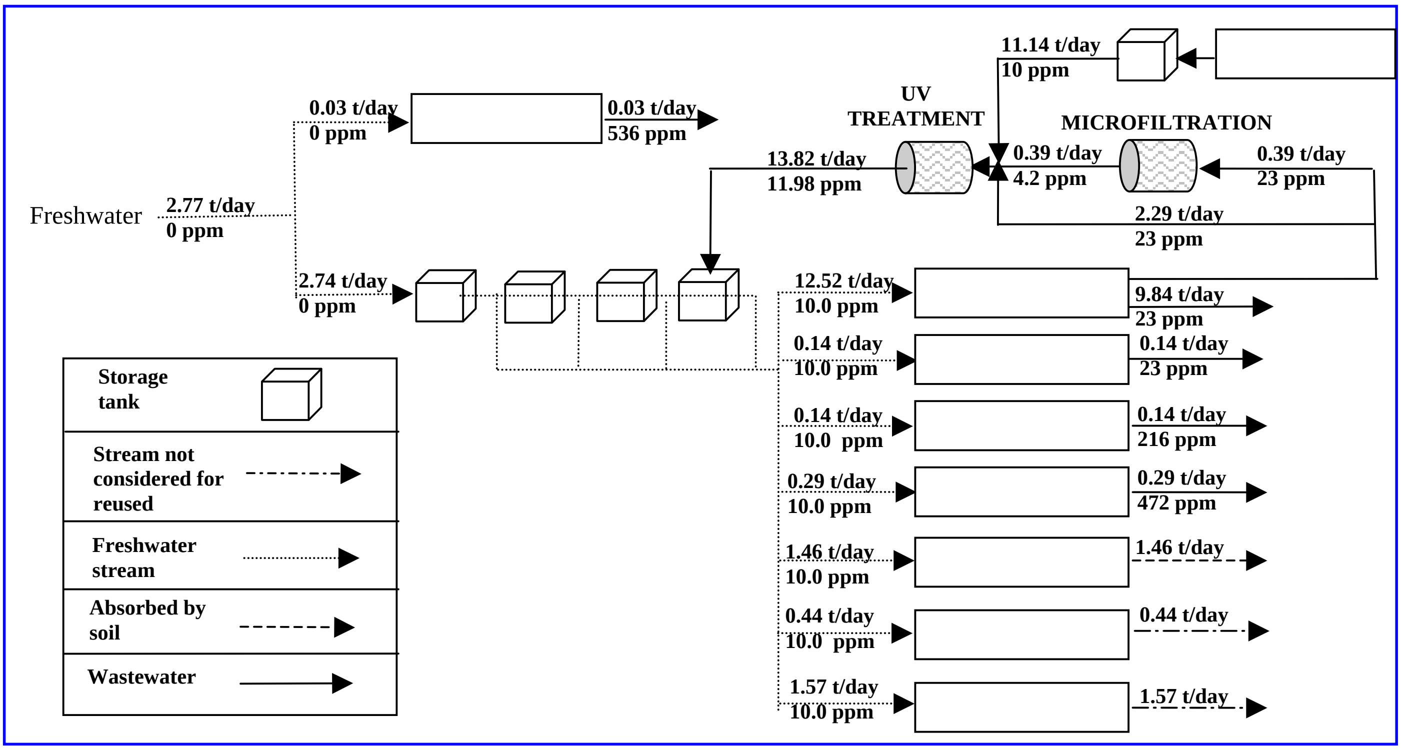

Figure 9(a). CEMWN design for SIM (grassroots).

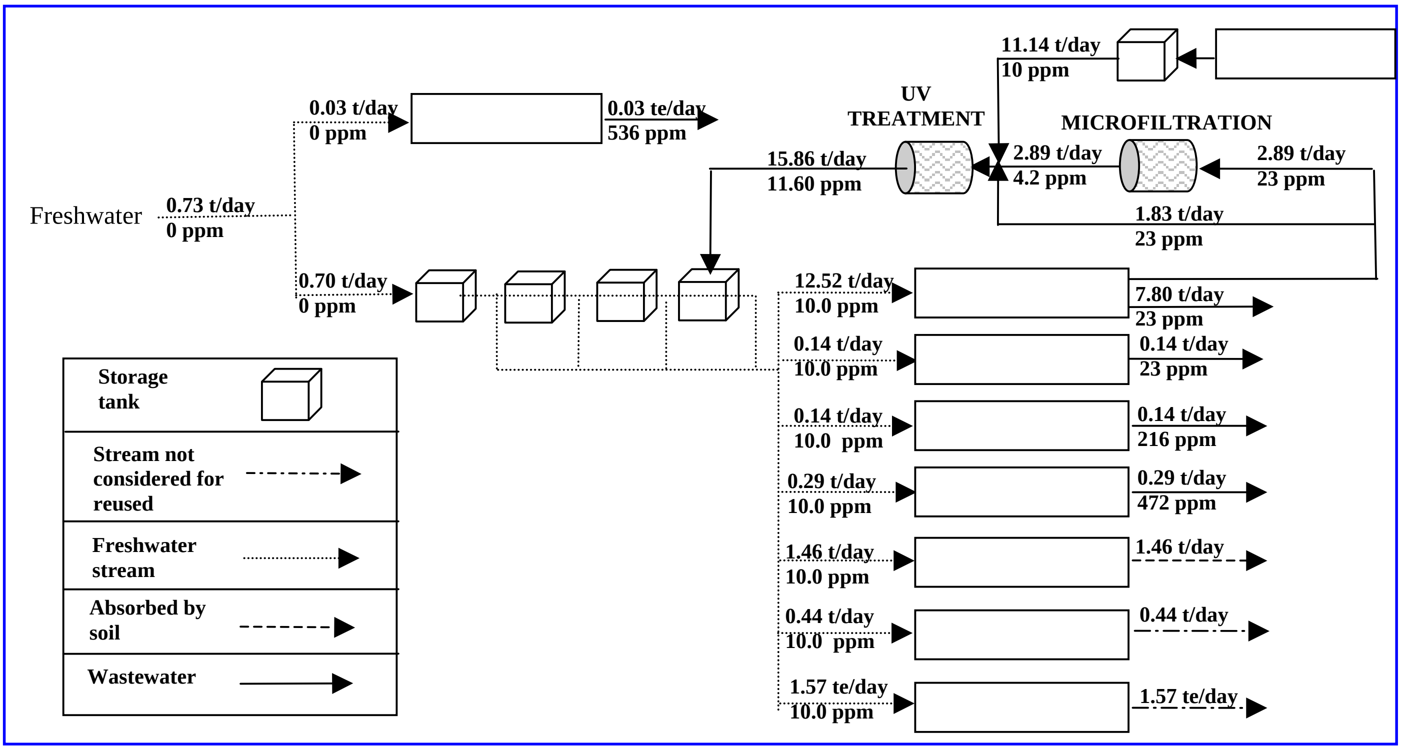

Figure 9(b). CEMWN design for SIM (retrofit).

Nomenclature

Acronym

IAS	Investment versus Annual Savings Plot
MWN	Minimum water network
MWR	Maximum water recovery
RO	Reverse osmosis
SIM	Sultan Ismail Mosque
TDS	Total dissolved solids
TSS	Total suspended solids
TPP	Total payback period
TPP_{AS}	Total payback period after SHARPS
TPP_{BS}	Total payback period before SHARPS
TPP_{set}	Desired payback period specified by designer
UF	Ultra filtration
UPW	Ultra pure water
WCA	Water cascade analysis
WMH	Water management hierarchy
WPA	Water pinch analysis

Symbols

C	Concentration
F	Flowrate

Subscripts

FW	Freshwater

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