WATER CONSERVATION SOLUTIONS FOR SAF USING ALTERNATIVE WATER SOURCES AND BEHAVIOURAL NUDGES

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Abstract

As part of Singapore Green Plan 2030 targets to reduce water use by 10%, there is a need to explore water conservation solutions. As such, water reuse as an alternate water supply was explored, specifically on the feasibility of implementing condensate recovery and greywater recycling systems which both have significant potential to yield reasonable payback over its life cycle.

To support implementation of condensate recovery and greywater recycling systems, payback calculators were created as a tool for design engineers to perform quick assessments on the viability of implementing such systems in their projects. Given their potential, they should be considered for implementation for SAF facilities, be it new build or renovation. However, it may only be financially feasible to implement condensate recovery and greywater recycling systems in buildings with an amply high peak air conditioner air flow rate or occupancy load respectively.

To further augment water conservation efforts, behavioural changes to drive water conservation habits are necessary. Recommendations proposed based on the COM-B framework include the conduct of water conservation training, use of colour choices to influence decisions such as having brown blemishes on dual flush buttons, fostering healthy group competition and installation of float boosters.

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1 Introduction

1.1 Water Shortage in a Global Context

Global population growth and the onset of urbanisation has heightened water consumption and strained available quality water sources. Additionally, climate change is affecting precipitation patterns and increases droughts, making water scarcer and more erratic. With a finite amount of freshwater, global water security is becoming a pressing concern[1].

1.2 Water Shortage in Singapore

With a small land area and little natural resources, Singapore draws on its 4 national taps — local catchment water, imported water, desalinated water and NEWater. However, with increasing demand and the bilateral water agreement ceasing in 2061, the need for Singapore to diversify supply lines and lower reliance on Malaysia is exacerbated. Novel water-conserving innovations to better manage and reduce our water demand are also equally essential. As such, SAF has committed to a 10% reduction in the Water Efficiency Index by 2030, in-line with the Singapore Green Plan 2030.

1.3 Purpose & Scope of Research

To support the goal of 10% reduction, this research explores the potential of intensifying water usage from an infrastructure design perspective to reduce water consumption, via air-conditioner condensate recovery systems and greywater recycling systems. Additionally, to promote sustainable water usage and drive superior water conservation habits, behavioural nudges were further examined.

The use of recovered condensate could be applicable for non-potable uses like vehicle washing or general cleaning, and other building operational usage like toilet flushing, refilling of make-up water tanks for cooling towers, or irrigation. For recycled greywater, its applications after necessary treatment include similar non-potable usages. The viability of applications, measured by return-on-investment and payback period, depend on expenditures incurred and cost savings. Hence, adoption of such systems may only be suitable in certain instances. The effectiveness of these solutions can be quantified through the use of payback calculators developed using Google Sheets as part of this study and which can be used as an assessment tool for future projects.

2 Materials and Methods

2.1 Literature Review

2.1.1 Condensate Recovery Systems

In Singapore's humid climate, air conditioners are commonplace, with nearly 99% of households owning one. As Singapore's average daily temperature continues to rise with climate change[2], many require air-conditioning to combat the heat and humidity. Most Singaporeans are now accustomed to air conditioning[3]. Moreover, interviews with over 43,000 Singaporean students revealed that their average exposure to air-conditioners daily was 6.2 hours[4]. As air-conditioning systems remain prevalent, it is worth exploring reusing condensate generated to aid water conservation efforts.

2.1.2 Greywater Recycling Systems

In Singapore, used water, including greywater[1] and blackwater[2], is collected through the sewer network leading to water reclamation plants , where it is treated to industrial water and NEWater. In 2013, greywater[5] made up 59% of domestic water consumption per capita in Singapore and greywater recycling has been shown to reduce water consumption by up to 40%. Thus, recycling greywater can maximise the value of water, thereby conserving water.

In SAF camps and bases, the main sources of greywater would be showers and washroom basins. The greywater collected will require treatment involving membrane filtration and disinfection to render it safe for non-potable use, complying with the required water quality as specified by PUB. It can be used for various non-potable end uses, but not for high pressure jet washing or sprinklers due to public health concerns.

2.1.3 Encouraging Water Conservation Behaviours

Behaviours that may influence water conservation can be constrained by barriers or facilitated by drivers. Barriers prevent people from acting pro-environmentally regardless of their

[1] Greywater, as defined by PUB, is untreated used water which has not come into contact with toilet waste. It includes used water from showers, bathtubs, toilet wash basins and water from clothes-washing and laundry tubs. It shall NOT include used water from urinals, toilet bowls (water closets), kitchen sinks or dishwashers.

[2] Blackwater, as defined by PUB, is domestic used water contaminated with faecal matter and urine.

attitudes or intentions. Drivers promote a desired activity, such as reduced water use or use of recycled water. The COM-B framework, which helps methodically assess barriers and drivers, is used to ideate behavioural nudges. The COM-B framework cites Capability, Opportunity and Motivation as three key components that are critical in shifting Behaviour. Capability refers to an individual's psychological and physical ability to participate in an activity. Opportunity refers to external factors that make a behaviour possible. Lastly, motivation refers to the conscious and unconscious cognitive processes that direct and inspire behaviour[6]. By analysing water conservation opportunities using the COM-B framework, this research aims to investigate factors that can better stimulate soldiers to conserve water.

2.1.3.1 First Barrier to Water Conservation: Capabilities

Capabilities comprise physical and psychological capabilities. Addo et al., 2018[7] found that respondents profiled to possess the capacity to engage in water conservation activities were more supportive of such behaviour. They were found installing water-efficient devices and supporting water-conservation policies more so than respondents from other profiles.

Enablers of physical capability include education and financial means. Biggest educational barriers associated with constrained personal capabilities include lack of knowledge and education about the need for water conservation, paucity of theory-based research-driven programs, and perceived lack of skills to participate in conservation activities. Participants reported that a lack of clarity on conservation programmes, shortage of theory-based research-driven programs, and inoperative campaigns weakened their knowledge of water conservation, causing elusive behavioural change, and that they would partake in water-conservation if they had relevant information about water-conservation strategies and the environmental and socio-economic effects of their actions. Financially, participants with a higher education level and thus income experienced heightened readiness to install water-efficient devices that can cut household water consumption.

The enabler of psychological capability is education, which primarily tackles environmental apathy. Resistance to implementation is linked to an indifference toward water-conservation activities. Awareness surrounding water shortages and behavioural actions was shown to be a significant intervening variable between households' attitudes toward conservation and behavioural intentions.

2.1.3.2 Second Barrier to Water Conservation: Motivation

Enablers of motivation comprise social support, reward, and incentives. Barriers included a lack of incentives and environmental values. Most members of this group showed low commitment to engage in conservation behaviour, and a contributing factor was a lack of support from bodies such as government water agencies. This affected their intention to undertake conservation actions because water-efficient devices are costlier and less appealing. To circumvent this, incentives (emotional needs and fringe benefits) and rebate programmes can promote water conservation behaviour (Herzberg et al, 2011) via providing an achievable target and a desirable reward.

2.1.3.3 Third Barrier to Water Conservation: Opportunities

Physical opportunity enablers include knowledge and incentives. This group had positive perceptions about water-efficient devices and reported greater concern for future expectancy of water crises, and would support water-conservation given the necessary opportunities to act. They had barriers in relation to strategies proposed by government bodies such as paucity of rebates and inadequate monetary support to encourage water conservation. Thus, they showed lower levels of automatic motivation in conserving water because unsatisfactory policies restricted their tendencies to change their behaviour. However, combinations of increased rebate programs and public education in the performance of water-efficient devices could increase the effectiveness of conservation intentions. Community and social-based initiatives are another enabler. This group was challenged by the paucity of resources or time to engage in conservation activities. The perceived lack of support, funds, and resources from government water agencies to start conservation activities can negate the likelihood of individuals with this profile in taking part in water-conservation actions, since individuals are more likely to endorse an intervention if key personalities support the actions. Intervention includes committed individuals who serve as role models/guides for testing, carrying out, and promoting conservation activities.

2.2 Methodology

2.2.1 Assessing the Feasibility of Water Conserving Innovations

A dynamic model calculator was developed to yield results relating to the amount of greywater or condensate collected, the payback period, the return-on-investment (ROI) based on inputs of associated building design parameters. Payback periods are calculated by comparing the annual operating expenditure (OpEx) for obtaining treated greywater or condensate to annual cost savings from reductions in the use of potable water or NEWater. The model then produces a feasibility check comparing the payback period against the optimal timeframe for ROI. Both calculators include sheets for assumptions made, and a quick calculator (which displays purely the inputs required and the key output metrics).

2.2.1.1 Use of Condensate Recovery System Payback Calculator

The calculator is structured with sheets on (1) assumptions made, (2) a quick calculator, (3) the amount and cost of condensate recovered, and lastly (4) individual calculator for each of the 4 condensate recovery use cases (toilet use & general washing, vehicle washing, cooling tower and irrigation), which is more detailed than the quick calculator.

2.2.1.2 Use of Greywater Recycling System Payback Calculator

The calculator is similarly structured in the form of (1) assumptions made, (2) a quick calculator, (3) the amount and cost of greywater recycled, and (4) individual calculator for each of the 3 greywater use cases (toilet use & washing, cooling tower tank and irrigation), which is more detailed than the quick calculator.

2.2.1.3 Key Expenditure Line-Items[3]

Capital Expenditure (CapEx): Equipment for condensate recovery systems and greywater recycling systems includes a pump, collection tanks for untreated condensate and greywater respectively, feedtanks for treated condensate and greywater respectively, and the necessary water treatment systems.

Plumbing & Electrical: Plumbing and electrical related costs are required for the functioning of the implemented system.

[3] Equipment & Installation Fees and Professional Consultations & Submissions have been subsumed under the total expenses.

OpEx (Operating Expenditure): The system would incur maintenance fees, including manpower for scheduled service interventions, system (pumps) servicing, equipment and consumables replacement (if any), and chemicals for cleaning and disinfection to improve water quality. The system would also consume energy for pumping and transporting water along pipelines, incurring energy fees.

3 Results

3.1 Payback Calculator Simulations

3.1.1 Condensate Recovery Payback Period in Relation to Air Conditioner Air Flow Rate

In both simulations, recovered condensate is only utilised for 1 use case for assessment, comprising toilet use, boot washing & general washing, with the conditions assumed as shown in Table 1:

Table 1: Summary of Use Case Parameters for Condensate Recovery

Condition	Assumption
Occupancy Load	300 pax
Frequency of Toilet Bowl Usage	2 flushes/pax/day
Frequency of Urinal Usage	2 flushes/pax/day
Number of General Cleaning Fittings	4
Duration per use of General Cleaning Fitting	10 minutes
Frequency of Boots Washing	200 washes/day, 0.5 minute per wash

In the first simulation, the peak air conditioner air flow rate is assumed to be 30,000m^3/h. Table 2 shows the significant outputs from the payback calculator:

Table 2: Condensate Recovered and Payback Period for 30,000 Peak CMH

Variable	Output
Volume of Condensate Recovered[4]	4964m^3/year
Payback Period	9.75 years

As the payback period is shorter than the optimal timeframe for ROI, which is assumed to be 15 years, it is feasible to implement a condensate recovery system in this building with this peak air conditioner air flow rate.

The only parameter changed for the second simulation is the peak air conditioner air flow rate. In the second simulation, the objective is to find the minimum air conditioner air flow rate to achieve a payback period as close to 15 years as possible for the same building profile. Outputs obtained with a peak air conditioner air flow rate of 5539m^3/h are shown in Table 3:

Table 3: Condensate Recovered and Payback Period for Optimal ROI Timeframe

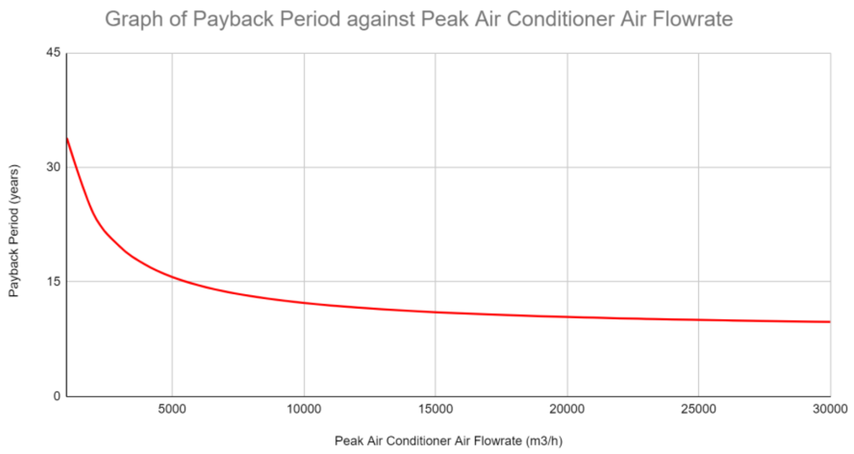
Variable	Output

[4] Estimated using equations (1) - (4) in Mathematical Formulae and Equations

Volume of Condensate Recovered	$1529m^3$/year
Payback Period	15.00 years

Figure 1 shows how the payback period decreases as the peak air conditioner air flow rate increases from $1000m^3$/h to $30,000m^3$/h for the same building profile:

Figure 1



3.1.2 Greywater Recycling Payback Period in Relation to Occupancy Load

In both simulations, treated greywater is only utilised for 1 use case for assessment, comprising toilet use and washing, with the conditions assumed as shown in Table 4:

Table 4: Summary of Use Case Parameters for Greywater Recycling

Condition	Assumption
Occupancy Load (Weekend)	100/day
WELS Rating of Showerheads and Basin Taps	3 ticks
Frequency of Shower Usage per pax	2/day, 10 minutes per use
Frequency of Basin Tap Usage per pax	4/day, 12 seconds per use
Frequency of Urinal Usage per pax	2 flushes/day
Frequency of Toilet Bowl Usage per pax	2 flushes/day
Average Daily Input from Purposes Besides Showers and Basin Taps (Weekday)	2000L
Average Daily Input from Purposes Besides Showers and Basin Taps (Weekend)	400L

In the first simulation, the occupancy load of the building is assumed to be 2000 pax per weekday. Table 5 shows the significant outputs from the payback calculator:

Table 5: Greywater Collected and Payback Period for 2000 pax Weekday Occupancy Load

Variable	Output

Volume of Greywater Collected	54599.98m^3/year
Payback Period	4.76 years

As the payback period is shorter than the optimal timeframe for ROI, which is assumed to be 15 years, it is feasible to implement a greywater recycling system in this building with this weekday occupancy load.

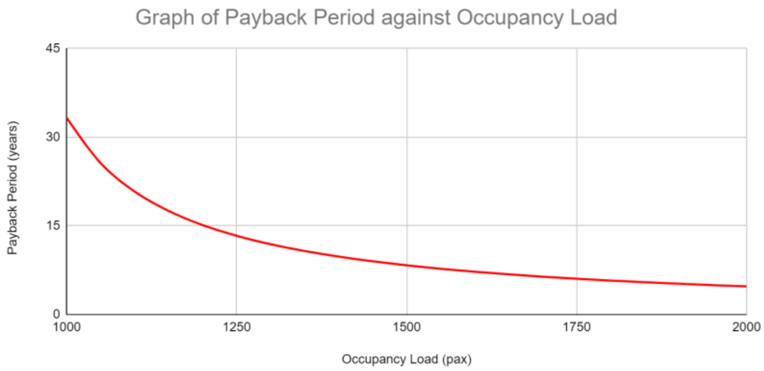
The only parameter changed for the second simulation is the weekday occupancy load. In the second simulation, the objective is to find the minimum weekday occupancy load to achieve a payback period as near to 15 years as possible for the same building profile. Outputs obtained with an occupancy load of 1204 pax per weekday are shown in Table 6:

Table 6: Greywater Collected and Payback Period for 1204 pax Weekday Occupancy Load

Variable	Output
Volume of Greywater Collected	33515.02m^3/year
Payback Period	14.98 years

Figure 2 shows how the payback period decreases as the occupancy load increases from 1000 to 2000 for the same building profile:

Figure 2



3.2 Recommendations to Shape Behaviours

SAF can employ efficacious short-term measures like incentive-based solutions or "nudges" to invoke action, or long-term solutions shifting soldiers' mindsets. Soldiers should pivot from "needing" to "wanting" to save water once they understand the impact of conserving water and the danger of water scarcity.

3.2.1 Proposed Solutions Regarding First Barrier to Water Conservation: Capabilities

Educating Soldiers Through Training/Workshops. SAF can place greater emphasis through education, to equip soldiers with better knowledge on water conservation actions and empower them especially since some may have misunderstandings that conserving water is inconvenient and time-consuming. Some examples of practical actions that soldiers can adopt are: consolidating laundries to use washing machines at full loads, establishing process for soldiers to check for and investigate leaks (e.g. using water meter to identify areas with anomalous water consumption) with the necessary follow up actions to resolve issue, using a pail for washing instead of a hose, and recycling water whenever possible.

3.2.2 Proposed Solutions Regarding Second Barrier to Water Conservation: Motivation

A. Instilling Competition

Establishing Water Consumption Targets and Incentivising Soldiers. Water consumption goals should decrease for an increasing number of months a soldier has served in the SAF camp/base. Tangible goals can galvanise soldiers into taking actionable steps to meet them, allowing soldiers to put into practice the water conservation strategies taught to them. This complements measures encouraging self-regulation as soldiers are able to constantly track their water usage. Adjusting monthly goals in accordance with soldiers' length of service encourages progression of their water conservation capabilities over time, and ensures that soldiers pick up new practices to conserve water once old ones have become routine. When meeting expectations culminates in rewards for soldiers, such as early bookout and cash vouchers, soldiers are further incentivised to work towards the water consumption goals set by SAF.

Foster Healthy Group (e.g. within platoons) Competition and Encourage Peer Education. According to a study conducted by Meleady & Seger, 2019, people's attitudes and behaviours change and align with those who share an important social identity with them. Hence, this initiative encourages positive social influence across peers, improving attitudes towards water conservation and increasing efforts to lower water consumption overall. SAF can consider carrying out trials in operational environments, such as in training school, to evaluate.

B. Platform to Empower Soldiers in Creating Innovative Water Conservation Measures

Implementation of a System to Share Innovative Water Conservation Measures with Unit Management. Challenging soldiers to constantly cut down water consumption compels them to create novel approaches towards water conservation. Such methods thought up by soldiers themselves may have a wider and deeper influence among peers as opposed to strategies imparted to them by higher-ups. These ideas can then be spread to wider audiences and utilised by more people, making a larger contribution to water conservation.

C. Methods to Discourage Water Consumption

Addition of Brown Blemishes to Dual Flush Buttons. People dislike colours strongly associated with objects they dislike (e.g., browns with faeces)[8]. Hence, brown blemishes could discourage soldiers from using dual flush and use the half-flush button instead, using less water per flush.

Implementation of Posters. Lining washrooms with graphics of children whose lives are affected in areas experiencing water shortage evokes pity and sadness, "guilt-tripping" soldiers into saving water by attaching strong emotions and thoughts to water conservation.

3.2.3 Proposed Solutions Regarding Third Barrier to Water Conservation: Opportunities

A. Engineering Solutions

Float Boosters. For old toilets without dual-flush options, installing float boosters which displace water in toilet tanks helps reduce water used per flush. This measure is low-cost, easy-to-implement and generates prodigious savings in the long run.

High Water Efficiency Appliances. These include water-conserving faucets that reduce water flow, increasing water efficiency by 30%, generating substantial water savings. To prevent 'behavioural offsetting', whereby people become over-reliant on innovative devices, breeding complacency and discouraging effort[9], and bring long-term behavioural change, SAF should also pivot towards pursuing innovations that provide opportunity by altering the environment around soldiers, supplying tangible avenues required to save water, thus stimulating effort.

Shower Timers and Water Meters. Shower timers help soldiers track the length of their shower and water meters in water-using devices tabulate in real time how much water is being consumed. These can be used tangentially to education, where soldiers gain awareness of their average shower duration and water consumption. This can inspire self-regulating behaviour amongst soldiers, enabling them to be more mindful about their water use.

Food Digesters. Implementing food digesters, besides reducing waste generated, can also help reduce water usage downstream (outside camps) at garbage disposal units, which consume 2-5 gallons of water per user each time one runs the garbage disposal[10]. Centralising food digesters could be considered for achieving economies of scale.

B. Administrative Control

Providing Soldiers with Tools to Encourage Water Conservation Behaviour. These include: collecting rainwater and reusing unused water for irrigation or flushing of toilets. Via furnishing concrete avenues that are simple to understand and use for soldiers to conserve water, water conservation behaviour is perceived as easier, which is imperative as inconvenience is a key impediment to water conservation. In this manner, such behaviour is more likely to be maintained long-term.

Establish Water Conservation Work Practices. SAF can establish work practices that reduce the duration, frequency, or intensity of water use. For example, soldiers may use hoses for outdoor cleaning purposes as it is the most time-effective method of washing, compared to less water-intensive albeit more time-consuming measures, such as washing vehicles using water pails and sweeping or scrubbing surfaces instead of using a spraying hose. Adequate time can be allocated for clean-up activities, providing soldiers with the capacity to select more water-conserving means of completing everyday tasks. For improved efficacy, SAF can consider enforcing such behaviour more strictly.

4 Discussion

4.1 Summary of Recommendations

The payback calculators developed have proved to be a useful tool for design engineers to perform quick assessments on the viability of implementing a condensate recovery and greywater recycling system for their projects. The calculators could also help design engineers understand the design parameters that could be adjusted to optimise and improve the feasibility of implementation for these systems.

Table 7 shows the ease of implementation (near-term or with further planning required) and types of changes (infrastructural or process) proposed as part of each recommendation, which helps to categorise how SAF can allocate its resources to the water conservation effort.

Table 7: Recommendations

Barrier	Recommendation	Ease of Implementation		Type of Change	
		Near-Term	Further Planning Required	Infrastructural	Process

Capabilities	Provision of Water Conservation Training/Workshops		✓		✓
Motivation	Establishing Water Consumption Targets and Incentivising Soldiers		✓		✓
	Fostering Competition and Encouraging Peer Education		✓		✓
	Implementation of System to Share Innovative Water Conservation Measures		✓		✓
	Addition of Brown Blemishes to Dual Flush Buttons	✓		✓	
	Implementation of Posters	✓		✓	
Opportunities	Float Boosters	✓		✓	
	High Water Efficiency Appliances	✓		✓	
	Shower Timers and Water Meters	✓		✓	
	Food Digesters	✓		✓	
	Providing Soldiers with Tools to Encourage Water Conservation Behaviour	✓			✓
	Establish Water Conservation Work Practices		✓		✓

4.2 Future Work

To further expand on the findings of this report, further use cases of condensate and greywater could be explored. In addition, the assessment on efficiency of consolidating all recovered condensate and treated greywater into one use case as compared to a combination of use cases could be explored. Additionally, payback calculators can also be created for other water conservation systems.

To assess the impact towards water conservation based on the recommendations for behavioural changes, trials could be conducted at small scales before scaling up if successful. Further study, iteration and development of policies for each of the recommendations would be required as part of the trial. Lastly, technology-watch for novel water-conserving solutions should be continually maintained and considered for implementation if viable.

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7 Annexes

7.1 Mathematical Formulae and Equations

(1) $$P_{ws} = 6.112e^{\left(\frac{17.67T_{db}}{T_{db}+243.5}\right)}$$

(2) $$e_w = 6.112e^{\left(\frac{17.67T_{wb}}{T_{wb}+243.5}\right)}$$

(3) $$P_w = e_w - P(T_{db} - T_{wb}) \times 0.00066(1 + 0.00115T_{wb})$$

(4) $$RH = 100\frac{P_w}{P_{ws}}$$

(5) $$x = \frac{C}{W_T(2.74W_p + 2.33W_N) - E}$$

P_{ws} = Saturation Vapour Pressure, mbar
E_w = Vapour Pressure related to Wet-bulb Temperature, mbar
P_w = Partial Vapour Pressure, mbar
P = Standard Atmospheric Pressure, 1013.25 mbar
T_{wb} = Wet-bulb Temperature, °C
T_{db} = Dry-bulb Temperature, °C
RH = Relative Humidity, %
x = Payback Period, years
C = Capital Expenditure (CapEx), $
W_T = Total Annual Water Consumption, m^3/year
W_p = Percentage of Potable Water Previously Used, %
W_N = Percentage of NEWater Previously Used, %
E = Annual Operating Expenditure (OpEx), $

7.2 Payback Calculators

Figure 3: Amount of Condensate Recovered

Amount of Condensate Recovered	
Per AC Unit	
Air Leaving (Off-Coil)	
Temp (Dry Bulb) (°C)	13.5
Temp (Wet Bulb) (°C)	12.7
Pws (saturation vapour pressure) (/mbar)	15.463
Ew (vapour pressure related to wet bulb temp) (/mbar)	14.675
Patm (Standard atm Pressure) (/mbar)	1013.25
Pw (Partial Water Vapour Pressure) (/mbar)	14.133
B (molecular mass of water: mol mass of gas) (kg/kg)	0.62198
HR (off-coil) [Humidity Ratio of Air Leaving] (kg/kg)	0.008798
Air Entering (On-Coil)	
Temp (Dry Bulb) (°C)	27
Temp (Wet Bulb) (°C)	19
Pws (saturation vapour pressure) (/mbar)	35.659
Ew (vapour pressure related to wet bulb temp) (/mbar)	21.960
Patm (Standard atm Pressure) (/mbar)	1013.25
Pw (Partial Water Vapour Pressure) (/mbar)	16.493
B (molecular mass of water: mol mass of gas) (kg/kg)	0.62198
HR (on-coil) [Humidity Ratio of Air Entering] (kg/kg)	0.010292
Difference in HR (kg/kg)	0.0014939
Peak CMH [Air Conditioner Air Flowrate (m3/h)]	30000.00
GFA (m2)	
Density of Air (kg/m3)	1.225000
Mass Air Flowrate (kg/h)	36750.00
AC Condensate Flowrate (lb/min)	54.9015
AC Condensate Flowrate (mL/s)	415.649
AC Condensate Flowrate (m3/h)	1.496337
Number of Operating Hours	
Number of Operating Hours (Day)	12
Number of Operating Hours (Night)	12
Load of CMH (Weekday Day)	70%
Load of CMH (Weekday Night)	20%
Load of CMH (Weekend)	30%
Load on Weekday	10.800
Load on Weekend	7.200
Condensate Flow (m3/week)	95.202
Condensate Flow (m3/year)	**4964.1**
Total Condensate Recovered (m3/year)	**4964**
Usage of Condensate	**Condensate Required (m3 / year)**
Irrigation	**1314.00**
Toilet, General Cleaning, & Boots Washing	**1189.90**
Vehicle Washing	**1299.40**
Cooling Tower	**1261.44**
Total	**5064.74**

Formulae Used

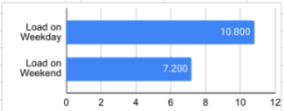
$$P_{ws} = 6.112e^{\left(\frac{17.67T_{db}}{T_{db}+243.5}\right)} \quad (1)$$

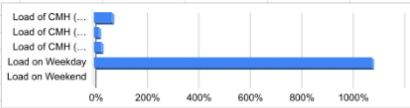
$$e_w = 6.112e^{\left(\frac{17.67T_{wb}}{T_{wb}+243.5}\right)} \quad (2)$$

$$Pw = e_w - P\,(T_{db} - T_{wb}) \times 0.00066(1 + 0.00115T_{wb}) \quad (3)$$

$$RH = 100\frac{P_w}{P_{ws}} \quad (4)$$

P_{ws} = Saturation Vapour Pressure, mbar
e_w = Vapour Pressure related to Wet-bulb Temperature, mbar
P_w = Partial Vapour Pressure, mbar
P = Standard Atmospheric Pressure, 1013.25 mbar
T_{wb} = Wet-bulb Temperature, °C
T_{db} = Dry-bulb Temperature, °C
RH = Relative Humidity, %





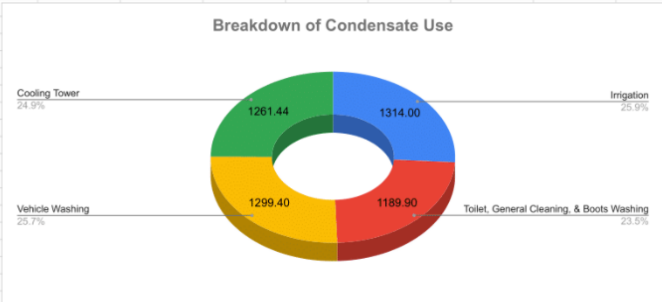


Figure 4: Condensate for Toilet Use, General Cleaning & Boots Washing

Condensate for Toilet Use, General Cleaning, & Boots Washing				
Total Water Consumption			**Total Expenses**	
Toilet Use Water Consumption			**Non-Recurring**	
			Pump	$5,000.00
Toilet Bowl Flushing			Collection Tank (untreated condensate)	$5,000.00
Average water used per flush (litre)	4		Advanced Filtration System	$10,000.00
Number of users	300		Feedtank (treated condensate)	$5,000.00
Number of flushes per user per day	2		Plumbing & Electricals	$2,500.00
Number of flushes per day	600		**Total Cost**	**$27,500.00**
Total Water Consumption (L/day)	**2400**			
			Recurring	
Urinal Flushing			**OpEx (Annual)**	
Average water used per flush (litre)	0.5		Operation & Maintenance Cost	
number of users	300		Total OpEx (Annualised)	$0.00
Number of flushes per user per day	2		Useful Life (/years)	15
Number of flushes per day	600		**Total OpEx Over Useful Life**	**$0.00**
Total Water Consumption (L/day)	**300.0**			
			Total Expenses ($)	**$27,500.00**
General Cleaning WC				
Number of Fittings	4			
Water Consumption (L/min use)	4			
Duration of Use Per Fitting (min)	10			
Total Water Consumption (L/day)	**160**			
Boots Washing WC				
Number of Washes	200			
Duration of Use Per Wash (min)	0.5			
Water Consumption (L/min use)	4			
Total Water Consumption (L/day)	**400.00**			
Total Water Consumption (L/day)	**3260.0**			
Total Water Consumption (m3/year)	**1189.90**			
ROI Calculation				
Composition of Water Previously Used For This Purpose			**Payback Period (years)**	**9.75**
% of Potable Water Used	100.00%		**Feasible?**	**YES**
% of Rainwater Used	0.00%			
Annual Water Savings	**2820.9**			

Figure 5: Amount of Greywater Collected

Greywater Collection (input)	
During Weekdays	
Occupancy Load (pax/day)	2000
From Showers	
Average Daily Number of Uses per pax	2
Average Duration per Use (min)	10
Number of WELS Ticks of Showerheads	3
Average Flow Rate of Shower (L/min)	5
Average Input from Shower Water (L/day)	200000
From Washroom Basins	
Average Daily Number of Uses per pax	4
Average Number of Presses per Use	4
Average Duration of Flow per Press (s)	3
Number of WELS Ticks of Basin Taps	3
Average Flow Rate of Basin Tap (L/min)	2
Average Input from Washroom Taps (L/day)	3200
Others (e.g. Laundry, Boot Washing, Vehicle Washing etc.)	
Average Daily Input from Other Purposes (L/day)	2000
Average Input (L/day)	205200
During Weekends	
Occupancy Load (pax/day)	100
From Showers	
Average Daily Number of Uses per pax	2
Average Duration per Use (min)	10
Number of WELS Ticks of Showerheads	3
Average Flow Rate of Shower (L/min)	5
Average Input from Shower Water (L/day)	10000
From Washroom Basins	
Average Daily Number of Uses per pax	4
Average Number of Presses per Use	4
Average Duration of Flow per Press (s)	3
Number of WELS Ticks of Basin Taps	3
Average Flow Rate of Basin Tap (L/min)	2
Average Input from Washroom Taps (L/day)	160
Others (e.g. Laundry, Boot Washing, Vehicle Washing etc.)	
Average Daily Input from Other Purposes (L/day)	400
Average Input (L/day)	10560
Total Input (m3/week)	1047.12
Total Greywater Collected (m3/year)	**54599.97816**

Figure 6: Greywater for Toilet Use & Washing

Greywater for Toilet Use & Washing			
Total Water Consumption		**Total Expenses**	
Occupancy Load (pax)	2000		
		Non-Recurring	
Toilet Use Water Consumption		**CAPEX**	
		Pump	$25,000.00
Toilet Bowl Flushing		Collection Tank (untreated greywater)	$110.00
Average water used per flush (L)	3.5	Water Treatment (advanced filtration, disinfection and chlorine dosing system)	$7,533.00
Number of users	2000	Feedtank (treated greywater)	$15,840.00
Number of flushes per user per day	2	Plumbing & Electricals	$4,848.30
Number of flushes per day	4000	**Total Cost**	**$53,331.30**
Total Water Consumption (L/day)	**14000**		
		Recurring	
Urinal Flushing		**OpEx (Annual)**	
Average water used per flush (L)	0.5	Operation & Maintenance Cost	$7,999.70
Number of users	2000	**Total OpEx (Annualised)**	**$7,999.70**
Number of flushes per user per day	2		
Number of flushes per day	4000		
Total Water Consumption (L/day)	**2000**		
Washroom Taps			
Number of Users	2000		
Average Daily Number of Uses per pax	4		
Water Consumption (L/min use)	2		
Duration of Use Per Tap (min)	0.2		
Total Water Consumption (L/day)	**3200**		
Total Water Consumption (L/day)	**19200**		
Total Water Consumption (m3/year)	**7008.00**		
ROI Calculation			
Composition of Water Previously Used For This Purpose		**Payback Period (years)**	**4.76**
% of Potable Water Used	100.00%	**Feasible?**	**YES**
% of NEWater Used	0.00%		
Annual Water Savings	**17718.8**		

7.3 Condensate Recovery Systems

The operation of an air conditioner is based on the withdrawal of warm, humid air from the environment, concomitant with the introduction of cold air. The evaporator unit is located indoors, where cool air is introduced. It helps capture warm air indoors, which is directed to and released at the condensing unit (air-handling unit) located outdoors. The AHU captures air from the external environment and directs it through cooling coils into the evaporator unit, which releases cooled air to the internal environment. The process of cooling air in cooling coils promotes condensation of water vapour present in the warm air mass, generating liquid water as a by-product. With condensate recovery systems in AHUs, instead of condensate being drained, it is collected in pans and channelled to a collection barrel via a condensate drain pipe, where water can be volumetrically collected via a tap. The system line requires periodic sanitization with 1.0 N hydrochloric acid solution followed by three successive flushes with ultrapure water to yield higher quality condensate. At the Technology Centre of UFRN-Brazil, AHUs produced a mean flow rate of 2.25 L/h for a 24,000 BTU unit, 1.06 L/h for a 12,000 BTU unit, and 1.04 L/h for a 9,000 BTU unit.

7.3.1 Pros and Cons of air-conditioner condensate recovery systems

7.3.1.1 Water Savings

These systems aid water conservation. Air-conditioner condensate systems have yielded laudable results in supplying condensate water in other countries. Furthermore, condensate is relatively clean, being low in mineral content and sometimes as pure as distilled water. Hence, it has multitudinous applications besides cooling towers, including irrigation, ornamental fountains and ponds, and flushing toilets. E.W. Bob Boulware, president of Design-Aire Engineering, adds that condensate can be used in swimming pools if biocide is added to remove biological contaminants. The Austonian, a 56-story residential skyscraper in Austin, Texas, captures 12,800 gallons of condensate a year, using this to irrigate a 10th-floor green space. Bahrain Airport Services in the Middle East generates 8,700,000ℓ of condensate water annually, which it harnesses for various non-potable purposes like sanitation (Taroepratjeka et al., 2015).

7.3.1.2 Cost Savings

The price of a condensate recovery system varies from a few hundred to thousands of dollars, depending on its design and how much piping is required to supply water for non-potable uses, such as supplying water to cooling towers. At Rice University, England, they used a pump to force condensate in the water pipe into the cooling tower basin without need of major reconstructions, minimising costs. Unless they need not be retrofitted into existing SAF buildings, including offices and residences, the cost of installation and maintenance of the condensate recovery system represents a high upfront capital expense. Nevertheless, the substantial value of water saved can justify this. The potential savings associated with replacing costly, treated water with free, clean condensate are substantial, stripping back on money expended to purchase unclean water and treat it. Expenditures for water and sewer services in the U.S. federal sector are as much as $1 billion annually. Moderate gains in water efficiency through condensate harvesting can save as much as $240 million a year. In addition, Rivercenter Mall in San Antonio collects 250 gallons of condensate daily, used to replenish the cooling tower water losses, while the San Antonio Public Library collects 1,400 gallons of condensate per day, which is used for irrigation. Within 6 months, cost savings from water conserved matched installation and maintenance fees for the condensate recovery system. The return-on-investment is likely more apparent in Singapore, where the more hot and humid climate can yield a higher condensate volume and conserve more water.

7.3.2 How savings from condensate recovery differs in Singapore

7.3.2.1 Differing Water Price

In Singapore, as of December 2022, water price from NEWater plants for non-domestic (business) users is S$2.33/m^3 (equivalent to 1000ℓ) and S$1.58/m^3 for industrial water. This includes tariffs, a water conservation and waterborne fee, and excludes GST.

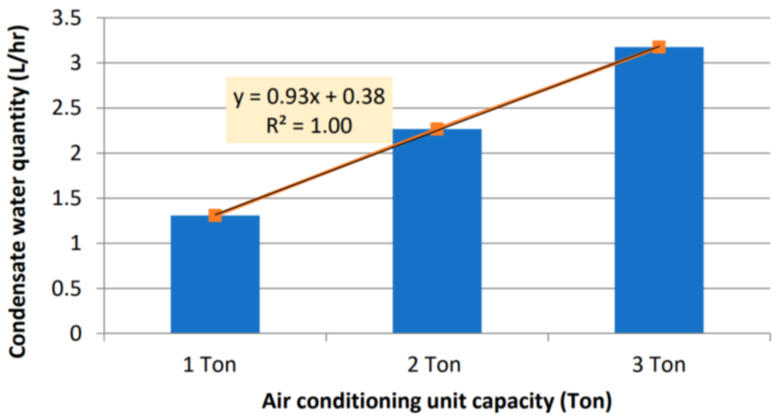
7.3.2.2 Unique Temperature & RH

The impact of the differing relative humidity and temperature in Singapore on the volume of condensate recovered can be investigated by modifying the inputs in the ROI calculator.

7.3.3 Effect of Air conditioning unit capacity / Temperature Change on Condensate Yield

7.3.3.1 Ramallah City, Palestine

Figure 7



The observed condensate water measurements in Figure 3b shows that at 18°C operating temperature the 1-, 2- and 3-Ton air conditioning units generated, on average, 1.30, 2.26 and 3.17 L/h, respectively. The observed condensate water volumes were considered to be significantly high.

A high R-squared value (R2) of 1.00 was obtained from the developed linear regression, which shows a close proximity of the fitted data between the water volume generated and the unit capacity. If these rates are calculated for an average working day of 6.64 h per day, the water volumes of the collected condensate water would reach 8.63, 15.00 and 21.10 L per day for the 1-, 2- and 3-Ton units, respectively. The relationship developed through the collected data confirmed the proportional increase between the condensate water volume and the air conditioning capacity in Tons.

Figure 8

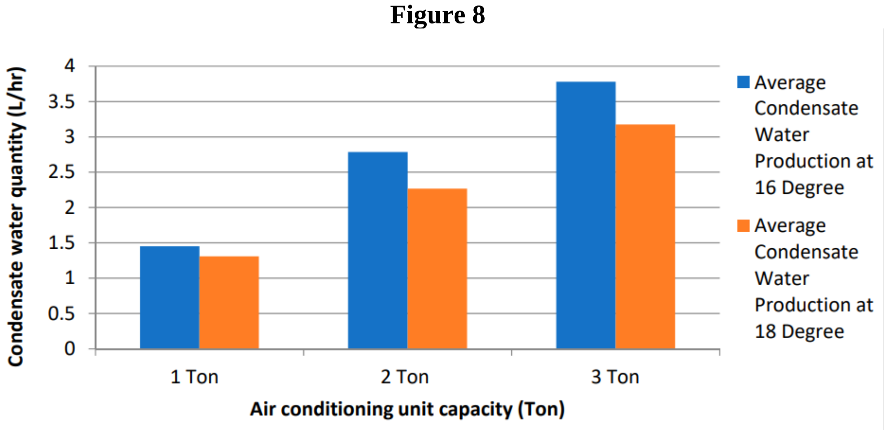


Figure 4 shows the relationship between the condensate water quantities at the different operating temperatures for the same unit capacity. Figure 4 shows the condensate water generated at both 16 °C and 18 °C operating temperatures. It can be noted that as the operating temperature decreases, the volume of the condensate water increases. Conceptually, it can be said that a slight decrease in the generated water volume of 10% is caused by a 2°C increase in the operating temperature.

7.3.4 Assessing Condensate Water Quality

Figure 9: Physical and chemical analysis for condensate water samples. Source: Siam, L. (2019). Developing a Strategy to Recover Condensate Water from Air Conditioners in Palestine. MDPI. Retrieved September 8, 2022.

Parameter *	Reading Range	Reading Mean	PSI (2005) Drinking Water Guidelines [19]	PSI (2012) Reused Irrigation Water Guidelines [20]
T (°C)	15.5–22.5	18.05	20	25
pH	6.4–7.59	7.12	6.5–8.5	6–9
TDS (ppm)	15.2–76.4	42.48	<1000	1200
EC (µs/cm)	30–220.4	79.40	-	700–3000
DO (mg/L)	0.36–5.9	2.52	-	>0.5
Turbidity (NTU)	0.55–6.69	1.97	1	5
BOD (mg/L)	1–6	2.23	-	20 (A Category)
COD (mg/L)	18–150	101.71	-	50 (A Category)
SO_4 (mg/L)	0.001–0.006	0.0033	200	300

*Temperature (T), acidity (pH), total dissolved solids (TDS), electric conductivity (EC), dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD) and sulphate (SO4).

Comparing the obtained results shown with the PSI standards, the following analysis can be developed:

The results of temperature measurements for the condensate water samples show that the samples fall approximately within the acceptable ranges of both the drinking water guidelines (less than 20 ◦C) and treated water reused for irrigation (less than 25 ◦C), and range at (15.5–22.5 ◦C).

Values of pH for the 65 collected samples fall within the range of 6.4–7.59, with an average value of 7.12, indicating that condensate water is approximately neutral and safe for consumption and irrigation.

TDS in condensate water samples range between 15.2 and 76.4 ppm, with an average of 42.48 ppm, far below the maximum allowable standards stated by the PSI for drinking water (1000 mg/L) and treated water reused in irrigation (1200 mg/L).

EC estimates the total amount of solids dissolved in water. Very low values of EC were presented, with a range of 30–220.4 µs/cm, and an average of 79.40 µs/cm, far below the maximum allowable standard for irrigation water (700-3000 µs/cm), though unsuitable for consumption.

DO concentrations in 65 condensate water samples ranged from 0.36 to 5.9 mg/L with an average of 2.52 mg/L, making it generally suitable for consumption (DO below 5 mg/L) and exceeding minimum requirements of the PSI for irrigation purposes (DO above 1 mg/L).

Turbidity analysis for tested samples show that the range of the measured turbidity was 0.55–6.69 NTU, with an average of 1.97 NTU. According to the PSI, the acceptable limit of turbidity for drinking water is 1 NTU. High turbidity in drinking water means it is unsuitable for consumers due to high amounts of sediment and other matter. For agricultural purposes, water with a maximum turbidity of 50 NTU is suitable, hence turbidity measurements for all samples fall under the acceptable limits of agricultural water.

BOD: the tested condensate water samples for the BOD level ranged from 1 to 6 mg/L, with an average value of 2.23 mg/L, which is suitable for agriculture (below 20 mg/L) but not for consumption (1-2 mg/L or below).

COD: COD level ranged from 13-150 mg/L, with an average of 101.7 mg/L. Of 65 samples, 7 were placed within the range of the A Category of the water quality limits used for agricultural purposes (COD below 50 mg/L), 19 within the C Category (COD below 100 mg/L), and 39 in the D Category of water used for agricultural purposes (COD 100-150 mg/L).

Sulphate (SO4): Sulphate concentrations were very low, ranging from 0.001 to 0.006 mg/L, with an average of 0.0033 mg/L, indicating that condensate water samples fall within PSI acceptable limits of drinking water (200 mg/L) and agricultural water (300 mg/L).

In summary, the assessment of physical, chemical, and microbial water quality data for condensate water indicates a fair water quality, which conforms to the Palestinian standards for reused irrigation water. In comparison with drinking water standards, concerns are raised relating to turbidity, BOD, and COD measurements.

7.4 Greywater Recycling Systems

7.4.1 Pros and Cons of Greywater Recycling Systems

7.4.1.1 Pros

Reducing potable water consumption. It is estimated that the AQUS system, an example of a greywater recycling system, can reduce potable water usage by 37.8 to 75.7 litres a day in a two-person household[11].

Less costly to implement. As greywater is used for non-potable end uses such as toilet flushing, requirements for treated greywater quality are markedly less tedious to meet as compared to requirements for drinking water quality, and as such, treatment systems of greywater for such purposes are less costly to implement.

Suitable for irrigation. Greywater often contains detergents that have nutrients such as nitrogen and phosphorus, which are beneficial to plant growth[12], making it doubly suitable as a replacement for potable water for the purpose of irrigation.

7.4.1.2 Cons

Limited use cases. Without further treatment, greywater has limited uses due to its lower water quality[13].

Additional OpEx. Greywater recycling systems require a degree of control and maintenance, incurring additional operational costs[13].

Risk of pollution of potable water. Hence, it is vital to install suitable equipment to prevent public health and environmental impacts[14].

7.4.2 Factors Affecting Greywater Yield

Treated greywater yield is determined by the volume of greywater collected from used water. As the main sources of greywater in SAF camps/bases would be showers, washroom basins and other purposes such as boot and vehicle washing, the volume of water used for these purposes would determine greywater yield.

There are multiple variables affecting the volume of water used for such purposes, which are listed in the table below:

Table 8: Factors Affecting Greywater Yield

Factor	Affected Purpose
Occupancy Load	All
Average Daily Number of Uses per pax	All
Types of Fittings and WELS Ratings of Showerheads/Basin Taps	Showers, Washroom Basins
Average Duration per Use	Showers
Average Number of Presses per Use	Washroom Basins
Average Daily Input from Other Purposes	Boot Washing, Vehicle Washing etc.