Design of waste and Sanitation treatment system for a proposed artificial island for Kiribati

A thesis submitted for the degree of Masters of Science in

Engineering with Finance

by

Ernest Young, Manufacturing and Mechanical Engineering BEng(Hons.) Department of Mechanical Engineering

University College London

I, Ernest Young, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

September 2019

Student number: 18141915

Total number of words: 11,962

2019

Design of waste and Sanitation treatment system for a proposed artificial island for Kiribati

Abstract

The consequences of human and industrial activity have long accumulated and plagued our natural environment. Now, in the 21st century, those consequences pose a threat to human life in parts of the world, with low lying countries like Kiribati facing no other option but to relocate and avoid the destruction of rising sea levels. In previous literature, a robust case has been made to relocate onto a buoyant structure. What is yet to be addressed, and hence the focus of this project, will be the waste and sanitation system which would support the population of the country.

This project will aim to conduct a front-end engineering design (FEED) for such a system using a proposed artificial island concept. This comprises a reverse osmosis desalination plant and its associated pre, and post-processing facilities able to operate above a 576,200m^3 daily capacity.

Within the next 3 decades, the impact of global warming could see Kiribati's capital submerged. Hence guiding principles to ensure minimal contribution to emissions, maximum utilisation of land and a feasible capital demand govern this design. With an estimated price tag of over £80 million, this proposal comprehensively outlines not only the processes required, but strong elements of reusability. With 1/3 of output products able to be reused in the process; cementing a stamp of sustainability on this project.

A feasibility assessment of capital requirements is also considered for this project; revealing the strength of its financial system will make it difficult to secure loans by intergovernmental funds. Instead, this project will either have to yield returns in the form of economic stimulation and savings or, incorporate elements of depreciation into the funding method to lower cost. Overall, this project has revealed the success of such projects is dependent on a range of social, economic and political factors.

Acknowledgements:

I would like to acknowledge my Project Supervisor Ema Muk-Pavic for supporting this project from the outset, providing resources, regular consultations and pointing me in the right direction throughout the project. The knowledge and skills I have gained have definitely enriched my understanding and competency in undertaking such a project now and in the future.

I would also like to acknowledge Simon Hulme and Dr. Itxaso Del Palacio Aguirre for their support and engaging lectures during the Entrepreneurial Finance module. The knowledge acquired during this model has featured subtly in parts of this project and added an interdisciplinary element to the financial aspects of this project.

Finally, I would like to acknowledge the Mechanical Engineering Department for the support sessions provided to supplement our knowledge and preparations for this project. This was invaluable support along with that of which I received from peers, friends and my family (the Youngs et al.) in all forms; and to whom I dedicate this.

Table of Contents

Contents

Table of Appendices

Table of Figures

Glossary:

Term	**Definition**
Potable water	Drinking water
Greywater	All wastewater generated in households or office buildings from streams without faecal contamination
Black water	Water which has come into contact with faecal matter
Brackish water	A type of water which contains more salt than fresh water but less salt than salty water.
Basic sanitation service	A household has access to basic water supply service when a water point is available with a collection time is no more than 30 minutes for a roundtrip, including queuing (SDG definition)
Subsistence farming	A form of farming in which nearly all of the crops or livestock raised are used to maintain the farmer and the farmer’s family, leaving little, if any, surplus for sale or trade (Britannica)
Storm surge	The temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds)

Nomenclature:

K	constant, for clean inorganic solids
f’	Darcy Weisbach friction factor (for sewers = 0.03)
SS	Specific gravity of sediments
g	gravity acceleration
d’	diameter of grain, m
hf	Friction head loss in pipe per meter of piping (m)
Q	Volumetric flow rate (m^3/s)
C	Hazen-Williams “C” factor (dimensionless)
D	Internal pipe diameter (m)
$\mathbf{hr}_{\mathbf{installed}}$	Hours installed

Acronyms

International Development Association	IDA
United Nations Educational, Scientific and Cultural Organization	UNESCO
International Labour Organisation	ILO
World Health Organisation	WHO
International Monetary Fund	IMF
Joint Monitoring Programme	JMP
United Nations	UN
Government of Island of Jersey	GOJ
Gross Domestic Product	GDP
diethyl paraphenylene diamine	DPD
Combined Heat and Power	CHP
New Zealand Aid Programme	NZAID
South Pacific Applied Geoscience Commission	SOPAC
South Tarawa	ST
Electrodialysis	ED
Electrodialysis Reversal	EDR
Multi-Effect Distillation	MED
Upflow anaerobic sludge blanket digestion	UASB

Reverse Osmosis	RO
Sea Water Reverse Osmosis	SWRO
Per Person Per Day	PPPD
The International Convention for the Prevention of Pollution from Ships	MARPOL
Total Dissolved Solids	TDS
Return on Investment	ROI

1.0 Introduction

The consequences of human and industrial activity have long accumulated and plagued our natural environment. Now, in the 21st century, those consequences pose a threat to human life in parts of the world, with low lying countries like Kiribati facing no other option but to relocate and avoid the destruction of rising sea levels caused by global warming.

In previous literature, a robust case has been made to relocate onto a buoyant structure, an artificial island designed by Lister [1]. What is yet to be addressed, and hence the focus of this project, is the waste and sanitation system which would support the population of the artificial Island. Hence this project will aim to conduct a front-end engineering design for such a system using the proposed artificial island concept.

The proceeding background and literature review will shed light on the socio-economic background of Kiribati, identify the necessity for this project, the possible methods to achieve the project aim, and the conditions and requirements which govern the sustainability of such projects in an environment like Kiribati.

This design will be executed with the goals of ensuring capital requirements are kept to a minimum, improve access to clean water, minimise waste and pollution output and ensure a simple but robust system. This system will be designed to accommodate the country's population to the year 2050 but will be constructed and expanded further in gradual stages.

The method undertaken to achieve this goal initiated with a definition of the needs and associated criteria for Kiribati. This will encompass the socio-economic state (including economic activities and access to facilities), and its environmental and technological capacity to front such a project. The literature review will translate the needs and criteria for the country into prioritised requirements and specification. The identified methods will be scrutinised according to these requirements as well as their suitability to Kiribati. This analysis will use specific metrics such as CO_2 emissions per kg of clean water processed, land requirements and potential impedance to local activities.

Following this, two concepts will be chosen to be assessed in detail for its implementation through spatial planning, simulated processes (to identify limits) and choice of proposed infrastructure e.g. pipeline design and material.

From a variety of qualitative and quantitative assessments into these technologies, the one which aligns most to the requirements of operation will be adopted. This would therefore yield the most optimum technology from which at least three design configurations will be devised and assessed once again against socio-economic requirements. Additionally, feasibility assessments on performance under some given conditions will be determined. This will be completed using a software package such as MATLAB's Simulink program to simulate the volume of water able to be pumped for given inputs and the period of time taken, leading to suggestions on specifications for pumps and other vital elements.

Part of this will look at the economic assessment of this in terms of potential sources of revenues it could generate or impede, and at least two assessments of financial feasibility and funding methods.

Finally, the assumptions and conditions for optimal implementation of this system will be identified as guidelines for the country as it grows and potentially looks towards materialising this design. Conclusions on this design; its selling points, potential areas for further improvement and assumptions are reviewed as areas and opportunities to gain a better understanding of limitations surrounding such projects.

2.0 Background

The Island Republic of Kiribati constitutes 33 coral atolls stretched across the equator in the Central Pacific. The country is situated over 2100 nautical miles North-East of New-Zealand and over 2000 nautical miles South-West of Hawaii.

The country's population stood at a total of 116,398 (as of 2017) with approximately half inhabiting the capital city of South Tarawa (ST) [2]. The last source of evidence for Kiribati's employment (2010 census) shows the country had an unemployment rate of 30.6% in 2010 and a youth unemployment of 54% [3] [4].

With its Gross Domestic Product (GDP) hovering around $186 million the country is one of the poorest in the world [1]. As of 2018, the country has received almost a third of a 43 million loan from the International Development Association (IDA) and 94% of a 43 million grant from the IDA. Kiribati also receives significant loans equating to 15% of its GDP from Australia [5] with similar estimates from New Zealand [6] and smaller aid from Japan [7].

Given its isolated location and limited resources, its main economic contributory activities include agriculture, forestry, and fishing (accounting for 31% of GDP), exports of goods and services (13%) and industrial activity (12%) [8]. Aside from aid, significant imports also come from its closest neighbours Australia (29.3%), Fiji (17.3%) and New Zealand (New Zealand Aid Programme (NZAID) - 10.7%) [3].

As expected, the lack of financial resources in Kiribati is proportional to its socio-economic development. In the most recent WHO/UNESCO Joint Monitoring Programme (JMP), 64% of the country had access to 'at least basic' drinking water in 2015 with only 40% with access to 'at least basic' sanitation [9].

2.1 Social Life in Kiribati

The main form of trade and activity in Kiribati is through farming (particularly in the rural areas), however, since the 2000's the International Labour Organisation (ILO) have reported an influx of people to urban areas [10]. This has likely led to the increased unemployment rate as the report highlights the fact that many rural-urban migrants lack the education and skills to undertake employment beyond the agricultural sphere [10]. Due to overcrowding in cities, subsistence farming has become impossible. The majority of paid workers are involved in low skilled professions such as vehicle repair, agriculture, and manufacturing.

2.2 The rising sea level threat

In and amongst many problems facing the country, one stands tall beyond the sandy shores of its islands, the sea. The 33 islands of Kiribati are extraordinarily shallow, with the highest point being south Tarawa; just three metres above sea level [11].

Global warming contributes to rising sea levels in two major ways. Firstly, the melting of glaciers increases the volume of water in the oceans, and secondly, the increase in temperature causes water to expand.

With current sea-level rise at a global mean of 3.7mm/year and rising at an accelerated rate [12], scientists have concluded an overall rise of 2m by the end of the century is very likely. With such a rise, Kiribati will see at least 1/3 of its islands submerged [13], hence a warning from the World Bank to start considering “wholesale migration” of its population [14].

In an attempt to assist the country with future planning and development, many studies have designed and evaluated a variety of ideas on where Kiribati could call home in the decades to come [1] [15]. Though these ideas have broadly identified an overall overhaul of inhabitation, few have elaborated on the intricacies behind designing a suitable and fit-for-purpose sanitation method to complement such a change.

2.3 Socio-economic considerations

Research into current social conditions in Kiribati found rural-urban migration has led to overcrowding in South Tawara. As a result, the country saw a Water, Sanitation and Hygiene (WASH) death rate of 25 per 100,000 of the population in 2015. This yields a requirement for any newly implemented system to carry a strong element of durability and simplicity to sustain its demands [16].

Being the major urban city; the cost of electricity is subsidised for those in South Tawara [17]. This has been instrumental in building the city to its status and supporting the services and amenities provided there. With this project, an increase in electricity demand will undoubtedly be seen. However, the challenge lies with ensuring the extra demand from the waste treatment system doesn’t widen the gap between supply and demand significantly to the extent where the subsidy is lost. Such a scenario may have unforeseen consequences for the city and businesses.

Further, the country has experienced a depletion of natural resources due to overutilization [18] which has undoubtedly led to a slight increase in the amount of food and water being imported. Though this project looks to indirectly influence this, up until the full operation of this project, all required activities cannot interfere with such trade or distribution routes as this may compromise human life.

Recently, the country has seen an increase in debt being taken on. Kiribati’s debt was equivalent to 23% of the country’s GDP in 2017 which although seems modest, the IMF’s Debt Sustainability Analysis (DSA) commented: “Kiribati remains at high risk of debt distress” [19]. This project must therefore propose a system within the financial capacity of the nation.

Considering the country has a high proportion of debt relative to its GDP, and its fragile ability to pay those back, the funding modes for this project must ensure little to no erosion to the country’s financial stability. Innovative and alternative methods such as grants or payments through equity of stimulated businesses should be considered.

Beyond the above-mentioned characteristics, this project will also take into consideration the shifts and trends seen in the country, particularly that which has seen a growth in the low skill and manufacturing sectors. Where this can contribute to the main forms of employment and activities in Kiribati (agriculture and fishing) it should. However, this project must adhere to international standards to abstain from practices which infringe the stature and quality of these activities; given their significance to nationals.

3.0 Literature Review

3.1. Waste treatment process

The following subsections detail the processes identified through literature for the treatment and neutralisation water; which is then followed by various methods and technologies capable of carrying this out.

3.1.1 Particle removal

The first step in the treatment of nearly all forms of waste is screening. This removes large solid objects which should not have been part of the mixture in the first place such as nappies, wipes, debris, etc. Following this, solid organic matter is removed through Coagulation. Coagulants are substances, primarily metallic salts, such as aluminium sulphate (alum) and ferric sulphate. These cause particles in liquid to stick together, allowing solids to be easily removed from them.

However, there are preliminary requirements needed for this process as the pH of water needs to be accounted for. As the solubility of aluminium is dependent on the pH of the solvent. If the pH of water is between 4-5, hydrogen is present as positive ions (Al(OH)2+, Al3+), however, if the water is of pH 6-8 then Aluminium presents negative ions, hence the neutralisation process begins [20]. As one charge neutralises the other, the particles binding together form "floc". As shown by figure 1 below [13]; the pump-setting and stroke also have an impact on the chemical dosage required to be pumped through.

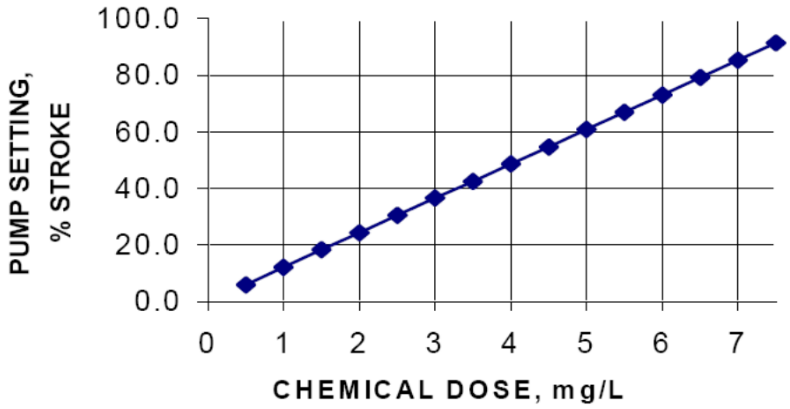


Figure 1 - Chemical dosage graph [20]

Following this, flocculation is undertaken (process to increase particle clump size), which can also be strengthened through the use of polyelectrolytes e.g. pectin and alginate (alginic acid); naturally occurring and organic. the floc settles to the bottom of the mixture due to its relative weight; known as sedimentation before being filtered out. An alternative to this process is dissolved air flotation which saturates the water with air under high pressure forming bubbles. This locks on the particles in flocculated water and brings them to the surface.

Once filtration begins, the clear water is passed through filters of varying compositions (sand and gravel) and pore sizes to eliminate dissolved particles e.g. viruses, chemicals, and bacteria. In the absence of coagulation, this step is completely ineffective. The method described above is known as rapid gravity filtration, however, this process can also be achieved using grown filtration. This method filters at high pressure using prefabricated membranes giving better quality water at a higher cost. Up to this point, it should also be noted that the water is greywater. It should also be noted that the process for sewage and water treatment (including desalination) are almost identical up to this point. Hence the final step to obtaining potable water is a form of desalination.

3.1.2 Removing taste and odour

In dealing with the odour and taste remaining in the water, Granular Activated Carbon (GAC) is added to the water (in powder form). These absorb materials contributing to any taste or odour in the water at the time.

3.1.3 Disinfection

Disinfection is a critical procedure for this project. Not only does this convert non-potable to potable water, but is critical to system performance and more significantly; preventing the spread of waterborne diseases. The WHO World Water day Report 2019 found water-borne diseases are responsible for 3.4 million deaths annually [21].

The most common form of pre-treatment disinfection is through the addition of Chlorine. Chlorine is used mainly for disinfection in either liquid or gas form. However, for consumer consumption, only a small amount is used; less than one milligram per litre [22]. Chlorine therefore presents a strong case for its use in disinfection compared to other popular methods such as ultraviolet light as it is less energy-intensive and compliments the processes of coagulation and flocculation which are important subprocesses of the proceeding technologies [23].

3.2 Current examples of water treatment

Evaluation of cruise ship desalination process reveals almost all ships and submarine transportation forms rely on the reverse osmosis process of desalination. This method is illustrated in figure 2 [14]. The significance of this is that ships are the most representative of an independent self-sufficient offshore island concept. Given they are offshore floating structures with limited resources and capacity, yet still need to produce clean water, they act as an excellent model for the basic process outline and efficient use of resources. This therefore points out where quality and resource inputs should be controlled in the process to prevent wastage and degradation.

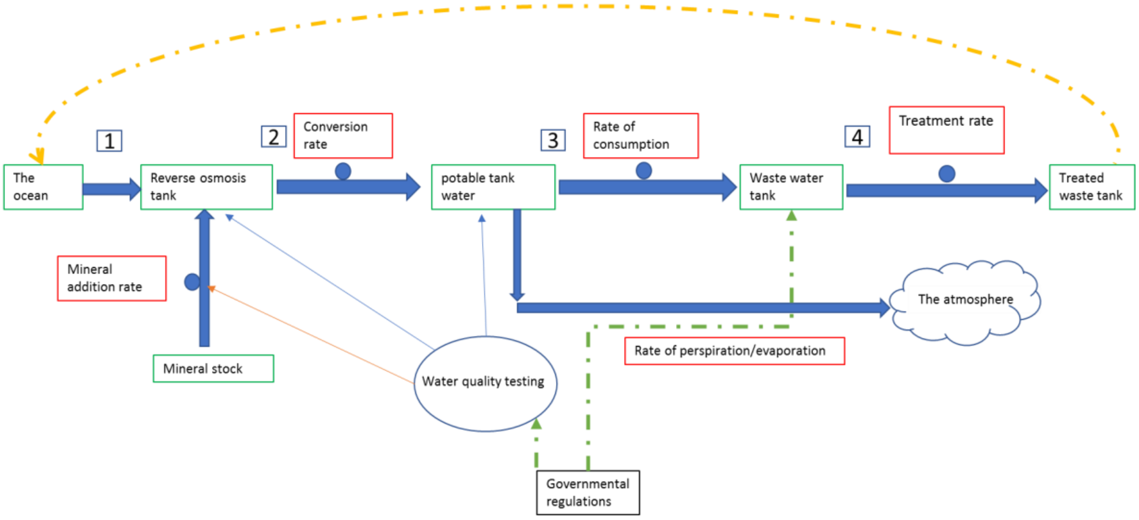


Figure 2 - Ship osmosis process overview

As shown, water is taken first from the surrounding ocean. Following this, it goes through a reverse osmosis treatment process which applies hydrostatic pressure greater than osmotic pressure to separate the clean water molecules from larger particles such as salt, bacteria, and viruses. Mineral stock is added to the reverse osmosis water to enable a more pleasant taste and odour of the water. This Potable water is then stored in a tank and drawn for human consumption. Once consumed, the rejected water is channelled to a waste tank for treatment (to remove microbes and bacteria) to ensure its quality at least complies with international law on quality.

At various stages e.g. 2 & 3, the quality of water is measured to ensure a benchmark quality is achieved. The type and frequency of this testing vary according to the parameters being measured. For example, chlorine residual testing occurs daily on ships through the DPD (diethyl paraphenylene diamine) indicator test. This dissolves a tablet reagent into a sample of water inducing a red colour. The strength of this colour is matched against a standard of shades to determine chlorine concentration [24].

Governmental regulations also control how much waste is released, the quality of this, and where it can be released. Details on handling requirements can be found in the UK Government's Maritime Labour Convention, 2006 [25], and section 12, chapter 5, subsection 2 of WHO's International Health Regulations Guide to Ship Sanitation [26].

3. 3 Other methods and technologies

Reverse Osmosis is a form of 'Membrane Technology' method which defines a separation method which involves the use of a membrane. Other similar methods include Electrodialysis (ED) and Electrodialysis Reversal (EDR).

3.3.1 Reverse Osmosis

Reverse Osmosis is a mature and simple process which applies pressure to a concentrated solution; forcing it through a membrane to yield water molecules through that membrane and separate it from the solution. The result of this is a more concentrated solution on one-side of the arrangement and water on the other as shown in figure 3 [15] below. The pressure required for this process is influenced by the salt concentration of the feed water and is provided by a pump. The higher the salt concentration, the more pressure is required to overcome the naturally occurring osmotic pressure.

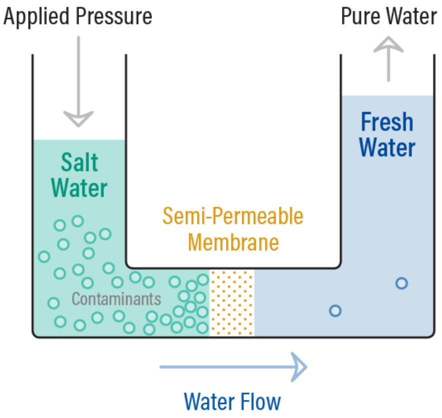


Figure 3 - Reverse Osmosis illustration [61]

Figure 4 [16] below captures the Cangzhou Reverse Osmosis plant in China. This plant is a $10.3 million project with two phases; an initial 50,000 litre capacity and a second 50,000 litre capacity. This plant will also be used as a model to interpolate an estimated area required for this Kiribati project due to the wealth of information provided by its manufacturers [27].

Figure 4 - Aqualyng Cangzhou Seawater Desalination Project

Similar methods under membrane technology such as Electrodialysis can be found in Appendix A3.

3.3.2 Thermal technology

Thermal technology methods are also known to produce the other half of the world's desalination processes. As implied, this involves heating of water and collecting distillate to obtain pure water.

One of the earliest methods of this is Multi-Effect Distillation (MED), used since the late 1950s. This method occurs at pressures below the ambient pressure in order to reduce the evaporation temperature of the water. The seawater enters into a chamber where it is heated. The water then evaporates, following a path into the next chamber where its thermal energy is used to evaporate another stream of incoming sea water, causing the original steam to condense and is collected at the bottom of its chamber. This process is continuous; as the newly formed steam enters another chamber to evaporate, another stream of incoming water enters the previous to continue the cycle (figure 4).

However, this process is limited by decreasing temperatures as the process moves along. The input temperature generally cannot exceed 70^{o}C otherwise scaling begins to form on the pipes. Further, the output temperature must also be equal to ambient temperatures to allow the water to condense. However, in arid areas (where desalination is most required), this can exceed over 40^{o}C. Nonetheless, an improvement to this in the form of Absorption Desalination; which incorporates an absorption process at the end; lowering the final temperature to around 7^{o}C. This allows condensation to occur faster and the process can occur over a larger temperature range (figure 5) [16].

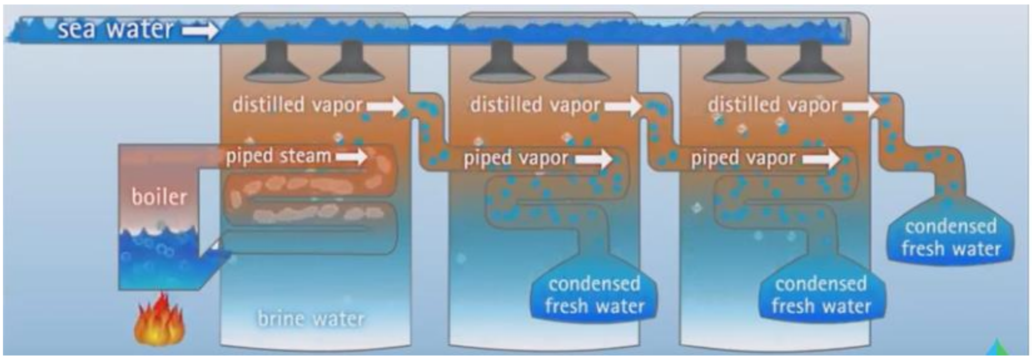


Figure 5 - Multi-effect desalination; Waterpedia [44]

Figure 6 - Multi-Effect desalination plant: Alfalaval [53]

Figure 7 - Absorption desalination; Waterpedia [28]

Figure 8 - Absorption desalination plant: Israel [29]

3.3.3 Multi-Stage Flash Distillation

Another popular technology is Multi-Stage Flash Distillation. This involves the feed water being heated under pressure and is then led into a ‘flash chamber’ where pressure is released causing water to boil and quickly evaporate or ‘flash’. The flashing of some of the feed continues to another stage where the pressure is even lower, and so on. The vapour generated is condensed to produce fresh water through a heat exchanger incoming feeder; shown below in figure 9 [18].

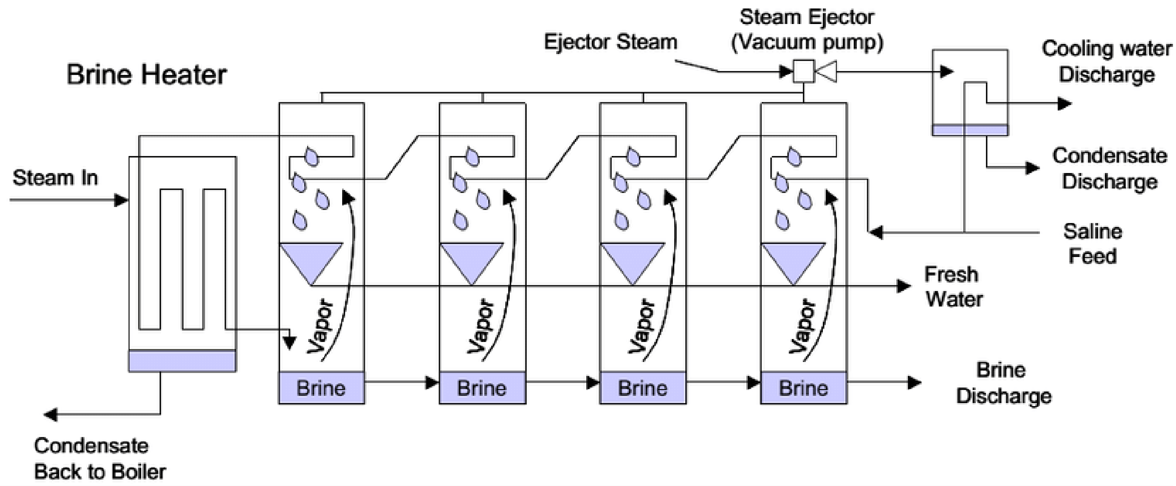


Figure 9 – Multi-Flash Distillation process; [30]

Figure 10 - MSF Desalination Plant at Jebel Ali G Station, Dubai: [28]

Further information on other methods such as the Anaerobic Digestion method can be found in Appendix A4.

3.4 Preliminary analysis of Literature review methods

Table 1 below makes a brief comparison of the technologies explored in the preceding section, evaluating them on a range of parameters; each with an associated priority concerning the aim and objectives of this project. This is followed by a synthesis of ideas from table 1 and the 'Socio-economic considerations' of Kiribati

A visual inspection of this table reveals the highly prioritised parameters are the volumes of thermal and atmospheric pollution released and the capital expenditures of these technologies. At this stage, it's important to point out the main constraints for the country are money, land, and resources (including expertise). However, only the financial constraint and environmental pollution issues are within the top three priorities. This is because this project was initiated as a result of the impact of climate change caused by environmental factors associated with global activities therefore to neglect this as a top priority would be neglectful of the greater objective. A skim of the results of these parameters show a strong affinity to the Reverse Osmosis technology.

Table 1 - Brief Tabular Comparison of various technologies

Various technologies				Priority score (1 = highest priority)
Comparison parameters	**Reverse Osmosis**	**Multi-Stage Flash Distillation**	**Multi-Effect Distillation (MED)**	
Pre-treatment processes	The drawback to RO systems is the amount of pre –treatment required for the process. Sub-processes are required to remove the biological organisms, suspended solids and other debris. This includes: Feed water treatment, Growth of bacteria (considering average temperatures), Regular system disinfecting and fouled membranes from insufficient removal of chlorine from feed.	Since MSF is a vaporisation process; such elaborate pre-treatment facilities are not required	Little to no pre-treatment	9
Visual pollution	Impact of buildings on the land scape	MSF plants are considerably larger than RO plants with special materials [6]. Often built with power plants and difficult to scale down [31]	MED plants are larger than RO plants as they often built with power plants and cannot be easily scaled down as RO can [31]	10
Atmospheric discharge	For the plant powered by fossil-based grid electricity, researchers at Murdoch University found the electricity used in the operational phase is responsible for more than 92% of its GHG emissions [32]with further research showing the overall environmental impact of RO plants is significantly dependent on their energy mix [33]. Brine is also produced.	Heat is not wasted to the environment in heat rejection stage	Non-Condensable Gases (NCGs) are released from the plants [34]	8
Thermal energy (MW) dissipated in the Ocean per 10 Million Imperial Gallons per Day (MIGD) [35]	Negligible	150-170	120-160	2

	Various technologies			Priority score (1 = highest priority)
Comparison parameters	**Reverse Osmosis**	**Multi-Stage Flash Distillation**	**Multi-Effect Distillation (MED)**	
Approximate Kg CO_2 per m^3 of produced water [35]	3.6	19.6	17.2	1
Total Dissolved Solids increase in the reject brine compared with seawater baseline [35]	50-80%	15-20%	15-20%	7
Traces of chemicals in the discharge	The RO system is known to produce water with dissolved solids ratio of 400 mg /L [6].	MSF systems produce water with less than 100 mg / L total dissolved solids [6]		11
Capital investment for required 8,900m^3/day capacity	£13,467,680	£12,374,477 Construction and land costs are high due to area required. [6]	£17,120,000 [36]	3
Maintenance	Enhanced membrane technology, use of low-cost material systems and the modular configuration all greatly reduce the maintenance costs significantly. These also improve the reliability of the RO system. [6]	Since steam is used; piping, condensate and other associated systems are involved. The result is increased maintenance costs. Scaling further adds to maintenance issues		4
Area required ($m^2/(m^3/hr_{installed})$) [35]	3.5-5.5	4.5-5.0	6.5-7.0	6
Energy requirement	RO systems require considerable energy for pressurizing the water to the membrane filters. 3 to 10 kWh (generally 3.0-4.0 for Pacific ocean) of electric energy is required to produce one cubic meter of freshwater [37]	MSF requires heat energy for heating the brine before vaporisation and requires around 17Kwh per cubic meter. [38]	Can be high due to heating at each stage. but almost any heat source can be used; hence adaptable [39]. Total energy requirement is 4.0-4.5 kWh/m3 [35]	5

Various technologies				Priority score (1 = highest priority)
Comparison parameters	**Reverse Osmosis**	**Multi-Stage Flash Distillation**	**Multi-Effect Distillation (MED)**	
Electrical energy Consumption kWh m^{-3} [40]	3 - 3.5	13.5 - 25.5	13.5 - 25.5	12

What may be surprising from this table is the priority given to the energy requirements of the plant. This is firstly due to the assumption that the energy source dominant within the next three decades will be a renewable type of energy, hence the associated concerns and premiums that come with that should be insignificant. This does, however, assume a strong abundant supply of this to the extent the country isn't constrained by the capital expenditure of operation.

Further quantitative analysis can be found in Appendix A13 on how and where each technology outperforms its peers.

3.4.1 Reverse Osmosis

Although desalination via RO looks promising there are issues, such as the production of brine as a by-product. This may be considered for agricultural purposes to help sustain the country's agriculture, however, the amount produced could outstrip the demand for such applications. Alternatively; it could be sold, as brine is used in the development is Salinity Gradient Power (harnessing of power from the difference in the salinity of water). This may open up a new form of market and exports for the country, dependent on the success of reverse electrodialysis technology. Further, a purified form of salt could be extracted from the brine to be sold as a food preservation agent which is still used in such countries today.

The use of microfilter methods of desalination such as reverse osmosis has been steadily increasing over the past decade. Once used to fulfil the rising demand for commercial and industrial activity, changes in geographical climates and reductions in groundwater supplies have meant a need for supplies to meet domestic needs. One country which has fully embraced this technology is Algeria, which is currently home to some of the world's largest capacity plants. However, in recent times the country has fallen victim to its decision to adopt technologies beyond the scope of its own capacity. In 2018 the country terminated a 25-year contract with the Algerian associates of Malakoff Corp Bhd which began in 2011, citing a breach of conditions due to a failure to honour remediation commitments. Firstly, this identifies the inability to control the environmental degradation caused by the processes leading to and during the plant's operation. Given the country has at least 15 reverse osmosis plants this looks to be less of a technological issue than a contractual one. Nevertheless, the nature of this issue seems to be one which degrades the environment and likely reduces its ability.

Considering the size of Kiribati and the importance of the environment to the economy, any form of degradation is unacceptable as land is a limited resource and the dependence of subsistence farmers on it is key to their survival. Further, given the population of Algeria is over three hundred and fifty times that of Kiribati, such an issue may bring a small region to a standstill, however, in Kiribati; this could bring the whole country to a standstill.

The manufacturing of the microfilters is a delicate process which is expensive to manufacture; given the technique and accuracy required during chemical synthesis. Their structure also makes them vulnerable to physical wear and tear. With the current technical capability of countries like Kiribati, such breakdowns mark the end of life of these devices as repair is not an option. Therefore, instead of adopting a filter which is synthetically manufactured and designed a naturally derived filter which could be grown within days is the key. However, this must be on the condition that these organic alternatives do not compromise agricultural activity as stated in section 2.3.

Such an organic polymer filter was highlighted by a UC San Diego bioengineering student in a TEDx talk. The polymer is grown using a specially sourced bacteria which secretes a fibre which weaves themselves together to form the biofilter in a growth tank. This process has been shown to take 3-5 days to culture with pore sizes on a micron which capture parasites and bacteria which could be harbouring in water [41]. This technology seems promising in the categories of affordability, accessibility, and sustainability. With such a filter, the processes and equipment required to produce a traditional filter (such as that used in RO) are trimmed down to the few nutrients needed to feed the bacteria, and the bacteria itself; which can be grown anywhere and anytime. Thus, the only material cost is that of the nutrients; at <$1 per filter. For a country like Kiribati with low technical capabilities and skills the ability to continuously produce filters is auspicious.

3.4.2 Anaerobic Digestion

The anaerobic method is one which may be unviable given the amount of time taken for water to be digested. This method would likely see an accumulation of water and the requirement for large pools. Given the WHO standard of adequate water consumption to be 50 litres [42] per person per day (pppd), a three-month waiting period for the maturity of an anaerobic process would require a facility with a minimum capacity of 576,170 m^3. This estimate encompasses the country's 2017 population (likely to have risen) and a safety factor of 10%. As there is no physical indication of the quality of water, this would require multiple tests including pathogen contamination (measured by the index of E. coli) to ensure water was adequate for the intended use.

Taking into account the size of the Kiribati population, much of the published literature which helped form section 2.0 has focused on large scale projects with capacities far exceeding that required for this project. Hence a shift of focus will be implemented in the proceeding analysis to countries which have adopted smaller-scale projects to ensure issues specific to smaller capacity units are not bypassed.

One such region is Greece where Islands have depended on desalination techniques since the 1960s with RO prevailing in the early '80s. The adoption of this technology was dictated by its fast installation (2-3 months), modular operation (to support variable demand), low energy consumption and "easy operation" [43]. The significance of such driving factors is their relevance to those identified for Kiribati. The regions with the lowest energy consumption were found to contain predominantly RO technologies of modular configuration [44].

The modular operation of RO technologies can be subdivided into four categories (according to membrane arrangement) from which the "Spiral" module has the lowest system cost and energy consumption. However, this comes at a trade-off as this design is considered to lack flexibility and is ranked 2/4 for space requirement. Though if considering a floating island, the hull provides excellent storage space.

The use of modular arrangements as opposed to a single integrated plant ensures that in the event of a system failing, this doesn't affect the overall capability to provide the required capacity and provides redundancy.

3.4.3 Political considerations

The notion of political stability influencing the development and strength of a country has been debated for years. However, in the case of Kiribati, government co-operation for this project is more crucial. This is due to the scale of this project; as NGOs would struggle to push through such a project without support from the local government, and secondly, the capital investment. As shown in table 6, the cost of the desalination unit alone is likely to cost nearly one-tenth of the country's GDP and will hence require a form of loan or grant to prevent damaging its weak financial position [45].

Following a recent trip to Tuvalu in May 2019, the United Nations (UN) Secretary-General António Guterres called out to South Pacific nation leaders, urging "political will must be found" in order to tackle the damaging effects of climate change [46]. Despite the Lowy institute recently labelling the status of Micronesian countries (such as Kiribati) as having "post-independence histories of political stability" [47].

On islands such as Fiji and the Solomon Islands, the urban sprawl has harboured pockets of instability between rural and urban dwellers. As urban areas engulf rural ones, conflicts and (even violence) with respect to ownership and custom have erupted; diverting government attention towards these issues and away from the climate change bubble. Though this ceases to be the case in Kiribati, there is no guarantee the continued urbanisation will not yield similar issues there. The government will hence need to ensure its priorities remain with the country's future and not with resolving state vs. government issues.

3.5 Artificial Island concept

The concept design by Lister for the relocation of Kiribati amid the threat of rising sea levels is depicted in figure 11 (23). This is a 400m side hexagonal design which each carries 3000 people with 1/3 of the space dedicated to allotments.

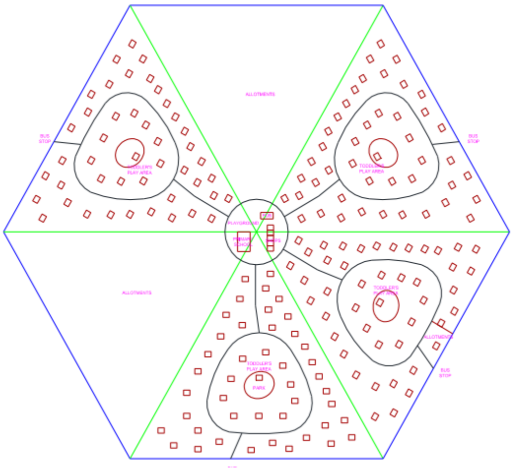


Figure 11 - hexagonal island layout; [1]

The decision to adopt this design stems from the advantage of having a circular and less spatially demanding structure. This ensures vital elements of the desalination process such as pipelines are restricted in length and thus capital requirements. Such a design provides easier access to centrally located facilities from anywhere on the Island as the distance to the centre is almost equidistant from every point and minimises transportation requirements. The red items denote housing, the black; road access passages. The centre contains local shops, commercial buildings and a primary school for each island.

Given the structure is floating, it has been proven to have a strong grasp in maintaining its structural stability while in operation. As the wastewater treatment system will transport relatively large volumes of water, this is a critical prerequisite.

4.0 Design Chapter

4.1 Design concept objective and methodology

As stated, the aim is to design a wastewater treatment system for the artificial island for Kiribati. The objective is to assess specific needs and design requirement for Kiribati; to design the system and perform a FEED study.

The associated requirements for this project were minimised the disruption caused in the event of a malfunction or breakdown of a sub-system, capital expenditure and the pollution from construction to operation and to ensure simplicity.

The methodology for this project approach first acknowledged the fact that Kiribati is a unique country with a variety of constraints. To approach the design without considering the technological and social requirements would have led to significant implementation challenges in later planning. The lack of information on the country and its history naturally gave way to exploring projects in environments close to that of Kiribati to get a basic sense of feasibility e.g. consequences of plant malfunction in Algeria. This method also ensured inappropriate assumptions about Kiribati were not being made e.g. their capacity to execute and maintain such a project independently.

Alternatively, another approach considered would have evaluated the current socio-economic status and activities of Kiribati and designed a system for the present which would then be expanded in future. Such a project would undoubtedly have had a more subtle capital requirement however would arguably have been ill-equipped or robust for the country in three decades. This is because growth or change in the country’s socio-economic status would not be linear to the size of its infrastructure and hence non-linear factors would render a largescale expansion useless and expensive very quickly. Hence the need to envision the country’s needs and capability in three decades and work backward to achieve a suitable solution.

To minimise the risk of encountering unknown issues arising from the proposed design, the technologies narrowed down were among some of the most mature from the methods identified. In the event where a malfunction, the likelihood of a swift solution is strong. As learned from its political state, this isn’t the only risk for any project. Though politics was beyond the immediate scope of this project, in places like Kiribati, this is a unique risk which needs to be factored and is only exposed through a socio-economic understanding.

Though the chosen method proved effective in identifying methods suitable for the project aim and Kiribati, there is also a significant risk in narrowing the design focus on requirements which may have seemed set in stone and hence prevented some innovation in this proposal. Nevertheless, this guarantees simplicity is achieved without compromising the operational functionality needed.

4.2 Design concept Proposal

A Process and Instrument Drawing (P&ID) for the proposed design is shown below in figure 12 [25]. Using the spatial constraints of the individual Island model proposals designed by Lister [1], the location of treatment facilities was selected to minimise land and infrastructure requirements. These treatment facilities were tried and tested in a variety of designs (Appendices A5 and A6) to identify the most optimum which adheres to the design objectives. The overall desalination process is split into three subprocesses. First, is the aggregation and separation process followed by pre-treatment, and finally the Reverse Osmosis process itself.

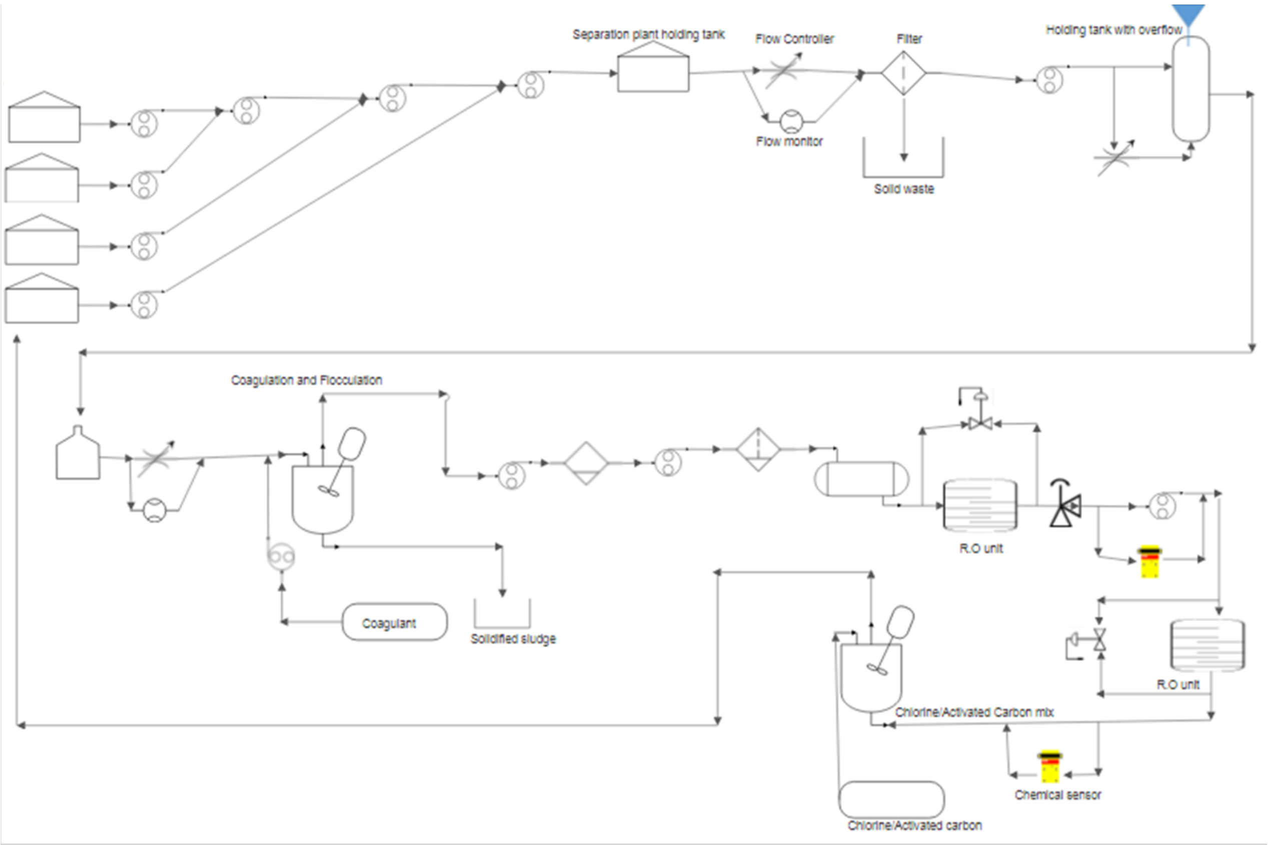


Figure 12 - P&ID diagram of sanitation process

The first subprocess sees the aggregation of water from various pipelines for ease and simplicity of transport to the separation plant where it is passed through a physical filter to remove solid particles. This process includes 3 separate filters of dimensions 100 x 100mm, 50 x 50mm and 10 x 10mm. The pre-treatment process consists of coagulation and flocculation before the yield is passed through a RO filters twice. Following this, small amounts of chlorine are added to eliminate taste and odour as mentioned in section 3.1.2. Along the process, chemical sensors monitor the water quality in order to flag when there is a loss of quality. The final potable result is pumped back to the island to be disseminated to consumers.

Following the project's design requirements to ensure simplicity, separation plants were devised to collect and filter out the solid contents of the waste water. This was chosen to serve multiple islands to reduce construction and associated environmental (e.g. pollution) costs (figure 13). Further, this allows the channelling of the product water to be sent through only one pipeline to the RO plant. This prevents a complex web of pipelines from consumers to the RO plant decreasing the overall length of pipeline required; and increases the accountability of flow.

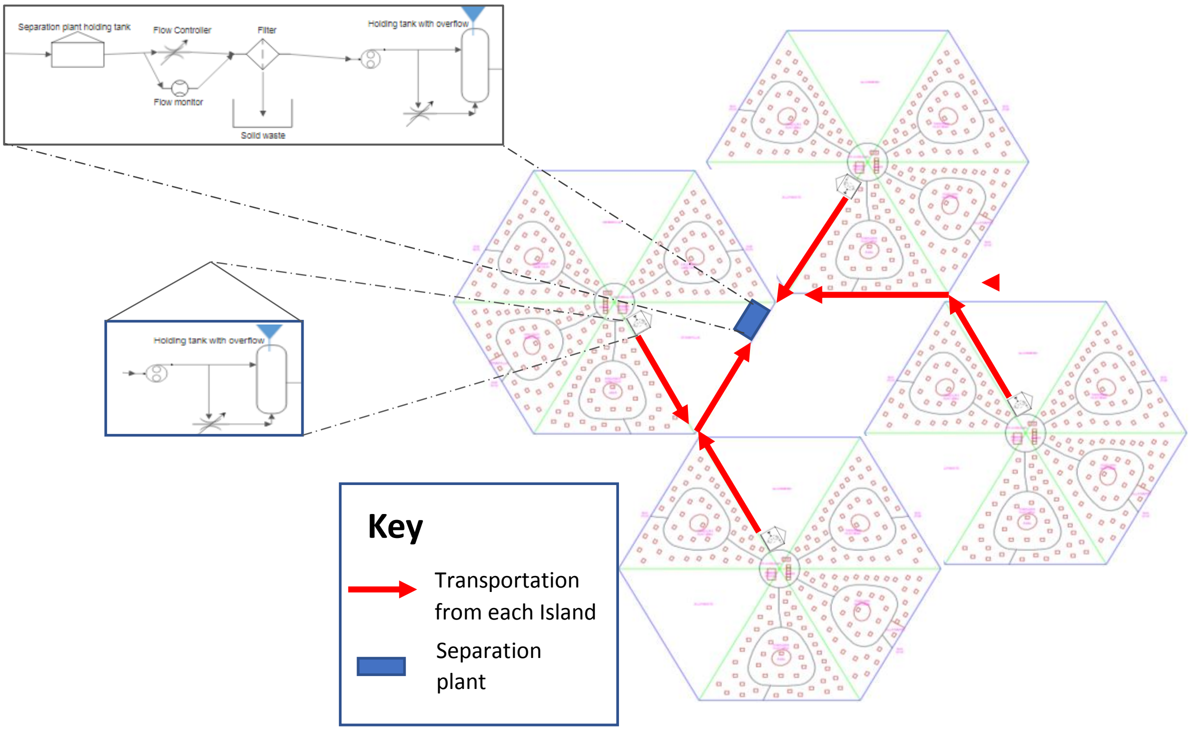
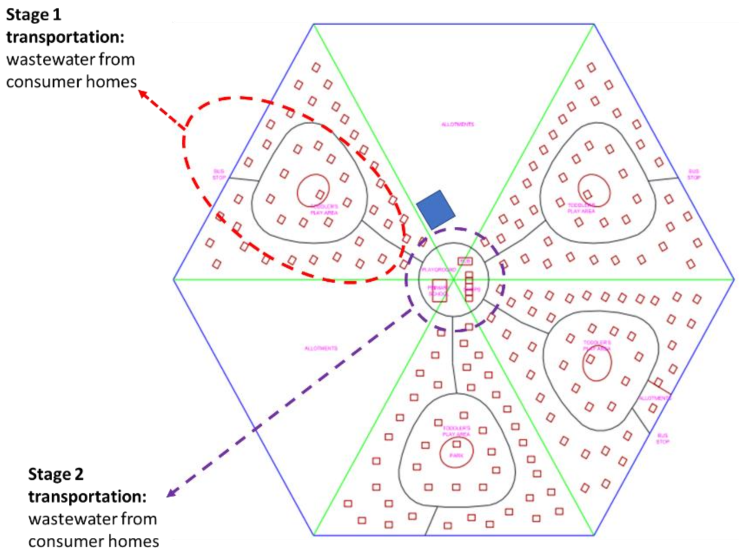


Figure 13 - Design configuration view of separation plant

At a closer look, it can be seen that some pipelines join others in the journey to the separation facilities shown in figure 13. Where this is seen, pipeline diameters are increased at each stage to prevent straining the facilities.

Figure 14 lays out design at the individual island level illustrating the "stage 1" and "stage 2" transportation route where waste from consumer homes are channelled towards the filtration plant. The diameters for these pipelines, along with that which is required for "stage 3" are given in table 8. This table shows an extrapolation of data published by the Government of Jersey on the expected sewage flow rates in a city, for areas with increasingly congested houses. This was extrapolated to the required number of dwellings for this project; details of the processing of this data can be found in section 5.1. Stage 1 transportation pipelines are those through which domestic waste will feed into homes. Stage 2 pipelines transport the accumulation of all stage 1 waste to the filtration facility.

From figure 12, it can be seen that the stage 1 transportation routes follow the implemented road layout of the islands. This positioning simplifies accessibility and utilises the already established infrastructure network established whilst minimising construction cost.



Stage 1 transportation: wastewater from consumer homes

Stage 2 transportation: wastewater from consumer homes

Figure 14 - Design view of one island

This design assumes island allotments have the flexibility for small areas to be used if required, given the minimum draught is 5.1m, there is potential to install pipelines within their hull. With this ability, the length of the pipeline required is almost halved. As illustrated, the aggregation and filtration points each serve an island. Therefore, the transportation pipes responsible to move sewage should comfortably channel the waste of over 3000 people (at least 150,000 litres a day).

The final part of this process is the movement of the waste to the RO plant which is shown below in figure 15 (28).

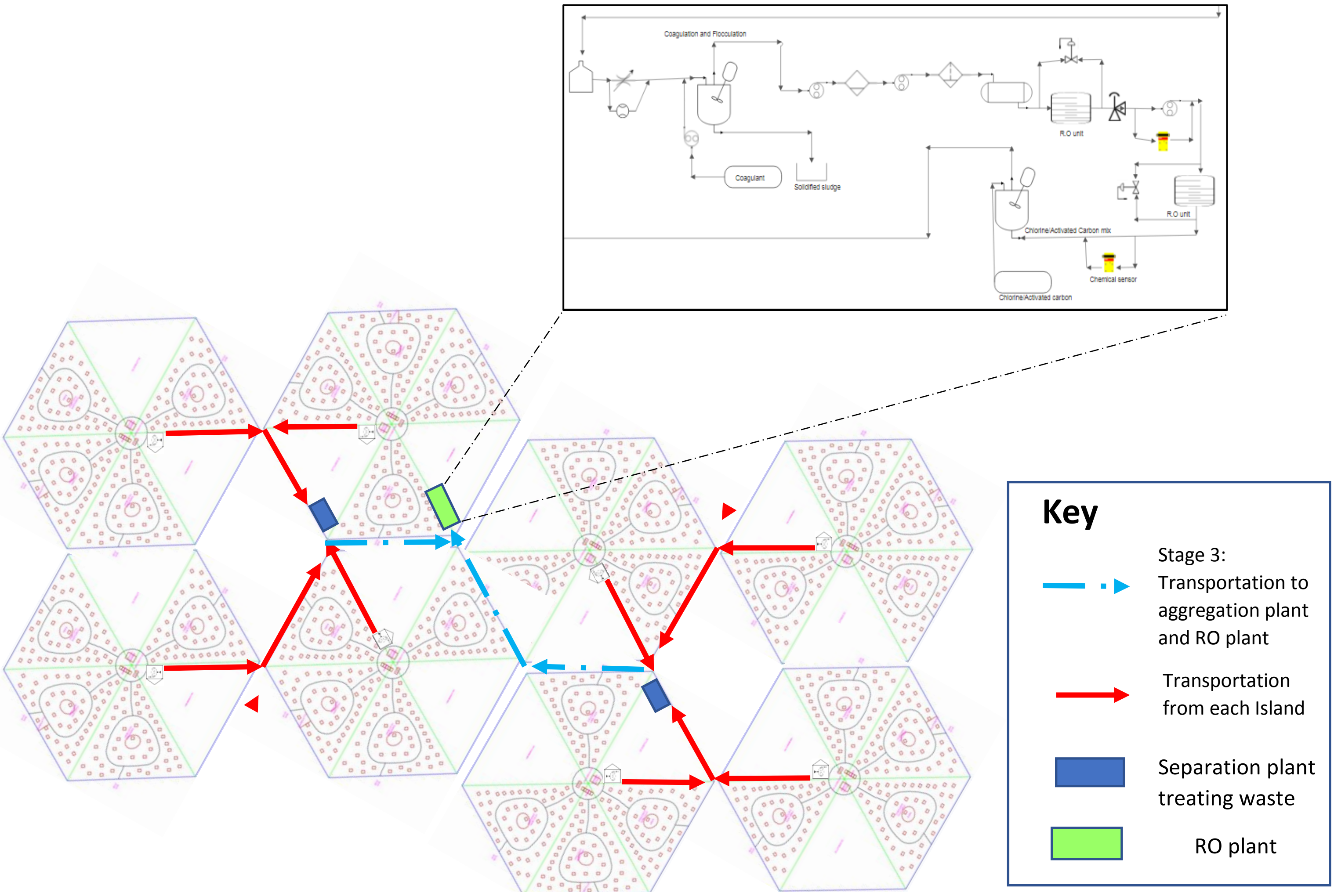


Figure 15 - Design view including RO plant

As part of the sustainability element of this project, this scheme will attempt to capitalise on the fact that the country receives a substantial amount of rainfall which could be utilised. As annual rainfall in South Tawara has been measured to be approximately 2100mm a year [48], placing Kiribati within the top 25 wettest countries in the world. This presents an opportunity where this can be harvested and utilised. Figure 16 (29) below illustrates the two alternatives for this.

Firstly, rainwater and ground harvested is non-potable water which should be channelled from consumer homes to aggregation facility from which it is disseminated for social amenities such as public toilets. Alternatively, during times of low volumes of waste input to the RO facilities, some rainwater should be channelled to make up for the shortfall of volumetric input.

The use of rainwater to support this process is beneficial for two excellent reasons. Firstly, this prevents the RO plant operating below optimal capacity. Considering the resource requirements for this project, it’s crucial to exhaust the products of this project to gain an adequate return on Investment (ROI). Secondly, as mentioned in section 3.3.1, the lower the salinity of input to a RO plant, the lower the amount of pressure required. As rainwater contains more minerals than waste, this will likely create a dilution effect on the overall input; reducing the pressure required for desalination.

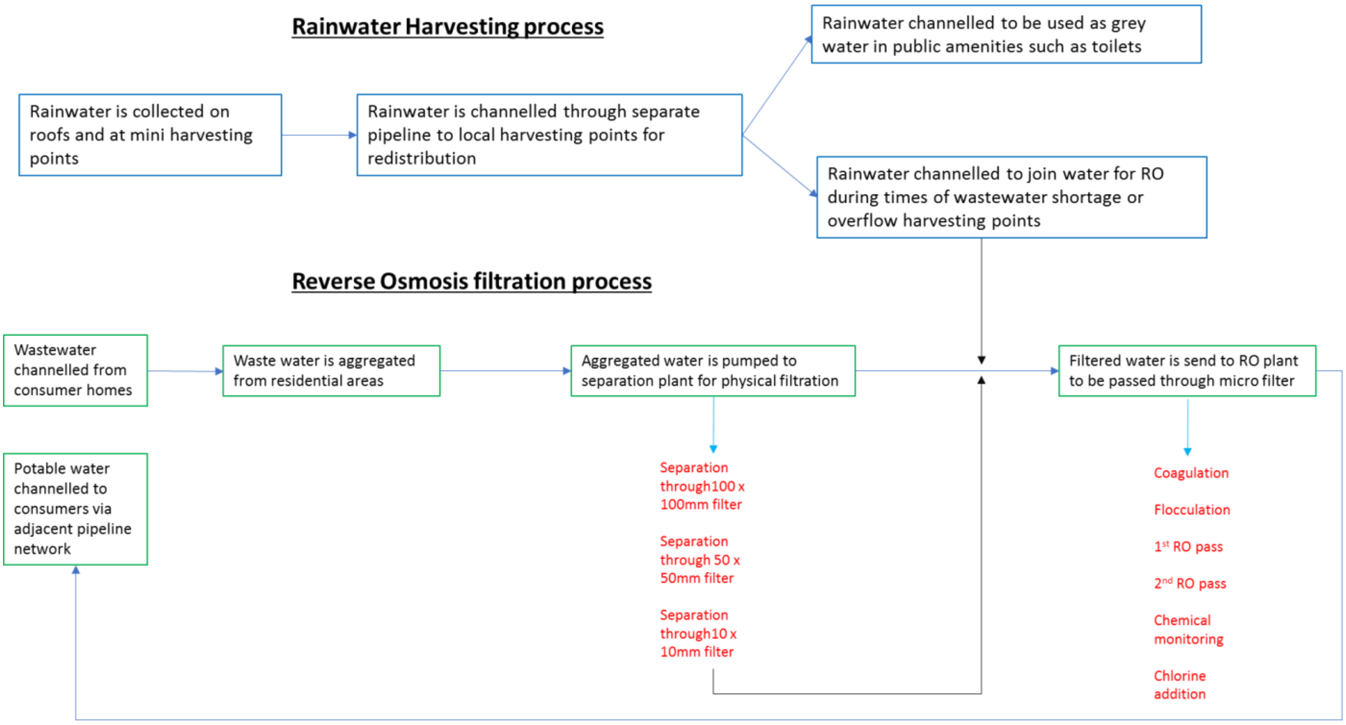


Figure 16 - Overall process overview with rainwater harvesting process

4.3 Alternative design considerations

As highlighted at the beginning of this section, a variety of designs were tried and tested. An example of one of these is shown below.

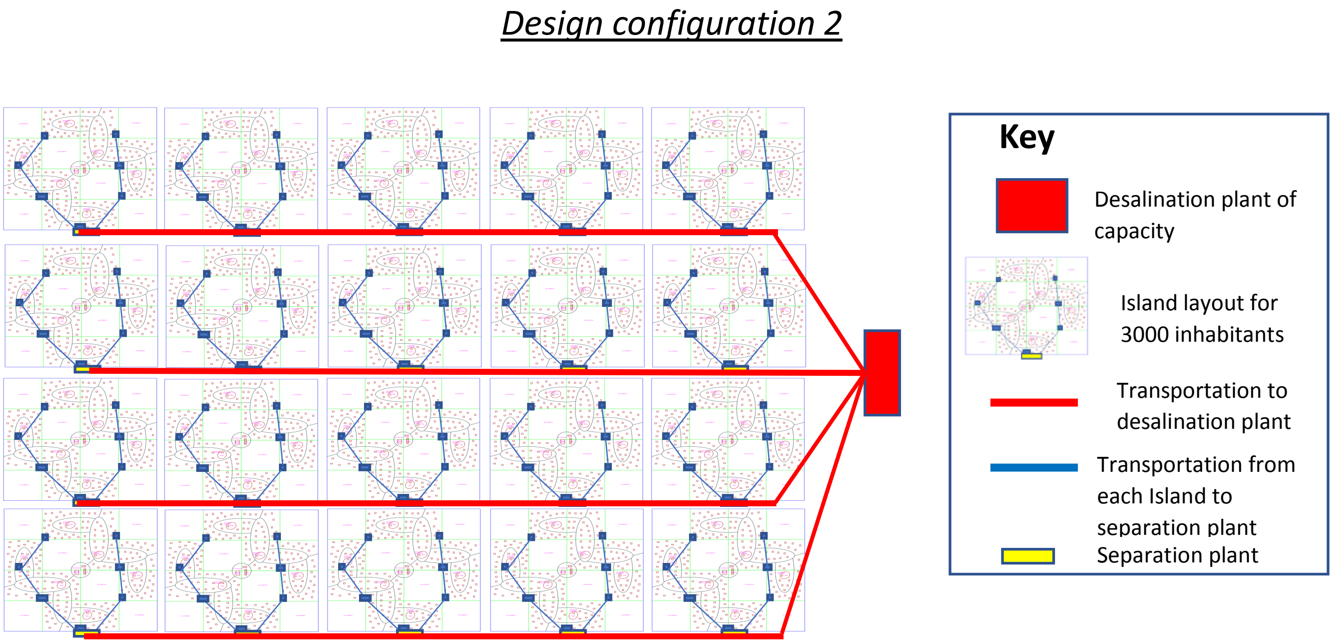


Figure 17 - Design configuration 2

Design configuration 2 illustrates one potential configuration for all 60 islands required for the 2050 population of over 178,100 [49]; following a more linear and straight forward design. This comprises of one big facility which undertakes all desalination processes and is fed by pipelines from individual separation plants from each island. In this respect, untreated waste is pumped linearly from one island to the next until it reaches this facility.

Though this has an element of simplicity, a breakdown of the separation plant prior to the pre-treatment and RO phase would disrupt the desalination process of the precedent islands whose filtered waste pass through it on their way to be treated. The breakdown of a desalination plant would affect 1/3 of the population whereas a breakdown of a separation plant could affect 1/15th of the total population (considering all 60 islands).

4.4.1 Pipeline Requirements

The backbone of the configurations examined are the pipelines which connect the different stages of treatment.

All pipelines shown in designs are assumed to be within the hull of the islands for financial reasons. If this were not the case, modifications would have to be made to pipelines which would make them durable to the physical and chemical processes associated with the oceanic environment; significantly impacting the financial expenditure.

As mentioned, the total population by 2050 would exceed 178,100 [49] hence to accommodate them, Kiribati would require 60 model islands as each has a 3000-person capacity [1]. This amounts to a total area of 32.1km^2. To carry the water from aggregation points to the separation point, a pipeline network of 1.7km is required worked out through a scaled model adaptation) per island. This is extrapolated to 85km for all 60 islands. Given each island is home to 3000 inhabitants [1], these pipelines should be able to handle the minimum 50l of water per person set by the World Health Organisation [9], however, to account for variations and solid debris, a safety factor of 25% is added.

5.0 Design element analysis

5.1 Pipeline Analysis

Self-Cleansing Velocity

According to the Eurocode incorporated sewage manual, the self-cleansing velocity is a minimum velocity which allows sewage flow to self-clean the nominal amount of silt carried through the sewer, helping minimise “sewer chokage” resulting from silt and grease accumulation [50]. This reduces the amount of maintenance required as well as the associated cost. However, the self-cleansing velocity is a function of particle size of sediment and hence difficult to determine. This is also influenced by the variety of particles in the flow.

The Self-cleansing velocity which would not permit solid particles to be deposited in pipelines should be attained at least once a day. If not, deposits will obstruct free flow, causing increased deposition. This minimum velocity is worked out through the Darcy Weisbach equation below:

$$V_S = \sqrt{\frac{8K}{f'}(s_S - 1)g.d'} \qquad (1)$$

Where

K= constant, for clean inorganic solids = 0.04 and for organic solids = 0.06
f' = Darcy Weisbach friction factor (for sewers = 0.03)
Ss = Specific gravity of sediments
g = gravity acceleration
d' = diameter of grain, m

Therefore, for very small particles such as sand of diameter 1mm, specific gravity of 2.65 and organic particles at roughly 5mm, a minimum flow velocity of approximately 0.45m/s. On the other side of the velocity spectrum, too fast a flow velocity leads to scouring of the pipes through abrasion of the interior. This occurs at velocities above the pipe’s maximum.

Being the closest developed neighbour to Kiribati, the Australian Sewage standard uses a benchmark average velocity of 0.7m/s as a base for self-cleansing which will be adopted as part of this project [51]. Additionally, The Code limits the pipe half-full velocity to 3m/s therefore Sewers must not be laid at grades where the maximum velocity will exceed 3 m/s in either partial or full flow.

The type of sewage pipeline to be adopted here would be a Vitrified Tile sewage system. This is due to the fact that it has the highest limiting velocity out of the most popular types; meaning water can flow at almost three times the brick lined sewer without scouring the interior surface [63]. Having a tiled surface also reduces the frictional forces against flow inside the sewage and hence the capacity for water to travel faster. Further, Vitrified tiles have a very low porosity; reducing the risk of leaks caused by incompetent materials [52]. In the long term, the savings made through the avoidance of leaks, scouring and breakdown should outweigh that of buying a cheaper material such as cement concrete.

Additionally, this type of pipe has a minimum transport velocity of 0.8m/s and a max transport velocity of 5m/s. As annual rainfall in South Tawara has been measured to be approximately 2100mm a year [48], Kiribati can be placed within the top 25 wettest countries in the world [53].

Therefore, the likelihood of pipelines receiving extra rainwater and hence increasing flow velocity is high. Appendix 9 Illustrates the amount of rainfall in South Tarawa relative to London

Pipeline Standards

Fortunately, BS EN 752: 2008 advises that self-cleansing of sewers of diameter less than 300mm can be achieved with velocities of at least 0.7 m/s. Alternatively, a gradient of at least 1: Nominal Diameter (in mm) should be acceptable. Larger diameter pipes should see higher velocities particularly where there is coarse sediment. Diameters of up to 900mm should be designed to self-cleanse at 1m/s [50].

Self-cleansing speeds are also advised to be attained during times of peak flow. However, a very fast flow is not desirable for a number of reasons. Firstly, this causes scouring and cavitation on the internal diameter (particularly where the surface is not smooth). Secondly, fast flow rates may lead to subcritical flow, causing hydraulic jumps which can also make it unsafe for manual cleaning and maintenance. The maximum velocity is advised to be up to 3m/s. Pipes of diameter less than 200mm should not normally be used as sewers [50].

In trying to identify the size and required dimensions of pipelines to transport sewage, guidance on drainage and waste disposal from the government of the Island of Jersey (GOJ) GDP has been used. The advantage of this stems from the fact that Jersey is an island, and secondly, it has a current population just shy of the population of Kiribati (106,000).

In the drainage and waste disposal document released by the GOJ [54], table 5 showed the flow rate which comes from an average household consisting of 1 WC, 1 bath, 1 or 2 washbasins, 1 sink and 1 washing machine. These characteristics were used for design purposes in the BS EN 12056. From this table, a positive correlation is observed between foul drainage flow rate and the number of dwellings. However, this is not a linear relationship hence a linear extrapolation cannot be made to identify the flow rate associated with the 750 dwellings supplying each aggregation plant. However, tabulating the gathered data in excel and using the “FORECAST” function, a flow rate of 80.6 litres/second is obtained. Details of this forecast and calculation can be found in Appendix A7. From this analysis, a flow rate of 1m/s would require a pipe of diameter 325mm. However, this is only applicable for stage 1 flow.

Stage 2 transportation involves a transfer of sewage from 3000 homes. For this, a pipeline diameter of 650mm is required, followed by a diameter of approximately 1300mm for stage 3. The calculations to obtain the flow rates and pipe diameters are given in Appendix A8. The results from this are supported by the Hazen-Williams formula which provides the flow velocity and discharge rate for a given pipe with known parameters:

$$h_f = \left(\frac{151Q}{CD^{2.63}}\right)^{1.85} \div 1000 \qquad (2)$$

h_f = Friction head loss in pipe per meter of piping (m)

Q = Volumetric flow rate (m^3/s)

C = Hazen-Williams “C” factor (dimensionless)

D = Internal pipe diameter (m)

Using the proposed 325mm diameter estimate [54], along with the vitrified tile factor of 100 and a minimum slope guidance by the North Carolina Department of Environment and Natural Resources [70], a flow rate was yielded within 5% of that predicted by the Jersey prediction.

Simulation:

A simulation was created in MATLAB’s Simulink software using key components from its Simscape fluids library [55]. The aim of this simulation was to evaluate the viability of the designed system and to test this using the equipment specified for this design. Given the simplicity of transportation infrastructure required, information such as pump size, volumetric flow rates, and time were input to simulate the impact in changes to any of those factors.

The results revealed that for a target flow rate of 1m/s the pumps required to move sewage from one aggregation point to another should have an operational specification to be between 2300 and 2500 rpm for stage 1 flow. Below this, the pump is unable to process the large volumes of water over approximately 380l/s (i.e. an increase of 19% in volume) within 12 hours let alone during the rainy season when surface runoff would increase the process input.

Given the country receives an extraordinarily high level of rainfall at various times of the year, this has the potential to double the amount of water passing through sewage pipelines from surface run-off. Hence the theoretical pipeline diameters have been increased by approximately 30% to 410mm for stage 1 pipelines, 600mm for stage 2 and 840mm for stage 3. As the proposed design uses gravity-fed pipeline, the vertical elevation with respect to horizontal distance to achieve a flow rate of 1m/s for stage 1, 2 and 3 are 1:500m, 1:750m and 1:1100m respectively.

5.2 Design analysis

The proposed process and series of activities for desalination is one of many approaches. The current sequence of events relies on a collective arrangement where waste is aggregated before being sent to the separation plant and reverse osmosis facilities. Alternatively, a more exclusive modular approach could have been taken. This would see each hexagonal island equipped with its own separation and reverse osmosis facility. However, as revealed by table 2 below, there are a variety of factors governing the decision not to adopt this approach.

The rankings from this are from 1-10 with 1 being a completely undesirable result or outcome and 10 being the best outcome.

Table 2 - Relative comparison of current design vs. Exclusively modular layout

Issue	***Proposed layout***	***Exclusively modular layout***	***Comments***
Social disruption to everyday life	*8*	*3*	*An exclusively modular layout brings facilities closer to people. Past reports have noted significant disruption to livelihoods including visual and noise pollution as well as disruptions to fisheries* [56]
Risk of flow falling below self-cleansing velocity	*6*	*4*	*An increase in volume of water means a decreased likelihood of flow velocity falling below self-cleansing however this is relative to pipe diameter*
Frequency at which membrane would have to be replaced	*4*	*7*	*The greater the volume of water passing though, the more frequent the membrane filter would have to be replaced*

Pressure and force on downstream pipes/pumps	*5*	*7*	*The proposed layout will carry water from multiple islands downstream increasing the pressure and weight inside*
Amount of employment created	*5*	*6*	*Having more plants will obviously lead to more jobs. This may be offset by the skills required however.*
Environmental damage from construction activities	*7*	*4*	*An exclusively modular arrangement would see more pipelines and processing plants*
Statistical risk of breakdown	*5*	*7*	*The greater the number of components in a given facility, the greater the risk of breakdown. As the proposed plant will handle a larger quantity of water this has a higher probability*
Total	*40*	*38*	

As can be deduced, this is a very close call in terms of rating important factors between the two configurations. Although both have a strong number of categories they outperform in, the proposed arrangement significantly outperforms in the first and second highest priority parameters for this project (table 1). On the other hand, the exclusively modular marginally outperformed in trivial categories where the issue is unavoidable in both cases e.g. disruption to lives is inevitable whether the plant is directly onsite or not.

Local vs Remote

As part of the proposed design, elements of the desalination process are conducted on each island (e.g. aggregation and physical filtration), others are offshored to another island (e.g. Reverse osmosis desalination and chlorination). However, the proposition to spatially split these processes presents challenges and risks within themselves. The following table briefly evaluates the risks of major elements being conducted onshore or moved offshore to another island.

Table 3 - Onshore vs. Offshore comparison table for conducting major processes

Process	*Onshore advantages*	*Offshore advantages*
Aggregation of wastewater	• *Facilities required are smaller as each island has its own plants* • *Lower risk of pipelines being blocked as water and solid waste is transported over relatively long distance* • *Risk of flow being below self-cleansing is higher as solid matter will slow down flow*	• *Major increase in length of pipeline required to transport all water to one area*

Physical filtration (separation)	• *Distance to travel for this is lower therefore less pipeline* • *Reduces weight and pressure* • *Removes need to transport waste and water back to island* • *Maintenance costs are kept low due to easier and quicker access.*	• *Any noise and pollution associated with process is conducted away from residents*
Coagulation + Flocculation	• *Transportation to, and access to facilities is lower*	• *Smell associated with mixing untreated water is reduced* • *Any potential vibration from parts is isolated from mainland* • *Leak of coagulant is isolated from islanders*
First and Second pass RO filtration	• *Transportation to and maintenance* •	• *Worst case breakdown or explosion of modules is unlikely to impact islanders* • *Organically grown filters can be grown around plant facilities*
Chlorination		• *Chlorine leak will not harm groundwater sources*

5.2 Waste management

All the system designs and proposed technologies yield a by-product which in one way or another must be utilised or discarded. The mode of treatment and discharge in Australia and around the world for ships was identified to be governed by The International Convention for the Prevention of Pollution from Ships 73/78 (MARPOL).

Given the waste produced from this process will not be discarded on the island where the plant is situated, it will require transportation elsewhere and hence be eligible for discharge out at sea. This comes with strict adherence to Annex IV - Regulations for the Prevention of Pollution by Sewage from Ships and Annex V - Regulations for the Prevention of Pollution by Garbage from Ships. Annex IV prohibits discharge into the sea unless the ship is equipped with an approved sewage treatment plant or waste is comminuted [57]. Additionally, adequately treated and comminuted discharge is permitted at a distance of three nautical miles from the nearest land, otherwise this must be twelve nautical miles. During this process, the ship must not be moving below 4 knots.

Using Australia as a developed neighbour to take precedence from in terms of regulation, the country derives its regulations for offshore platforms using the MARPOL framework. Under the Australian Maritime Safety Authority, discharge from offshore platforms situated twelve nautical miles from mainland is prohibited except Food waste comminuted or with a particle size less than 25 mm, and Greywater.

Annex V which relates to garbage prohibits the discharge of all garbage into the sea. Alternatively, it is advised for ships to have adequate port reception facilities to utilise particularly within “special areas” (areas where any discharge is strictly prohibited). Supplementary to this is a garbage management plan and log which must be updated [57].

5.2.1 Solid filter/separation:

The filtration process will yield various solid waste and matter including excrement. The sustainability element of this project considers the use of such material for the benefit of human activity. For example, human excrement can be used for the production of biogas. This application positions such resources to support human activity and whilst reducing the need for deforestation in order to fulfil that same need [58].

Non-degradable waste such as plastic should be sorted, and where applicable sent to the appropriate reclamation facility e.g. recycling for some plastics.

5.2.2 RO membranes: Brine

As mentioned, the Brine from an R.O plant can be utilised by farmers in the agriculture industry. This has been a vital ingredient in the production of liquid fertiliser which is dependent on having a low concentration of Total Dissolved Solids (TDS). However, as can be seen from Table 1, the Reverse Osmosis process generates the highest concentration of TDS and presents a slight issue in quality. On the contrary, looking at the status of Kiribati, this is unlikely to be a viable route as the technology involved is beyond their capability. As mentioned in section 3.2, this by-product has the potential to be used in Salinity Gradient Power which in 2040 could be a growing initiative in Kiribati.

5.3 Building footprints:

The table below identifies the key facilities which would be required as part of the RO process. The data for the Kiribati proposal was calculated using the Cangzhou Sea Water Reverse Osmosis (SWRO) plant [27]. This led to a linear interpolation between the output volumes of water for the Cangzhou plant and that required for Kiribati in 2050. However, this relies on one major assumption; the linear interpolation of output volume between the plants being equal to the size of the plants.

Table 4 - Building footprint table for RO plant

Ratio of Proposed plant to Cangzhou according to volumetric capacity *(0.18)*	***Cangzhou SWRO Case Study***	***Linear Kiribati extrapolation*** *(by 0.18)*	***Kiribati with 20% factor***	***Size of one island (m2)***	***% land of 1 island required for facility***	***% Land required with 100% factor***
Break eFacility	***Building foot print (m2)***	***Building foot print (m2)***	***Building foot print (m2)***	***415,900***		
Main plant building, including all processing infrastructure, the main workshop, control room, chemical dosing room,	*12,000*	*2,160*	*2,592*		*0.623%*	*1.04%*

pump room and general story						
Administration building	*324*	*58*	*70*		*0.017%*	*0.03%*
Utilities workshop	*400*	*72*	*86*		*0.021%*	*0.03%*
Auxiliary clarification workshop	*234*	*42*	*51*		*0.012%*	*0.02%*
Sealed area (exterior to the buildings), including vehicle access and parking	*234*	*42*	*51*		*0.012%*	*0.02%*
Landscaped area (improved site amenity)	*1,000*	*180*	*216*		*0.052%*	*0.09%*
Total					*0.737%*	*1.23%*

Table 5 - Pipeline dimensions table

	Pipeline dimensions		
Pipeline stages	*Diameter (mm)*	*Length required per Island (m)*	*Length required for whole project (m)*
Stage 1	*325*	*400*	*24,000*
Stage 2	*650*	*810*	*48,600*
Stage 3	*1300*	*520*	*31,200*

*Kiribati will need the exact same for water returning from RO plant

Table 6 - Project Costing table

Facility/ Amenity	***Approximate cost within project***
RO plant including all equipment, control room, processing and chemical treatment facilities	*£13,467,680**
Administration building	*£500*
Utilities workshop	*£800*
Aggregation plant	*£1m-£5m upfront* [59]
Pipelines	*£65, 710, 632* [60]
*Chlorine (1 day equivalent) – 576kg a day***	*£865*
*Aluminium Phosphate (1 day equivalent) – Approximately 680kg a day****	*£72,000*

*The method of estimation is given in Appendix A10

**Based on the average price of Chlorine and ratio of 0.25gdpm3 of chlorine per m3 of water.576

*** Based on the average price of Aluminium phosphate [61]and 1:10 ratio

Vitrified pipeline estimation of costs was made using the Hepworth play company (no.1 UK drainage brand) price estimations as of 1st March 2019. The pipelines listed here are in compliance with British Standard BS EN295 (Vitrified clay pipe systems for drains). This consisted of extrapolating the price of 300 mm diameter pipe lines according to the percentage increase of diameter for the required pipes. As a safety measure, all required pipelines were increased by 20% than that required to accommodate total population to account for surface water run-off into the pipelines [12].

5.3 Maintenance and operational sustainability

Considering the capital investment objective of this project, the adoption of the organic polymer described in section 2.4.1 is paramount to the survival and self-sufficiency of this process. Assuming this develops enough to become mainstream, this is a major element of the process which Kiribati will not rely on any nation to provide assistance. This crucially eliminates the majority of maintenance cost to the availability of skilled farmers (which the country has no shortage of), fertile soil, and land (which they have abundantly).

Further, another major element of maintenance would be the pumps required to feed the water as they wear over time or lose functionality due to vibrational factors. Considering the new wave of immigrants to cities such as South Tarawa possess basic skills for vehicle repair and manufacturing, the maintenance of this element actually provides an employment opportunity for this niche group. Economically, this should decrease the unemployment rate and stimulate consumer spending whilst strengthening local economies. Again, the upkeep of these fundamental components should be self-sufficient for the country and avoid the catastrophic results which followed the Algerian plant (section 2.4.1) and admittedly; many infrastructure projects in developing nations.

One of the most successful elements of this project and its maintenance is the provision of chlorine for the final part of the process (to remove adverse task and odour). Like the previous constituents of the sanitation project this is an input which can be self-sufficiently regulated by Kiribati itself. This crucial ingredient can actually be obtained by the very by-product the process yields; brine. Though this requires a process of electrolysis to obtain the chlorine, electrolysis is a well-known process which one could expect can be conducted effectively even in a country such as Kiribati by 2045.

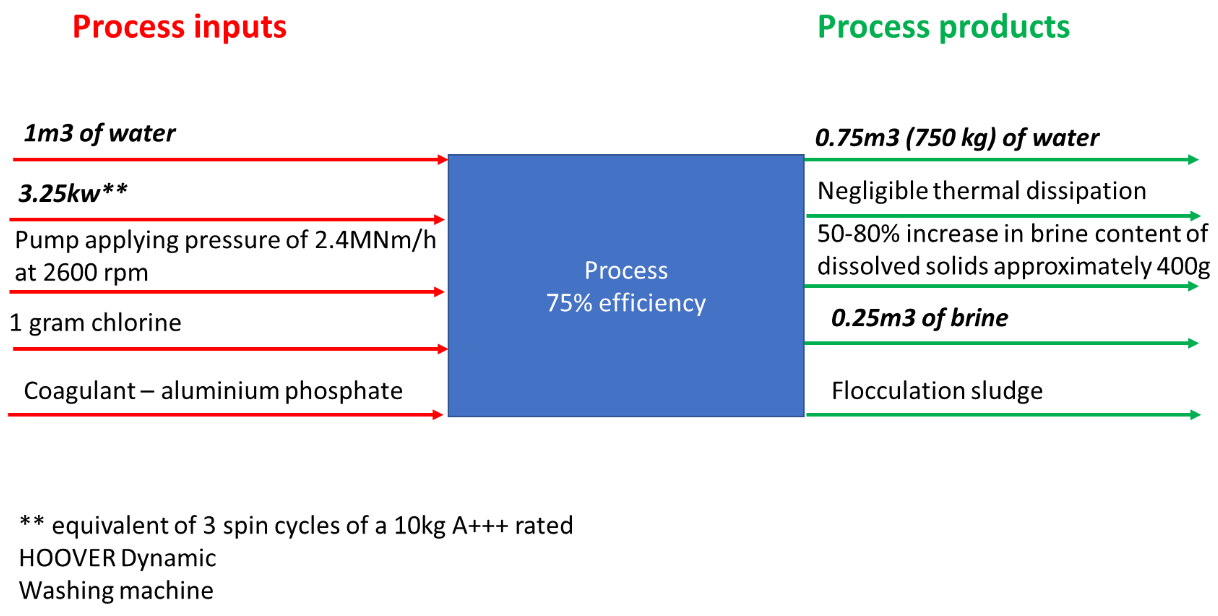


Figure 18 - Process main input/output components with 75% efficiency [62] However, other inputs such as the coagulant (e.g. aluminium sulphate) are inputs which may have to be imported from abroad.

Conversely, smaller components such as chemical and pressure monitors used throughout the process are some of the main components which may also be sourced from overseas.

5.4 Environmental emissions analysis

One major requirement of this design project is to keep environmental pollution to minimum. The construction phase is where most pollution for this project will result e.g. building materials, transportation of resources, and energy consumed. This is a phase where it will be difficult to cut emissions. However, a range of practices can be used to try and achieve this such as transportation method and materials used. For example, one way to reduce pollution from building materials would be to use locally sourced materials such as breeze blocks for buildings instead of imported clay bricks.

Additionally, reverse osmosis membranes are known to accumulate biological molecules and membrane surfaces. Over time, these molecules Will grow and under warm and wet conditions such as those found in Kiribati can decompose and release greenhouse gases such as methane. However, this is mitigated by regular replacement of the membranes which should be straightforward using the organic polymer fibres previously mentioned. Such practices would insure pollution in those delicate sub processes is kept to a minimum.

Having said that, one crucial point to bear in mind is the possibility of overflow through any pipelines or aggregation points which would lead to flooding. Considering Kiribati undertakes a large amount of agricultural activities any flooding of land would initiate the rotting vegetation and hence emission of methane. Therefore, a range of monitoring and redundancy mechanisms have been put in place to prevent this such as flow monitoring, overflow mechanisms and safety margins for tanks.

5.5 Capital investment methods assessment

One core method of funding would undoubtedly involve the use of aid from neighbouring countries. Currently the country receives substantial aid, however, the extent to which this provides extra capital for development projects is unknown. Intergovernmental funds are also a strong possibility with the IDA being the best source as they provide loans of 25 years onward with no interest and grace periods of 5-10 years, whereas organisations like the World Bank and IMF impose interest payments.

In a macroeconomics discussion paper [63], Guimaraes et al. conclude political proximity of the borrowing country to an intergovernmental Fund’s major shareholders has an “important” effect on the fiscal adjustment it gets along with the country’s fiscal deficit. A more concerning literature by the IMF in 2019 also explicitly stated the risks to Kiribati’s outlook are “substantial and skewed to the downside” and that “the fiscal position is expected to worsen under current policies” [64]. Should Guimaraes’ conclusion prove accurate, this rules out the possibility of funding from an intergovernmental agency like the IMF given their current perception.

Alternatively, it has been mentioned that some of the process by-products could be used as a bargaining tool. For example, the brine released from the process could be exported to Central Asian nations such as Uzbekistan which has begun development of electrodialysis methods of generating electricity [65]. Assuming Kiribati will lack the necessary expertise to have such technology to generate electricity, this prime could serve as an exchange to such regions for part funding of the project. However, should it be the case that in the future Kiribati can produce such technology itself, then the amount of electricity generated from the brine through electrodialysis can be discounted from the cost of the project over the given period of 20 years.

A simple Discounted Cash Flow analysis for this project using a total project cost of £82 million was firstly conducted. This yielded an initial saving of £4.5 million for the first year (less than 3% of current GDP). Thereafter, an increase in the saving of 5% annually was assumed for the next 20 years. Such savings would come in the form of growth in both population and economic activity due to lower mortality rates and increase the literacy rates, potential exports of by-product outputs of the process and savings from reduced expenditure and flood defences and mitigation projects.

A linear analysis to ensure this is paid fully in 20 years produces an internal rate of return (IRR) of 5.45%. This essentially means that in order to guarantee a break-even or full payment with no surplus, a discount rate greater than 5.45% cannot be used or assumed. Using a rate of 5% under the same conditions of growth in terms of revenue or savings this project would yield a surplus of £3.7 million in year 20.

Alternatively, since the project is completed in stages, if costs are split linearly i.e. fixed instalment per year then it can be justified that the cost of the proceeding stage can incorporate the depreciation of the preceding stages up to that point. This is due to the fact that before the whole project is fully complete, previously completed sections would have started to depreciate, therefore, as a logical goodwill, this can be deducted from future payments. This is a purely creative method of financing devised specifically for this project using basic accounting principles and named "Aggregated Infrastructure Depreciation". A full explanation of this is found in Appendix 15

Conclusion

Overall although the aim and objectives for this project have been tough to comprehensively fulfil, it can be considered a successful endeavour to find a solution fit for Kiribati.

Reflecting on the socio-economic considerations (such as workforce skill and energy demand) it can be seen that the proposed project for Kiribati is feasible. Through the literature review; competent technologies were identified for the project such as Multi-stage flash distillation (MSF) and Multiple-effect distillation (MED). However, when considered relatively against their social and environmental influences through quantitative and qualitative analysis, the RO technology emerged the strongest in terms of minimising environmental disturbance and maximising water output per unit input.

It has been identified that this project strikes a good balance between environmental and social considerations. Section 5.2 demonstrated that most of the decisions made on the design and its configuration included considerations of the environment under which processes would be conducted within, as well as considerations of financial capacity. This section also illustrated how the "waste" from this process can be utilised for productive human activity; from the output of the flocculation process to the brine of the reverse osmosis process; a major selling point.

Further, some of these outputs have been identified to be potential iterative inputs to be used back into the process; thereby cementing the stamp of sustainability on this project and upholding the objective to minimise waste and pollution. Although this project hasn't been simulated in an environment representative of Kiribati, it has incorporated processes to mitigate the potential risks associated with this environment through a simple yet robust structure.

Additionally, major assumptions have been made which are critical to the development and maintenance of this project. The most crucial of these lies with the successful rollout of naturally derived microfilters and the ability of Kiribati to yield these at a rate faster than that at which they are being consumed. Secondly, an abundant source of renewable energy by the year 2045 is required, and finally, the development of skills and knowledge of the country.

The proposal for this project has proven a method of desalination is possible which can cater to the population of Kiribati in the next three decades. This project has demonstrated it provides the lowest energy consumption of currently known technologies, sustainable process features (e.g. organic microfilters) and a minimises disturbance to social activities.

Further work

In order to build a more accurate picture when designing projects such as this, further information and research will have to be conducted into the significant variations between similar projects executed in developing countries and those in developed countries. For example, estimations made; such as safety factors did not have strong empirical evidence to back that up. Further, research on the impact of the climate of countries like Kiribati (and other developing countries) on technology would shed light on where some weaknesses may lie. This would allow effective tailoring and redesigning of current systems to comply with such environments.

Within the social sphere, a greater insight could be provided into the influence of government and official figures in countries like Kiribati. As highlighted in section 3.4.3, socio-political influences play a major part in the top-down adoption of new technology. With capital investment looking like the biggest obstacle for this and many other projects, an insight into how to alleviate this with political support will be invaluable to the simple adoption to infrastructure projects such as this.

A major issue with development projects is their lifecycle. This means most projects are bound to begin to deteriorate after a set amount of time or when inputs and demand fluctuates. This is a significant engineering issue which affects almost all projects. However, the need to innovate projects with self-healing and adaptability capabilities may soon become inevitable. In countries like Kiribati where resources are scarce, a stronger element of automated self-sufficiency is bound to change the face, demands and considerations for development projects irrespective of location now, and of those to come.

References

[1] N. Lister and E. Muk-Pavic, “). Sustainable artificial island concept for the Republic of Kiribati. Ocean Engineering,” *Ocean Engineering,* pp. 78-87, 2015.

[2] W. Bank, “Kiribati,” 21 03 2019. [Online]. Available: https://data.worldbank.org/country/kiribati.

[3] C. I. Agency, “Kiribati — The World Factbook - Central Intelligence Agency.,” Central Intelligence Agency, Australia - Oceana.

[4] G. o. Kiribati, “Kiribati Development Plan 2016-19,” Government of Kiribati, South Tarawa, 2015.

[5] D. o. F. A. a. Trade and Australia, “Overview of Australia's aid program to Kiribati,” Department of Foreign Affairs and Trade; Australia, Canberra, 2019.

[6] N. Z. M. o. F. A. a. Trade, “Aid partnership with Kiribati,” [Online]. Available: https://www.mfat.govt.nz/en/aid-and-development/our-work-in-the-pacific/kiribati/. [Accessed 31 March 2019].

[7] M. o. F. A. o. Japan, “Japan-Kiribati Summit Meeting,” [Online]. Available: https://www.mofa.go.jp/a_o/ocn/ki/page3e_000862.html . [Accessed 31 march 2019].

[8] W. Bank, “Country Profile,” [Online]. Available: https://databank.worldbank.org/data/views/reports/reportwidget.aspx?Report_Name=CountryProfile&Id=b450fd57&tbar=y&dd=y&inf=n&zm=n&country=KIR . [Accessed 31 march 2019].

[9] W. H. Organisation and U. N. C. F. (. , “Progress on Drinking Water, Sanitation and Hygiene: 2017 Update and SDG Baselines,” World Health Organisation, 2017.

[10] I. L. Organisation, “). The ILO in Kiribati. [online] Suva, Fiji: International Labour Organisation,” International Labour Organisation, 2019.

[11] W. Bank, “ International coalition tackles impacts of climate change in Kiribati.,” Washington DC, 2005.

[12] M. McGrath, “Climate change impacts 'accelerating',” 2019. [Online]. Available: https://www.bbc.co.uk/news/science-environment-47723577. [Accessed 6 April 2019].

[13] DeSmogBLog, “Antarctic Melt Accelerates Sea Level Rise—and the Likelihood of Climate Migration,” 2019. [Online]. Available: https://www.desmogblog.com/2018/07/20/antarctic-melt-accelerates-sea-level-rise-and-likelihood-climate-migration . [Accessed 6 April 2019].

[14] D. Debabrata Chattopadhyay, M. D. Brazilian and M. Chattopadhyay, “Commentary: How to tackle the next big blackout before it happens,” 2019. [Online]. Available: https://www.channelnewsasia.com/news/commentary/tackle-next-big-blackout-causbefore-it-happens-11245882. [Accessed 6 April 2019].

[15] J. Vidal, “Artificial island could be solution for rising Pacific sea levels,” 2019. [Online]. Available: https://www.theguardian.com/environment/blog/2011/sep/08/artificial-island-pacific-sea-levels . [Accessed 13 April 2019].

[16] D. P. Narsey Lal, “The economic burden of inadequate water and sanitation in South Tarawa, Kiribati: Who bears the cost?.,” The Commonwealth Scientific and Industrial Research Organisation, Australia, 2015.

[17] E. D. D. o. t. P. Community, “Review of fuel subsidies,” Pacific Community, Suva, 2017.

[18] T. Awerika, “National Biodiversity Strategies and Action Plan 2016-2020,” Government of Kiribati, Tarawa, 2015.

[19] I. M. Fund, “STAFF REPORT FOR THE 2016 ARTICLE IV CONSULTATION— DEBT SUSTAINABILITY ANALYSIS,” International Monetary Fund (IMF), 2017.

[20] O. H. Authority, “Coagulation. Oregon: State of Oregon,” Oegon Health Authority, Oregon.

[21] W. H. O. (WHO), “WHO World Water day,” World Health Organisation (WHO), Geneva, 2019.

[22] M. Al-Abri, B. A.-G. Al-Ghafri, T. Bora, S. Dobretsov, J. Dutta, S. Castelletto, L. Rosa and A. Boretti, “Chlorination disadvantages and alternative routes for,” *npj Clean Water,* vol. 2, no. 1, 2019.

[23] N. E. S. C. (NESC), “Disinfection,” National Environmental Services Centre (NESC), 1996.

[24] W. H. O. (WHO), “How to measure chlorine residual in water,” World Health Orgnisation (WHO), Geneva, 2005.

[25] T. Water, “The Sewage Treatment Process,” 2019. [Online]. Available: https://www.southernwater.co.uk/water-treatment . [Accessed 14 April 2019].

[26] W. H. O. (WHO), “International Health Regulations Guide to Ship Sanitation. Edition 3,” World Health Organisation (WHO), Geneva., 2007.

[27] A. H. AS, “Cangzhou SWRO Desalination Plant,” July 2013. [Online]. Available: https://www.miga.org/sites/default/files/archive/Documents/ESIA-Cangzhou-china-June-2015.pdf. [Accessed 17 July 2019].

[28] Alfalaval, “MED Multi-effect desalinaiton,” [Online]. Available: https://www.alfalaval.com/products/process-solutions/desalination-solutions/multi-effect-desalination/med-multi-effect-desalination/ . [Accessed 5 June 2019].

[29] C. World, “Switching desalination plants from carbon dioxide source to sink,” *Chemistry World,* 5 June 2019.

[30] A. H. M. Saadat, S. Islam, M. Islam and P. Fahmida, “Desalination Technologies for Developing Countries,” *Journal of Scientific Research,* vol. 10, no. 1, pp. 77-97, 2018.

[31] J. Martinez Beltran and S. Koo-Oshima, “Water desalination for agricultural applications,” FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, 2006.

[32] S. P. Maedeh, A. McHugh, M. Anda and G. Ho, “Environmental life cycle assessment of seawater reverse osmosis desalination plant powered by renewable energy,” *Renewal Energy,* vol. 67, pp. 53-38, 2014.

[33] J. Stokes and A. Horvath, “Energy and Air Emission Effects of Water Supply,” *Environmental Science and Technology,* vol. 43, no. 8, pp. 2680-2687, 2009.

[34] B. Hughs, F. Rezazadeh and H. Chaudhry, “Economic viability of incorporating multi-effect distillation with district cooling systems in the United Arab Emirates,” *Sustainable Cities and Society,* vol. 7, pp. 37-43, 2013.

[35] C. Sommariva, “Desalination and advanced water treatment. Hopkinton,” Balaban Desalination Publications, 2010.

[36] G. P. M. O.-D. B. C. A. a. A.-P. D. 59. Kosmadakis, “Correlations for estimating the specific capital cost of multi-effect distillation plants considering the main design trends and operating conditions,” *Desalination,* vol. 447, pp. 74-83, 2018.

[37] R. Dashtpour and S. N. Al-Zubaidy, “Energy Efficient Reverse Osmosis Desalination Process.,” *International Journal of Environmental Science and Development,* vol. 3, no. 4, pp. 339-345, 2012.

[38] J. Zactruba, “Reverse Osmosis vs. Multi Stage Flash Distillation: A Comparison Between Different Desalination Methods,” 2019. [Online]. Available: https://www.brighthubengineering.com/power-plants/29621-comparison-between-the-reverse-osmosis-and-multi-stage-flash-distillation-methods/. [Accessed 19 May 2019].

[39] “What is Desalination,” 2019. [Online]. Available: https://www.ide-tech.com/en/solutions/desalination/what-is-desalination/?data=item_1 . [Accessed 24 May 2019].

[40] Desware, “Encyclopedia of Desalination and Water Resources: Energy Requirements of Desalination Processes,” [Online]. Available: http://www.desware.net/Energy-Requirements-Desalination-Processes.aspx . [Accessed 11 June 2019].

[41] Banrie, “How to start a biofilter,” 2013. [Online]. Available: https://thefishsite.com/articles/how-to-start-a-biofilter . [Accessed 14 June 2019].

[42] G. o. Kiribati, “Fresh Water Supply | Climate Chnage,” [Online]. Available: http://www.climate.gov.ki/effects/fresh-water-supply/ . [Accessed 17 May 2019].

[43] A. Kartalidis, E. Tzen, E. Kampragkou and D. Assimacopoulos, “Responding to water challenges in Greece through desalination: energy considerations,” *International Journal of Water Resources Development,* vol. 32, no. 3, pp. 428-441, 2015.

[44] E. Dialynas and A. Angelakis, “IWA Regional conference on wastewater purification and reuse: Desalination in Greece,” Crete, 2012.

[45] B. News, “Kiribati Country Profile,” 2013. [Online]. Available: https://www.bbc.co.uk/news/world-asia-pacific-16431122. [Accessed 5 June 2019].

[46] U. Nations, “‘Save Tuvalu; save the world’; UN chief echoes rallying cry from front lines of global climate emergency,” *UN News,* 6 June 2019.

[47] S. Firth, “Instability in the Pacific Islands: A status report,” Lowey Institute, Sydney, New South Wales, 2019.

[48] G. o. Australia, “Pacific Climate Change Science Program,” Government of Australia, Sydney, 2011.

[49] WorldPopulationView, “World Population View,” [Online]. Available: http://worldpopulationreview.com/countries/kiribati-population/ . [Accessed 3 August 2019].

[50] G. o. t. H. K. S. A. Region, “Sewerage Manual,” Government of the Hong Kong Special Administrative Region, Hong Kong.

[51] Kharagpur, “Hydraulic Design of Sewers and Storm Water drains,” [Online]. Available: https://nptel.ac.in/courses/105105048/M7L7.pdf . [Accessed 16 June 2019].

[52] T. Lacoma, “Difference between Ceramic Tiles & Vitrified Tiles,” Huker.

[53] I. Mundi, “Countries Ranked by Average precipitation in depth (mm per year),” [Online]. Available: https://www.indexmundi.com/facts/indicators/AG.LND.PRCP.MM/rankings . [Accessed 29 June 2019].

[54] G. o. Jersey, “Drainage and waste disposal Approved document H,” Government of Jersey, Jersey, 2019.

[55] Mathworks, *MATLAB,* Natick, Massachusetts: The MathWorks Inc., 2019.

[56] G. Tularam and M. Ilahee, “Environmental concerns of desalinating seawater using reverse osmosis. Journal,” *Journal of Environmental Monitoring,* vol. 9, no. 8, p. 805, 2007.

[57] Imo, “Prevention of Pollution by Garbage from Ships,” [Online]. Available: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/Sewage/Pages/Default.aspx. [Accessed 1 July 2019].

[58] C. E. Future, “Top 10 Ways to Put Human Waste to Use in an Environmentally-Friendly Way,” [Online]. Available: https://www.conserve-energy-future.com/top-ways-put-human-waste-use-environmentally-friendly-way.php . [Accessed 4 July 2019].

[59] W. S. R. Authority, “Water 2020: Regulatory framework for wholesale markets and the 2019 price review,” Water Services Regulation Authority, Birmingham, 2015.

[60] Hepworth, “Trade Price List March 1st 2019,” 2019. [Online]. Available: http://file:///C:/Users/User/Downloads/4555-Hepworth-Clay-CL103-March-1st-2019--WEB%20(4).pdf. [Accessed 29 July 2019].

[61] Chemicalbook, “Aluminium phosphate price, buy Aluminium phosphate,” [Online]. Available: https://www.chemicalbook.com/Price/Aluminium-phosphate.htm. [Accessed 7 August 2019].

[62] T. L. S. a. K. W. Chonga, “Energy-efficient reverse osmosis desalination process,” *Journal of Membrane Science,* no. 473, pp. 177-188, 2015.

[63] B. Guimaraes and C. E. Ladeira, “The determinants of IMF fiscal conditionalities:,” Centre for Macroeconomics (, Sao Paulo, 2017.

[64] I. M. F. (IMF), “KIRIBATI 2018 ARTICLE IV CONSULTATION—PRESS RELEASE;,” IMF, Washington D.C., 2019.

[65] W. Bank, “Seawater and Brackish Water Desalination,” World Bank, Seawater and Brackish Water Desalination, 2004.

[66] A. D. Bank, “Poverty in Kiribati,” 2019. [Online]. [Accessed 31 march 2019].

[67] A. D. Bank, “Poverty in Kiribati,” 2019. [Online]. Available: https://www.adb.org/countries/kiribati/poverty. [Accessed 31 march 2019].

[68] J. Barnett and N. W. Adger, “Climate dangers and atoll countries,” *Climatic change,* vol. 61, no. 3, 2005.

[69] A. Mackay, “Climate CHange 2007: Impacts, Adaptation and Vulnerability,” *Journal of Environmental Quality,* vol. 37, no. 6, 20008.

[70] B. C. Douglas, “Global sea rise: A redetermination,” *Surveys in Geophysics,* vol. 18, no. 2-3, pp. 279-292, 1997.

[71] S. P. R. E. Programme, “Environment Newsletter 53,” South Pacific Regional Environment Programme, 1998.

[72] S. Water, “How we treat water - Southern Water: Water and wastewater services for Kent, Sussex, Hampshire and the Isle of Wight,” 2019. [Online]. Available: https://www.southernwater.co.uk/water-treatment . [Accessed 13 April 2019].

[73] M. a. C. Agency, “Maritime Labour Convention, 2006: Food and Catering: Provision of Food and Fresh Water,” Maritime and Coastguard Agency, London, 2006.

[74] A. Environment, “Electrodialysis Reversal - wateions,” 2019. [Online]. Available: http://waterions.aceenvironment.com/edr . [Accessed 14 April 2019].

[75] T. D. Board, “Introduction to Desalination Technologies,” Board, Texas Development, Texas, 2019.

[76] W. Abdel-Halim, D. Weichgrebe and K.-H. Rosenwinkel, “Sustainable Sewage Treatment and Re-use in Developing Countries,” Research Gate, Hannover, 2008.

[77] S. Melvin, Y. Zadik and A. R. MArshall, “The ArrowBio Process for Mixed Municipal Solid Waste (MSW) : Responses to “ Requests for Information ” (RFIs),” Harrogate, 2005.

[78] A. News, “Emergency back-up power installed at Victorian desal plant,” 2017. [Online]. Available: https://www.abc.net.au/news/2017-03-01/generators-installed-victoria-desalination-plant/8313550 . [Accessed 26 May 2019].

[79] M. Darwish, M. Abdel-Jawad and G. Aly, “Technical and Economical Comparison Between Large Capacity Multi Stage Flash and Reverse Osmosis Desalting Plants,” *Desalination,* vol. 72, no. 3, pp. 367-379, 1989.

[80] M. Balaban, “Desalination and advanced water treatment. Hopkinton,” *Desalination Publication,* pp. 43-44, 2010.

[81] *Multi Effect Distillation Adsorption Desalination (MEDAD)..*

[82] Novasep, “Industrial Electrolysis,” [Online]. Available: https://www.novasep.com/technologies/industrial-electrodialysis-technology.html . [Accessed 5 June 2019].

[83] W. Sources, “Multi-stage flash distillation,” [Online]. Available: https://en.wikipedia.org/wiki/Multi-stage_flash_distillation . [Accessed 5 June 2019].

[84] Puretecwater, “Puretec Industrial Water | What is Reverse Osmosis?,” [Online]. Available: https://puretecwater.com/reverse-osmosis/what-is-reverse-osmosis. [Accessed 3 Aug 2019].

[85] J. P. C. A. C. J. G. S. J. A. L. M. M. G. M. R. N. P. N. A. P. W. P. D. S. a. A. U. Church, “Sea Level Change In: Climate Change 2013: The Physical Science Basis,” IPCC, 2013.

[86] W. Water, “Sewerage Design Standard,” Melbourne Retail Water Agencies, Melbourne, 2014.

[87] Calctool, “Gravity fed pipe flow calculator,” [Online]. Available: http://www.calctool.org/CALC/eng/civil/hazen-williams_g.. [Accessed 29 June 2019].

[88] 7. N. C. D. o. E. a. N. Resources, “Minimum design criteria for the permitting of Graviy Sewers,” North Carolina Department of Environment and Natural Resources , North Carolina, 2008.

[89] q. H. AS, “Multilateral Investment Guarantee Agency (2019). Report for Aqualyng Holding AS - Cangzhou SWRO Desalination Plant,” [Online]. Available:

https://www.miga.org/sites/default/files/archive/Documents/ESIA-Cangzhou-china-June-2015.pdf. [Accessed 4 July 2019].

[90] Knowledgepoint, “How can I estimate the quantity of flocculants needed for my surface water treatment station?,” [Online]. Available: https://knowledgepoint.org/en/question/5189/how-can-i-estimate-the-quantity-of-flocculan. [Accessed 7 August 2019].

Appendices:

Appendix A1: Global Sea level rise

Figure 19 (49) below illustrates the rise in global sea level over the centuries and more recently, over the past dozen decades. This data; obtained and published by the international Panel on Climate Change illustrates sea levels rising but at an increasing rate when observed more closely.

This not only suggests it is only a matter of time before countries like Kiribati are engulfed but the time remaining isn't linear and is approaching at an accelerating pace.

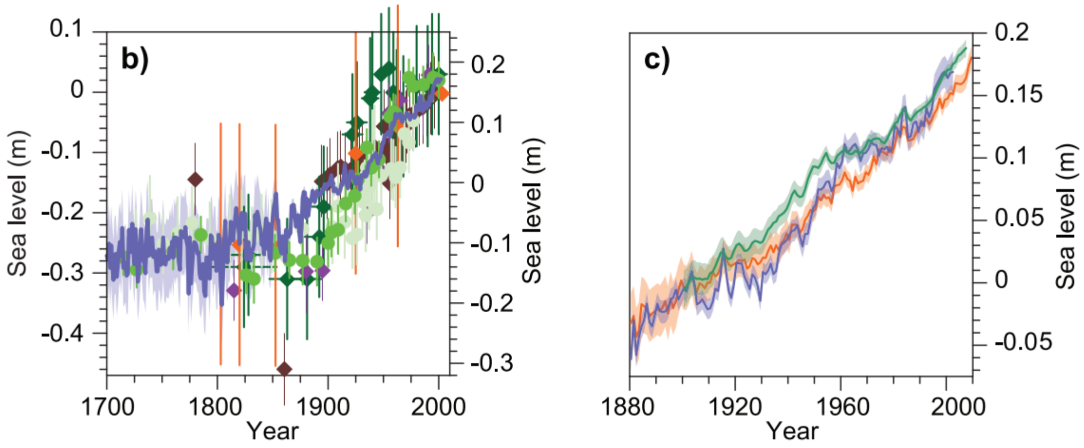


Figure 19 - Sea level rise [62]

Appendix A2:

Other issues

The pH of water may need to be monitored and controlled; as a very acidic pH may corrode domestic and distribution pipes. Alternatively, high alkalinity may leave deposits and hold unwanted tastes and odours.

Aside from methods involving chlorine, other processes such as ozone or ultraviolet light (which causes deactivation of microorganisms) may be used. However these methods require a lot of energy and are not suitable for water containing suspended solids, color, and soluble organic matter [23]. In addition, phosphates may be added to prevent Lead being extracted from the pipeline and into the water.

The sediment collected near the middle of the process can be put to good use with the majority able to be used by farmers as fertilisers [25]. In the UK, some have also been used to generate electricity through:

a. Combined heat and power (CHP) – The sludge is treated using anaerobic digestion; it is heated to encourage bacteria to digest it, creating biogas which can be burned to create heat for electricity.

b. Gas to grid – Natural gas extracted from the waste is injected into the gas grid

c. Thermal destruction – Drying the sludge into blocks ('cake') which are burned to generate heat for electricity.

Appendix A3:

3.3.2 Electrodialysis

An illustration of Electrodialysis is shown below. The raw wastewater is taken in through into two chambers where it flows under the influence of a potential difference applied between an anode and cathode. The positive Sodium (Na+) ions are attracted to the negative Cathode whereas the negatively charged Chlorine (Cl-) ions move towards the positive Anode. These ions flow through special membranes which only allows the appropriate ions to move towards their destination. The Cation membrane only allows the Na ions to pass through towards the Cathode (to the left-hand side) whereas the Anion membranes only permit Cl- ions to pass through towards the anode electrode. This therefore naturally creates three streams as the flow progresses. The first, which will be Chlorine rich (left-hand side of the water), the second, which hopefully contains little to no Na or Cl ions (in the centre) and the third, which is Na ion rich (on the right-hand side).

The effectiveness of this method wears over time as the ions begin to accumulate around the pores they flow through. However, a simple reversal of charge causes them to be ejected off in the opposite direction back into a mainstream flow where they can be removed. This brings the distinction between ED and EDR. For this reason, ED is generally used for desalination of brackish water, hence the need for reversal is significantly reduced [30].

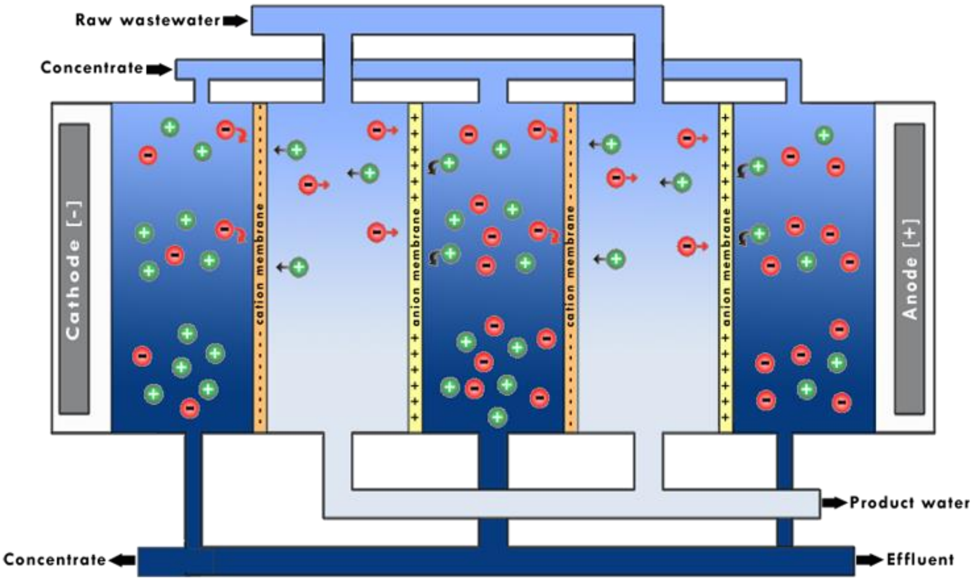


Figure 20 - Electrodialysis diagram: source [29]

Figure 21 - Electrodialysis plant: Novasep technologies [52]

Appendix A4:

Anaerobic Treatment

In a recent paper, researchers from Leibniz University singled out a potential treatment technology which hones on natural processes to treat wastewater and enhance its quality to produce greywater [32]. This process uses anaerobic respiration of micro-organisms to break down biodegradable material. This can be split into both liquid wastes (e.g. municipal wastewater) and bio-solid wastes (e.g. sewage sludge and agricultural wastes). An illustrative lifecycle of the process is shown below in figure 22 [52]. The products of this process can be used as soil fertilizer as valuable nutrients are kept in the water.

Zooming into the Anaerobic Treatment facility, this process is known as 'Upflow anaerobic sludge blanket digestion' (UASB). This is a tank where wastewater flows into, following which solid matter and sludge are dragged to the bottom of the tank leaving the water to float above. Within this, anaerobic organisms along with flocculants are added, aiding the digestion process of harmful bacteria. These anaerobes can be either unicellular (e.g. protozoans) or multi-cellular in nature. This mixture reaches maturity at approximately three months where a blanket is formed above the sludge containing sludge granules. These granules are coated with bacteria who use it as their only support mechanism for survival.

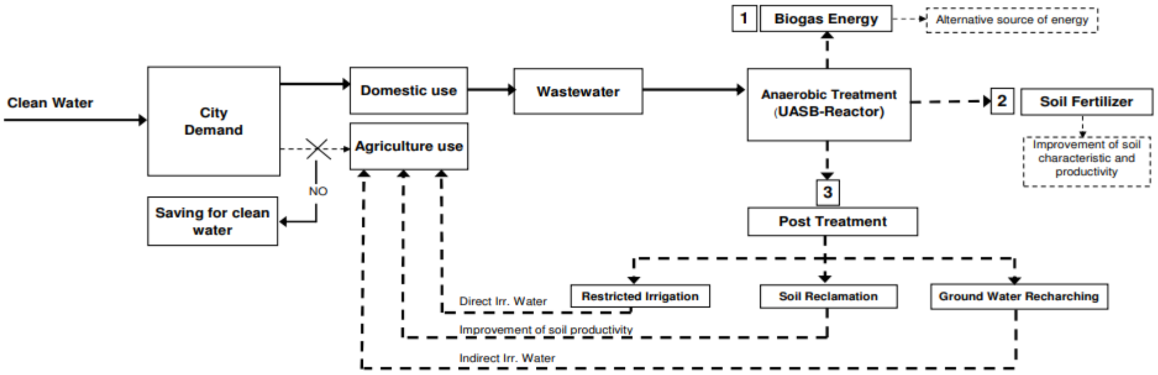


Figure 22 - Lifecycle of anaerobic respiration process [32]

Figure 23 - UK's largest anaerobic digestion plant in Staffordshire: Business Green [56]

As observed from the diagram, this method produces biogas as a by-product which has been a key element to UASB as this can be harnessed and used for electricity generation. Though this sounds straight forward, the appropriate infrastructure is needed to capture, store and transport the produced gas. Further pre-processing for UASB requires the wastewater to pass through a grit trap and splitter box before entering the digestion chamber.

Appendix A5

The first design configuration demonstrates the islands arranged in a more aesthetic but strategic arrangement which features a separation process plant which is fed by four aggregation plants on one island. Following this, four separation plants feed one desalination plant. Design configuration 2 follows a more linear and straight forward design. This comprises of one big facility which undertakes all desalination processes and is fed by pipelines from individual separation plants from each island. In this respect, untreated waste is pumped in a linear fashion from one island to the next until it reaches this facility

Although configuration 1 follows a more complex nature (relative to 2 (section 4.3)), it minimises the disruption caused by the breakdown of any element in the process. For example, a breakdown at any separation plant in configuration 1 would not influence the desalination process of all other islands.

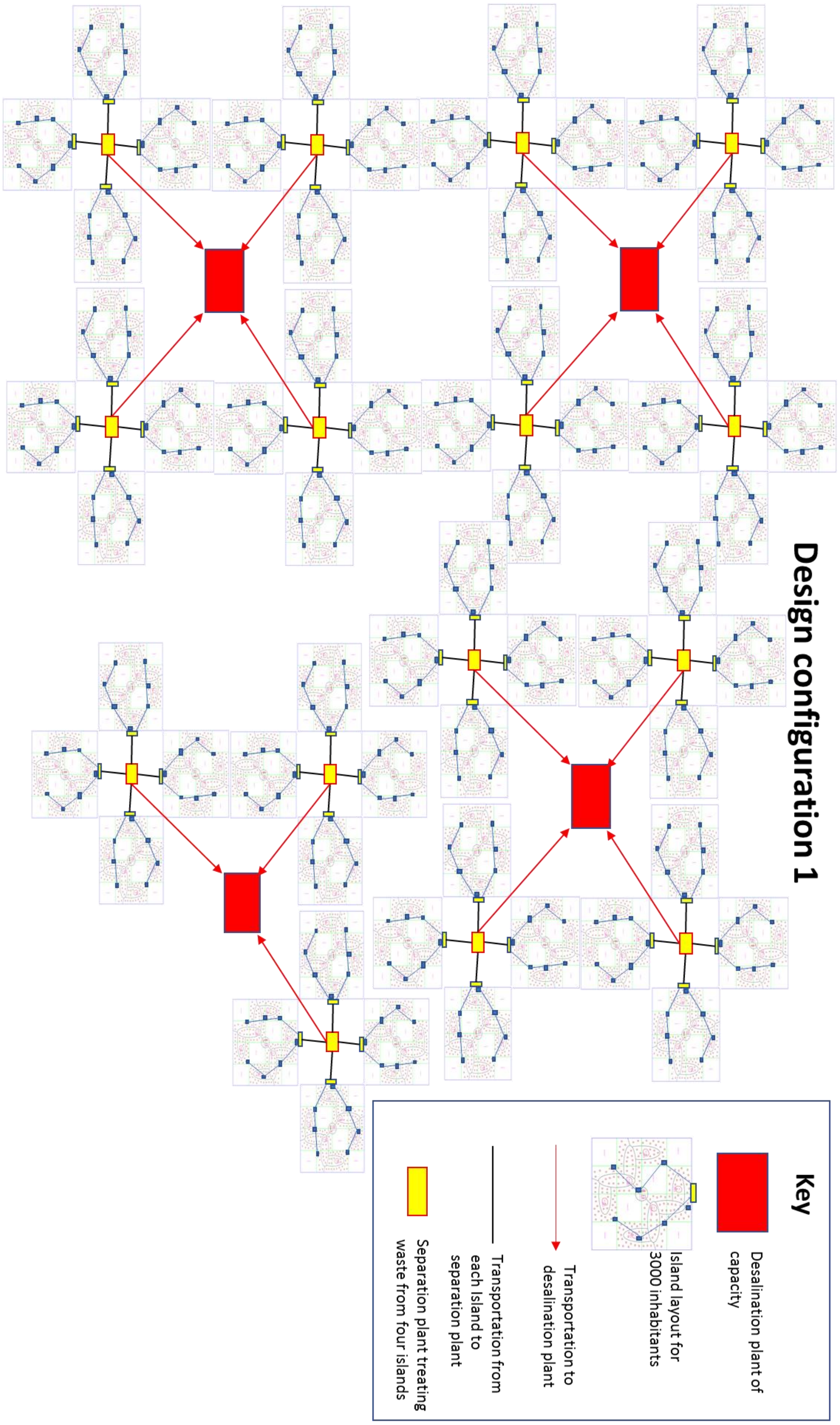


Figure 24 - Design confiuration 1

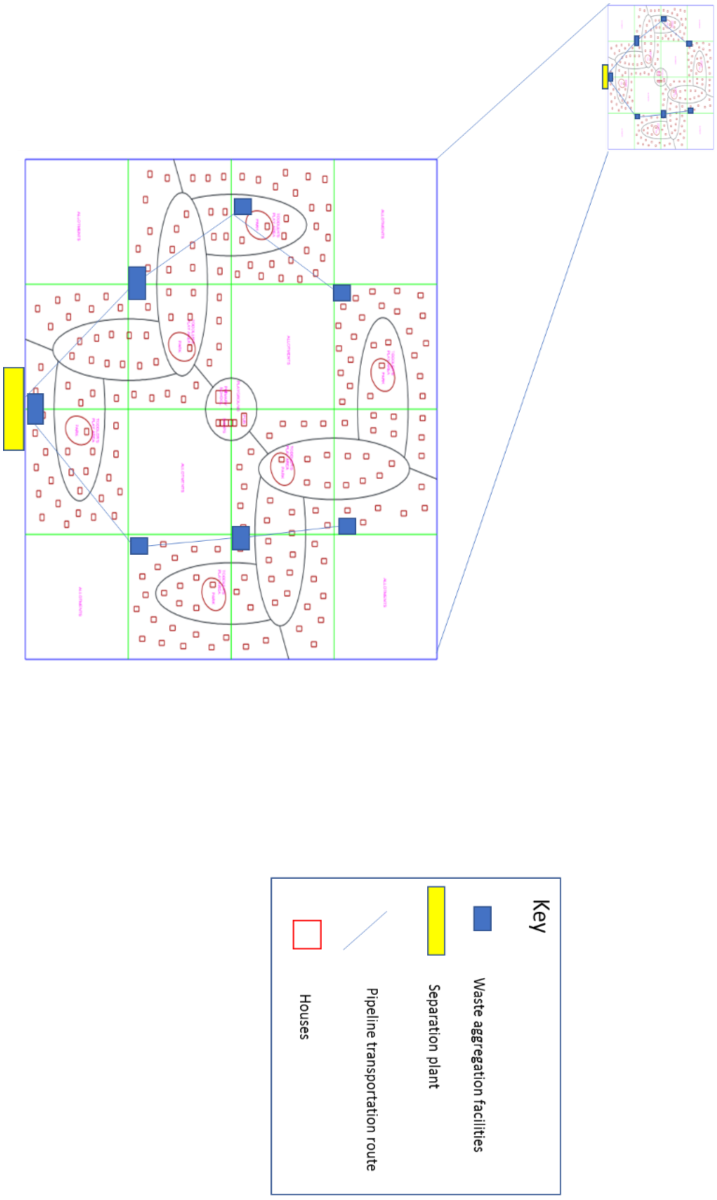


Figure 25 - Design confifuration 1 at island level

Configuration 4 Island view Island view

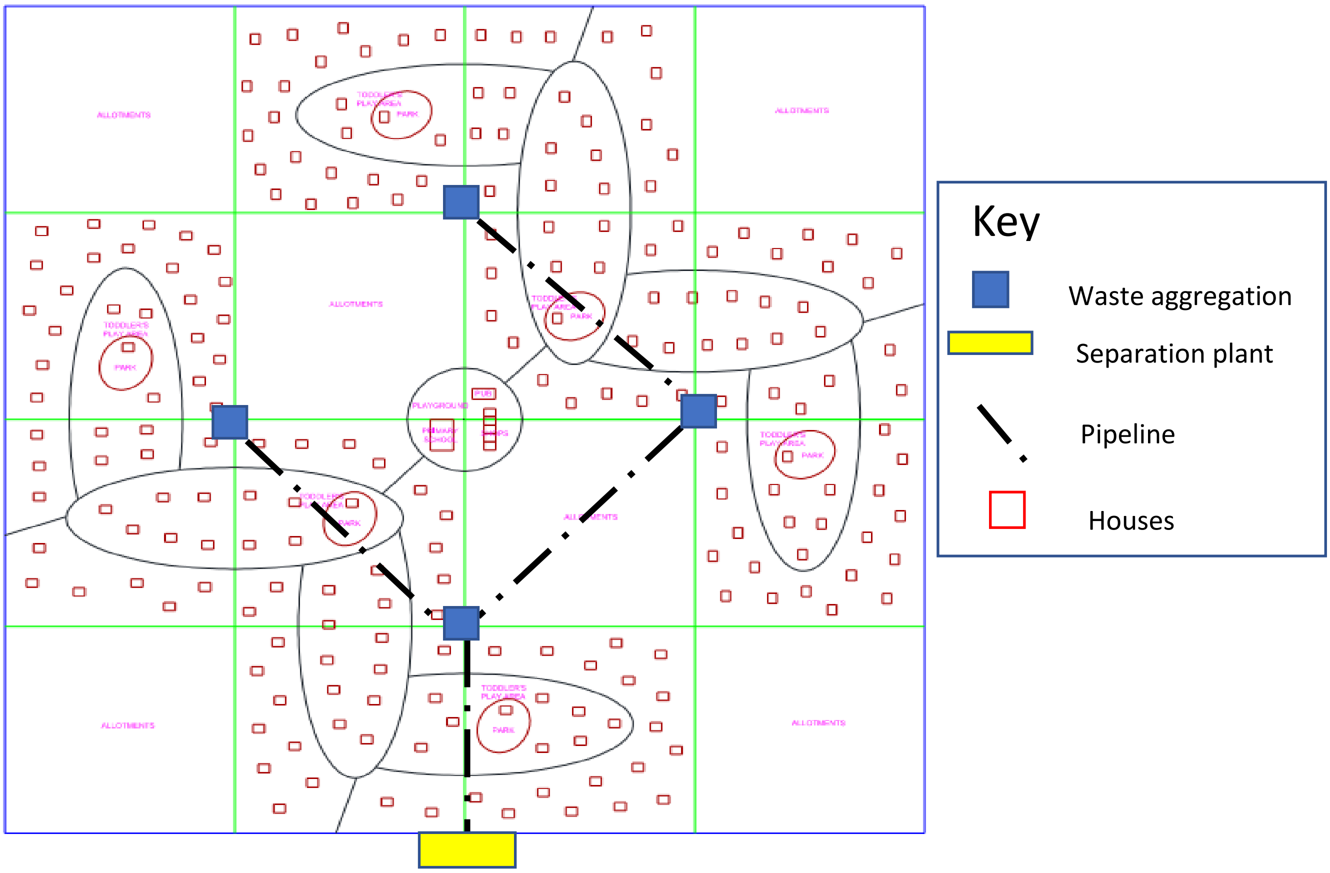


Figure 26 - Configuration 4 Island view Island view

Appendix A6: Design Configuration 3

Design configuration 3 (below) uses the “hexagonal towns” arrangement, however as seen in figure 4, this is a difficult arrangement to incorporate a waste aggregation and separation plant without increasing the length of pipelines. Further, this arrangement makes it very difficult to avoid ‘Allotments’ section which would likely require underwater pipes.

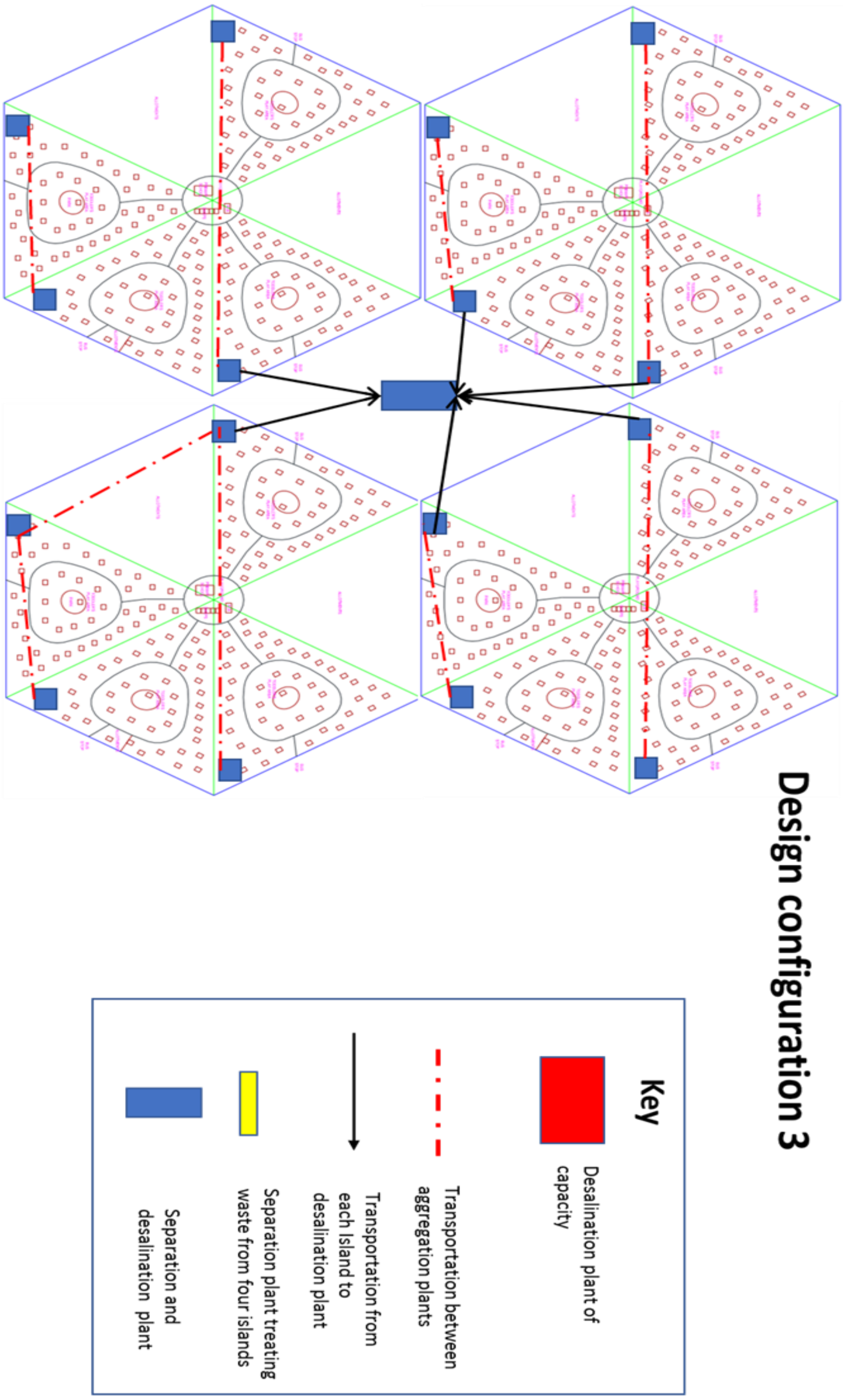


Figure 27 - Design configuration 3

Appendix A7: Flow rate extrapolation data

Table 7 - Flow rate extrapolation data table

No. of dwellings	Flow rate (litres/second)
1	2.5
5	3.5
10	4.1
15	4.6
20	5.1
25	5.4
30	5.8
50	8.147359455
60	9.214224872
100	13.48168654
200	24.15034072
300	34.81899489
400	45.48764906
500	56.15630324
600	66.82495741
700	77.49361158
750	82.82793867
800	88.16226576
900	98.83091993
1000	109.4995741
1100	120.1682283
1200	130.8368825
1300	141.5055366
1400	152.1741908
1500	162.842845
1600	173.5114991
1700	184.1801533
1800	194.8488075
1900	205.5174617
2000	216.1861158
2100	226.85477
2200	237.5234242
2300	248.1920784
2400	258.8607325
2500	269.5293867
2600	280.1980409
2700	290.8666951

2800	**301.5353492**
2900	**312.2040034**
3000	**322.8726576**

APPENDIX A8: Flow and pipeline Diameter calculation

Table 8 - FLow and pipeline Diameter calculation

Stage 1 transportation pipe calculation		
Volumetric flow rate for 750 dwellings (litres/s)	**Volumetric flow rate for 750 dwellings (m3/s)**	
82.82793867	0.082827939	
Required flow rate (m/s)	**Required Diameter (m)**	**Diameter (mm)**
1	0.324745757	324.7457574
Stage 2 transportation pipe calculation		
Volumetric flow rate for 3000 dwellings (litres/s)	**Volumetric flow rate for 1500 dwellings (m3/s)**	
162.842845	0.322872658	
Required flow rate (m/s)	**Required Diameter (m)**	**Diameter (mm)**
1	0.641166309	641.1663088
Stage 3 transportation pipe calculation		
Volumetric flow rate for 12000 dwellings (litres/s)	**Volumetric flow rate for 3000 dwellings (m3/s)**	
322.8726576	1.283	
Required flow rate (m/s)	**Required Diameter (m)**	**Diameter (mm)**
1	1.278110455	1278.110455

Appendix A9: Monthly Rainfall in Kiribati vs London

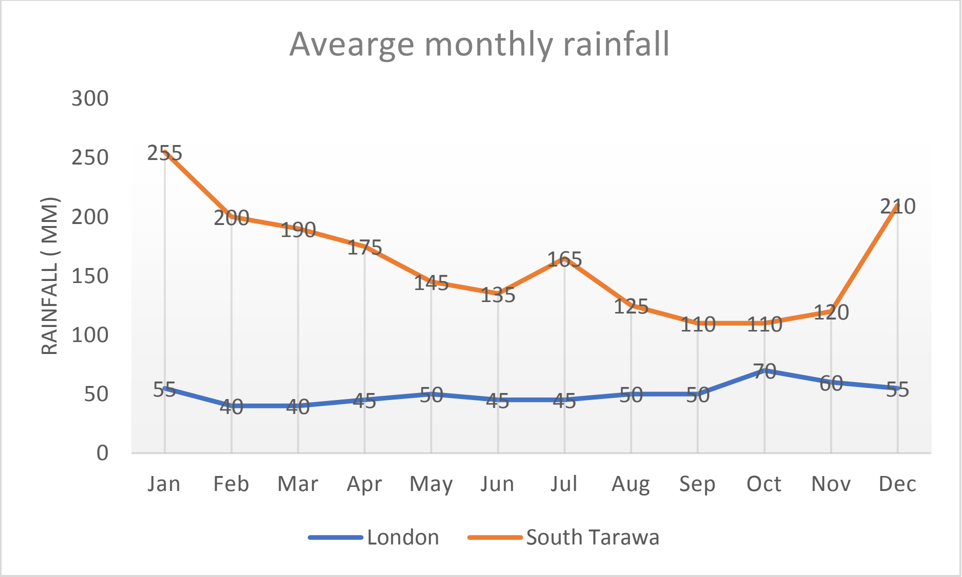


Figure 28- Rainfall in South Tarawa vs. London

As illustrated above, the volume of rainfall received in London is constantly below that of South Tarawa with South Tarawa receiving approximately five times what London receives between January and February.

Appendix A10: Costing estimation method for RO plant

The method of approach for establishing the cost was simple. Given a fruitful amount of information on current projects, capacity and cost of the Reverse Osmosis plant in particular, the capacities of these were scaled down to that required by this project and the cost extrapolated down. To account for non-linear factors in costing (particularly with economies of scale advantages) a weighting was used for the extrapolated prices in order to form the final estimation price. Lower plant costs were given a higher weighting as the price of these are more inclined to that of the required 8900m3 plant required with larger scales getting lower rankings. Prior to this however, as all projects were written off in various currencies and points in time, each project was scaled down to the required capacity (and hence the cost too) followed by a currency conversion to pounds using the conversion rate at the end of the year (for that particular year), then adjusted for inflation using the Bank of England's inflation calculator for the equivalent 2018 price.

As the table shows, only one project was found for the Multi-stage flash system. This was due to the fact that after much research, nearly all projects commissioned in the 21st century were Reverse Osmosis. This was due to the fact that MSF has been viewed by the industry as an old fashioned and one which requires nearly nine times the energy od RO; hence is to be slowly phased.

Table 9 - Cost estimation for RO plant

Reverse Osmosis Costing Method estimate					
Project	**Capacity per day**	**Actual cost current capacity**	**Scaled (to required 8,900 capacity) cost**	**Cost weighting (%)**	**Scaled cost in 2018 (£) – including 10% factor**
South Africa; Mossel Bay	15000	R200 million in 2011	R118.7million Ex. Rate -1 GBP:ZAR12.5202	25	12,485,721
Cyprus; Limassol RO:	40000	50 million euros in 2013	11.125 million euros Ex. Rate – EURGBP = 0.83	25	£11,434,614.4 (inflation averaged 2.4% a year)
Oman: Wilayat Diba RO	2000	$3.4 million in2011	$15.13 million Ex. Rate GBPUSD=1.5461	50	£12,887,703 (Inflation averaged 2.6% a year)
Overall cost					**£13,467,680**
Multi-Stage Flash Costing Method estimate					
Yanbu 3, Saudi Arabia	550,000	$1 billion in 2017	$16,181,818 Ex. Rate GBPUSD = 1.25	100	**£14,231,000** (inflation averaged at 3.3% a year
Multi-Effect-Desalination Costing Method estimate					
Manora Water Desalination plant, Pakistan	1136.5	$1.5 million in 2011	$11,746.590 Ex. Rate GBPUSD = 1.25	100	**£10,337,00**

References:

South Africa; Mossel Bay

Cost estimation source:

https://www.news24.com/Archives/City-Press/Top-desalination-plant-virtually-untapped-20150430

End of year exchange rate:

https://www.poundsterlinglive.com/bank-of-england-spot/historical-spot-exchange-rates/gbp/GBP-to-ZAR-2011

Inflation calculator:

https://www.bankofengland.co.uk/monetary-policy/inflation/inflation-calculator

Cyprus; Limassol RO

a. **Cost estimation source:**

https://www.desalination.biz/news/0/Cyprus-poised-to-tender-Paphos-SWRO-project/8793/ · http://www.desline.com/Limassol_Plant_Overall_Presentation.pdf

b. **End of year exchange rate:**

https://www.poundsterlinglive.com/bank-of-england-spot/historical-spot-exchange-rates/gbp/GBP-to-EUR-2013

c. **Inflation calculator:**

https://www.bankofengland.co.uk/monetary-policy/inflation/inflation-calculator

Oman: Wilayat Diba

a. **Cost estimation source:**

https://www.elsaie-engineering.com/details.php?id=491

b. **End of year exchange rate:**

https://www.currency-converter.org.uk/currency-rates/historical/table/GBP-USD.html

c. **Inflation calculator:**

https://www.bankofengland.co.uk/monetary-policy/inflation/inflation-calculator

Yanbu 3

a. **Cost estimation source:**

https://www.desalination.biz/news/0/Samsung-files-for-arbitration-against-SWCC-over-Yanbu-3-cancellation/8895/

b. **End of year exchange rate:**

https://www.poundsterlinglive.com/best-exchange-rates/british-pound-to-us-dollar-exchange-rate-on-2017-12-31

c. **Inflation calculator:**

https://www.bankofengland.co.uk/monetary-policy/inflation/inflation-calculator

Manora Water Desalination plant

a. **Cost estimation source:**

https://www.waterworld.com/municipal/technologies/article/16215892/desalination-plant-inaugurated-in-pakistan

b. End of year exchange rate:

https://www.poundsterlinglive.com/best-exchange-rates/british-pound-to-us-dollar-exchange-rate-on-2017-12-31

c. Inflation calculator:

https://www.bankofengland.co.uk/monetary-policy/inflation/inflation-calculator

Appendix A11: Vitrified pipeline cost estimation

Vitrified pipeline estimation of costs were made using the Hepworth play company (number one clean drainage brand in the UK) price estimations as of 1st March 2019. The pipelines listed here are in compliance with British Standard BS EN295 (Vitrified clay pipe systems for drains).

Consisted of extrapolating the price of 300 mm diameter pipe lines according to the percentage increase of diameter for the required pipes. As a safety measure all required pipelines will be increased by 20% than that required to accommodate total population to account for surface water run-off into the pipelines.

Table 10 - Vitrified pipeline cost estimation

Required pipeline diameter (x)	**Required (x) * 20%**	**Required-300 (y)**	**y/300**	**1+y**	**Price of 300mm per 2m length (£)**	**New price for 2m**	**Price per island (£) with 10% extra pipeline**
325	390	90	0.3	1.3	242.35	315.055	69,312.10
650	780	480	1.6	2.6	244.35	635.31	285,889.50
1300	1560	1260	4.2	5.2	245.35	1275.82	369,987.80
Sum of costs per island							725,189.40
Cost per island x Number of islands							**43,511,364.00**

Appendix A12: Simscape Simulation

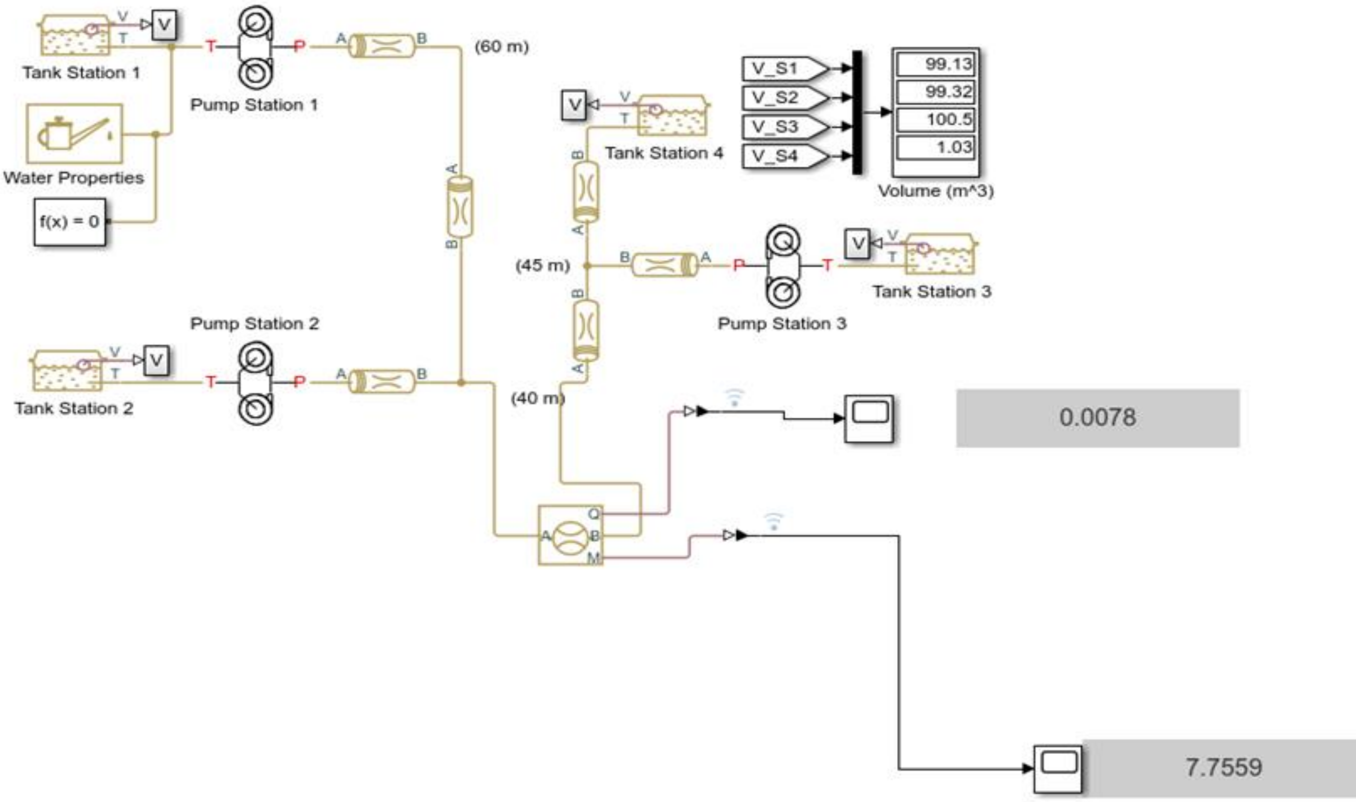


Figure 29 - Simscape simulation schematic

Appendix A13: Quantitative characteristics of various technologies

Technical specification	**Weight**	**Reverse Osmosis**	**Multi-Stage Flash Distillation**	**Multi-Effect Distillation (MED)**
Thermal energy (MW) dissipated in the Ocean per 10 Million Imperial Gallons per Day (MIGD) [50]	**10**	[✓ **(9)**]	**(3)**	**(4)**
Total Energy requirement – kWh per m^3	**9**	[✓ **(8)**]	**(2)**	**(5)**
Electrical energy Consumption kWh m^{-3}	**4**	**(4)**	**(5)**	[✓ **(8)**]
Amount of CO$_2$ produced per m^3 of water produced (Kg/m^3)	**15**	[✓ **(9)**]	**(2)**	**(3)**
Total Dissolved Solids increase in the reject brine compared with seawater baseline	**5**	**(4)**	**(8)**	[✓ **(8)**]
Area required (m^2/(m^3/hr$_{installed}$))	**10**	[✓ **(6)**]	**(5)**	**(4)**
Capital investment for required 8,900m^3/day capacity	**7**	**(3)**	[✓ **(4)**]	**(2)**
Lifetime of plant (years)	10	20/30y**(4)**	[✓ 40/50y**(5)**]	**(4)**
Modularity	**15**	[✓ **(9)**]	**(5)**	**(7)**
Technology maturity	**15**	[✓ **(8)**]	**(6)**	**(5)**
Total	**100**	**7.09**	**4.31**	**4.76**

The following matrix identifies key technical specifications with strong and important applicability specifically for this project. These have been arranged into three broad categories of energy consumption, harmful by-products and applicability for Kiribati. Each form of technology is ranked from 1 to 10, with 1 being a completely undesirable characteristic and 10 being the ideal.

As can be seen from the table, the Reverse Osmosis technology emerges a strong contender within the specifications attributed to applicability, particularly the final two specs. This is essential as a strong adaptability is required for the technology chosen to function in the given environment. Secondly, the technology maturity reduces the risk of encountering complications yet to be investigated. Even in developed countries such as the United States, this would cause a significant standstill in operation let alone a developing one like Kiribati.

However, there are areas of weakness particularly with the electrical energy consumption and the capital investment required for this.

Appendix A14: Net Present Value table of results

Table 11 - Net Present Value table of results

Year	Cashflows 1
0	- 82,000,000.00
1	4,500,000.00
2	4,725,000.00
3	4,961,250.00
4	5,209,312.50
5	5,469,778.13
6	5,743,267.03
7	6,030,430.38
8	6,331,951.90
9	6,648,549.50
10	6,980,976.97
11	7,330,025.82
12	7,696,527.11
13	8,081,353.47
14	8,485,421.14
15	8,909,692.20
16	9,355,176.81
17	9,822,935.65
18	10,314,082.43
19	10,829,786.55
20	11,371,275.88
IRR Hurdle Rate	**5.447%**
NPV at discount rate of 5%	**3,714,285.714**

As can be seen from the table above this hurdle rate is only achieved through an initial saving or revenue of £4.5 million resulting from this investment which continues to grow annually at 5% a year for the next 20 years. If the country is not able to achieve such results and falls short then the hurdle rate will decrease for the same period of 20 years. Alternatively, if they do exceed this revenue projection, then the hurdle rate can go up meaning even in high interest rate environments, this would still be just about profit making in the long run.

Appendix A15: Aggregated Infrastructure Depreciation method

Year		Total fee without depreciation	Total Fee to pay with depreciation
Year 1		4,100,000.00	4,100,000.00
Year 2		4,100,000.00	3,690,000.00
Year 3		4,100,000.00	3,649,000.00
Year 4		4,100,000.00	3,644,900.00
Year 5		4,100,000.00	3,644,490.00
Year 6		4,100,000.00	3,644,449.00
Year 7		4,100,000.00	3,644,444.90
Year 8		4,100,000.00	3,644,444.49
Year 9		4,100,000.00	3,644,444.45
Year 10		4,100,000.00	3,644,444.44
Year 11		4,100,000.00	3,644,444.44
Year 12		4,100,000.00	3,644,444.44
Year 13		4,100,000.00	3,644,444.44
Year 14		4,100,000.00	3,644,444.44
Year 15		4,100,000.00	3,644,444.44
Year 16		4,100,000.00	3,644,444.44
Year 17		4,100,000.00	3,644,444.44
Year 18		4,100,000.00	3,644,444.44
Year 19		4,100,000.00	3,644,444.44
Year 20		4,100,000.00	3,644,444.44
Sum		**82,000,000.00**	**73,395,061.73**

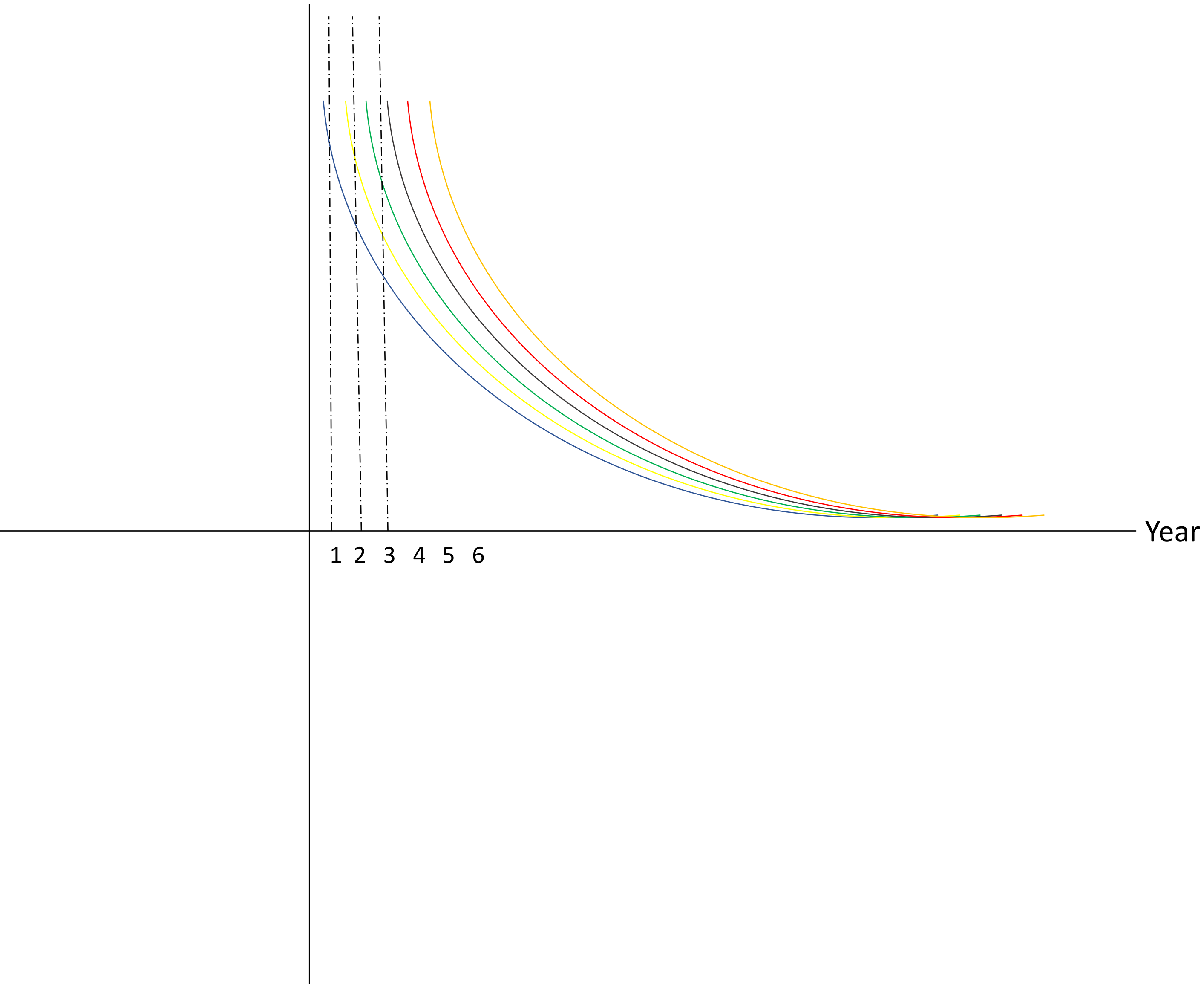
The aggregated reducing balance method compounded over the lifetime of the project has shown to yield a total cost of £73.4 million instead of the rounded up 82 million upfront cost. The Motivation behind this method is firstly to insert some good well given the circumstances of the country and its capacity to finance the project, and secondly to capitalise on the fact that parts of the project will begin depreciating as other parts are still being constructed therefore this loss in value can and should be captured in payments.

This model was created using a compounded depreciation rate of 10%. This was chosen as a subtle interpolation to that currently used for cars with an average life of 8 years. Therefore, with the assumption this project should last at least 20 years, an appropriate 10% rate was chosen.

The figure below illustrates this idea of having an aggregated and compounded reducing balance method for such a long-term project. For example, if we follow the graph from year one, it can be seen that the only depreciation required is that of the work from year zero which is taken away from the work or payments for year one.

The way to understand this is if we consider the project starting from year zero so if assuming the project Is split into 20 subsections (or years) in terms of cost, then we can start from year zero when construction begins. So considering after the first phase of year zero is complete, then the total cost for that phase is the full amount of £4.1 million. If we consider the next year; year one, after this phase is complete the cost would be equal to the standard cost of £4.1 million minus 10% as the cost of depreciation from the infrastructure completed in year 0; from the end of year zero to the end of year one. In year two, the cost of work will be equal to the standard £4.1 million, minus 10% of the standard cost of year one infrastructure, minus 10% of the current (already depreciated) cost of the infrastructure from year 0.
This goes on until the final payment but annual payments quickly converge to £3.64 million after year 4

Depreciation for various stages of project



Appendix A16: Project Risk Management

Risks to the project:

Table 12 - Project risks: Mitigation strategies monitoring table

Risk	Risk factors	Probability	Impact	Rating (PXR)	Mitigation actions	Status
Research	• Inaccurate or biased information obtained • Lack of appropriate technical detail • Too much time spent on research and side tracking on objectives	5	8	40	• Using reputable academic sources e.g. Science direct, Google Scholar and British Standard. • Refer to appropriate books or academic texts • Ensure clear and distinct objectives	
Resources	• Time • Supervisor appointments • Technical queries are not answered by product manufacturers or field experts	5	9	45	• Ensure continual reference to project monthly plans and update as appropriate to avoid running out of time. • Consult supervisor on progress for feedback on the best way to adapt • Ensure meetings are communicated prior and in good time to • Make contact as early as possible even	

					when likelihood of finding information elsewhere is high -	
Data storage and safety	- Data Loss	2	10	20	- Continuously save work and send through email every hour or less - Ensure copies are kept on University computers or USB drives as often as possible	
Quality	- Quality of work and analysis doesn't meet expected standard	9	10	90	- Consult supervisor regularly on work progress and ensure careful justification of methods and assumptions (taking guidance from past literature where appropriate) - Make regular reference to guidance session resources and marking criteria	

The above project impact matrix has been designed using a scale of 1 to 10; given further context in the table below.

Table 13 - Risk impact definition table

Probability scale – this scale ranges from 1 to 10 with values defined below	
Value	**Definition**
1	Almost certain to not happen
5	50/50 chance of occurrence
10	Almost certain to occur,
Impact scale – this scale ranges from 1 to 10 with values defined below	
Value	**Definition**
1	very minor or negligible impact on project deadline
5	Likely to impact quality and/or deadline attainment which may result in a 5% deviation from target grade
10	has significant impact on project deadline or outcome which will result in 10%+ grade deviation from target grade

Risks within project: Mitigation strategies

Table 14 - Risks within project monitoring table

Risk	Risk factors	Probability	Impact	Rating (PXR)	Mitigation actions
Social	• Design fails to be accepted by locals • Design gets in the way of daily life	4	6	24	• Ensure thorough investigation of daily life for inhabitants and activities which may be impacted are noted
Economic	• Design fails to at least generate more income than it consumes • Project adds to the long-term debt of the country • Project improves trade activities	3	7	21	• Identify adequate funding methods using previous donations or projects as case studies to justify costs and methods of funding
Environmental	• Project doesn't degrade the environment by more than 25% (how would this be measured) • Doesn't consume environmental resources used in subsistence agriculture	4	7	28	• The inputs and outputs of the process would have to be scrutinised for their source and their disposal

Political	• Does not interfere with political laws or agenda	6	5	30	• Research current laws governing the country and ones which have influenced previous projects
Moral	• Project doesn’t exploit resources or vital amenities in one area or region for the benefit of another	4	5	20	• Ensure critical analysis into resource impacts for all stakeholders
Legal	• Design doesn’t comply with international guidance	4	10	40	• Ensure appropriate legal guidance is looked at depending on the definition of the project

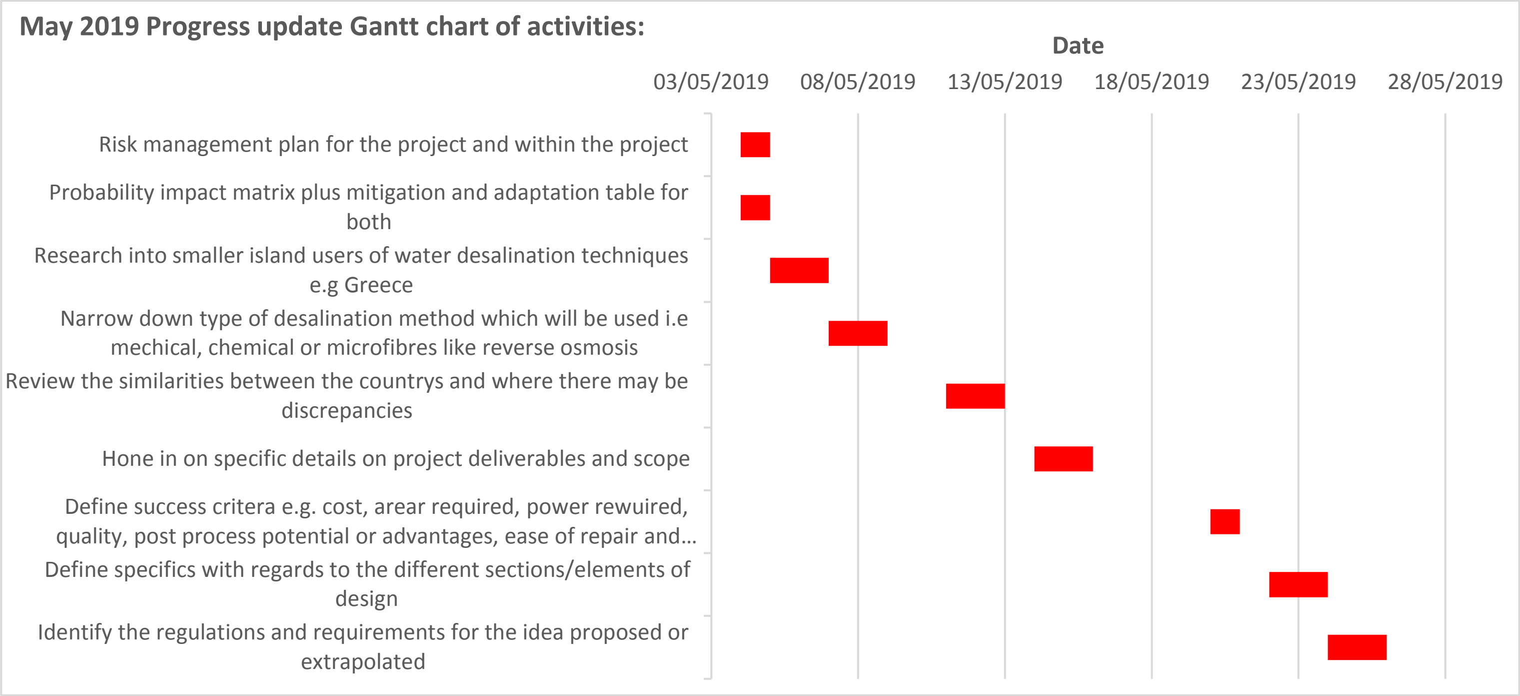
The above project impact matrix has been designed using a scale of 1 to 10; given further context in the table below.

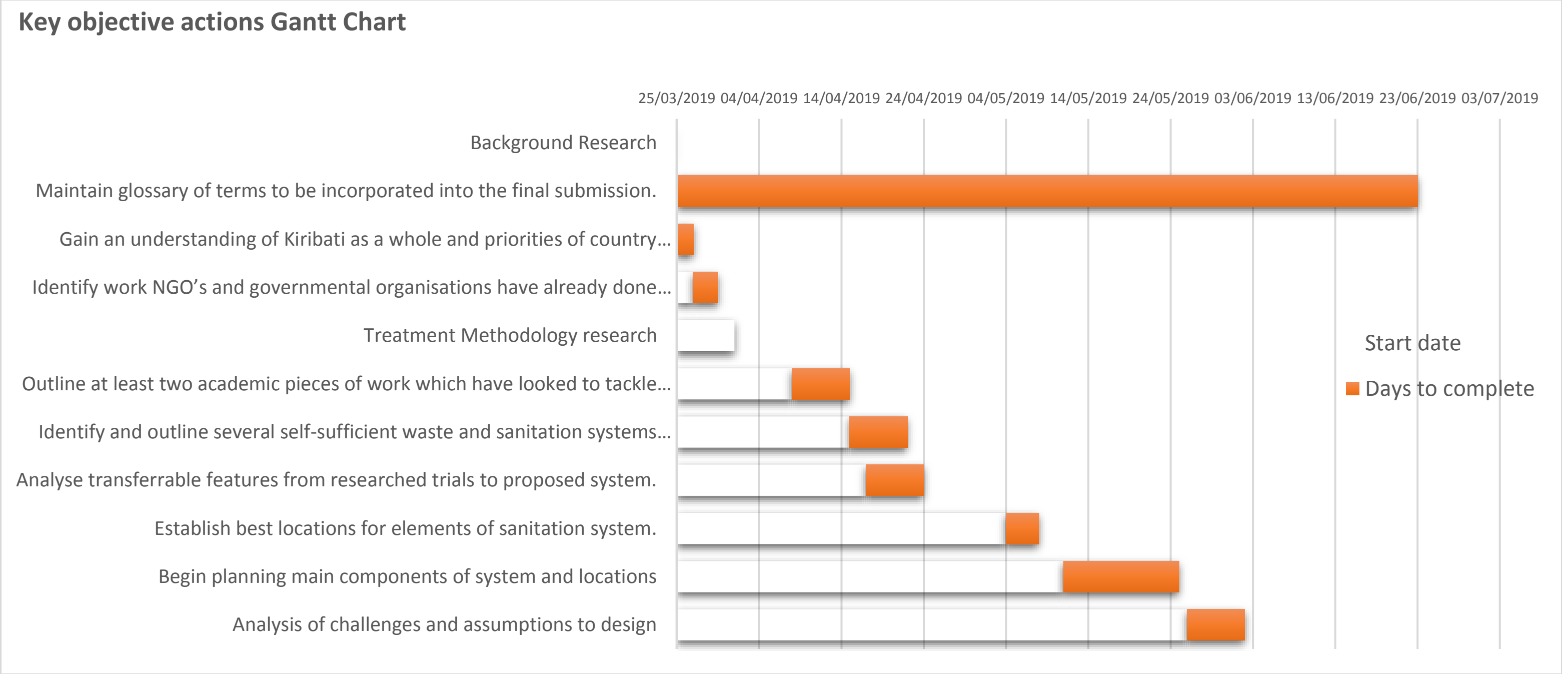
Table 15 - Risk impact definition table

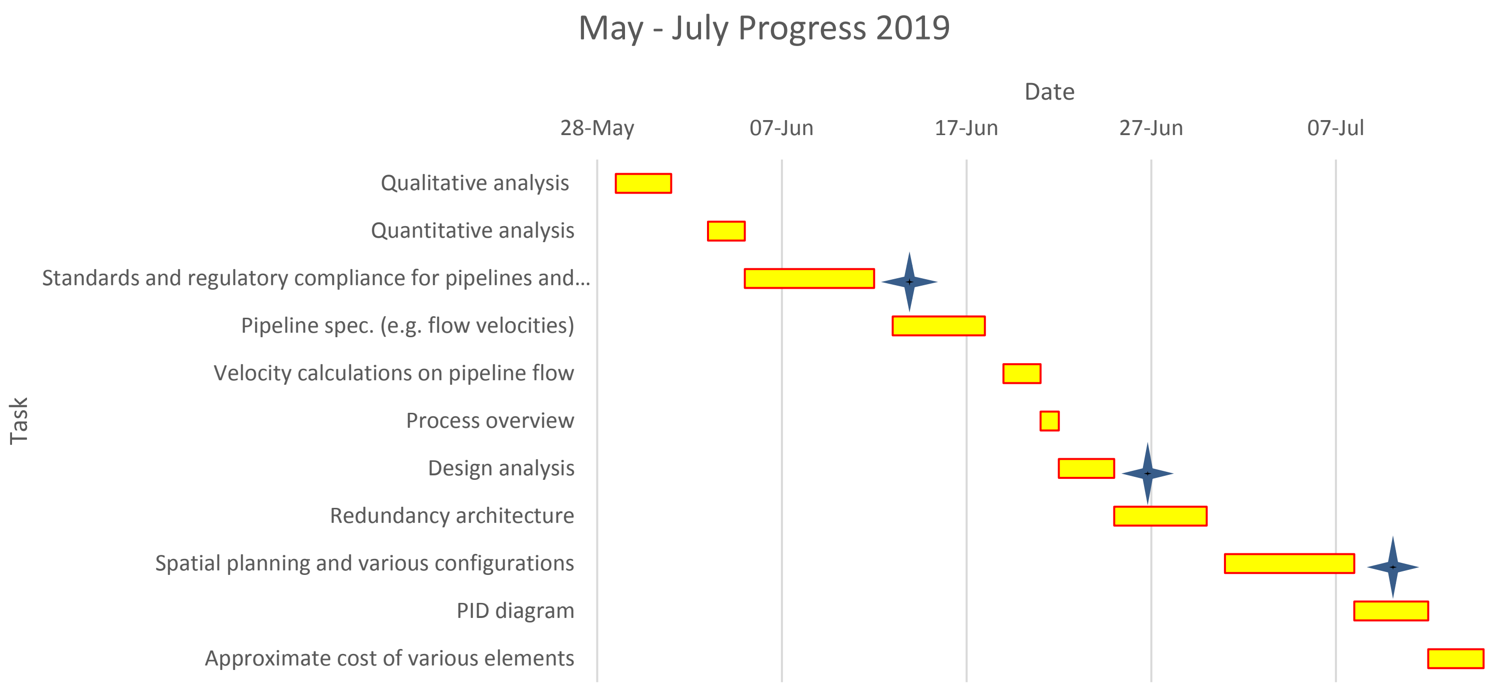
Probability scale – this scale ranges from 1 to 10 with values defined below	
Value	**Definition**
1	Almost certain to not happen
5	50/50 chance of occurrence
10	Almost certain to occur,
Impact scale – this scale ranges from 1 to 10 with values defined below	
Value	**Definition**
1	very minor or negligible impact on project deadline
5	Likely to impact quality and/or deadline attainment which may result in a 5% deviation from target grade
10	has significant impact on project deadline or outcome which will result in 10%+ grade deviation from target grade

Appendix A17: Gantt Charts from Progress reports:

Progress reports can be found on Moodle submissions.


May 2019 Progress update Gantt chart of activities:


Key objective actions Gantt Chart


May - July Progress 2019
Date
28-May
07-Jun
17-Jun
27-Jun
07-Jul
Task
Qualitative analysis
Quantitative analysis
Standards and regulatory compliance for pipelines and...
Pipeline spec. (e.g. flow velocities)
Velocity calculations on pipeline flow
Process overview
Design analysis
Redundancy architecture
Spatial planning and various configurations
PID diagram
Approximate cost of various elements