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Desalination Concentrate Disposal: Ecological Effects and Sustainable Solutions

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Faculty Adviser: Dr. Elizabeth Bruch

Essay completed in partial fulfillment of the requirements for graduation with Global Honors, University of Washington, Tacoma

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ABSTRACT

Freshwater availability is a growing global concern, and desalination is often presented as the solution, but from this important technology comes issues of toxic waste. Ecosystems are delicate areas that contain species adapted to that specific location, and any chemical or physical changes can disrupt the fitness of species. The concentrate byproduct waste from desalination plants is toxic to species if the concentrate is not compatible with the receiving water body. A critical review of scientific articles, industry-leading books, conversations with industry experts, and information from the American Membrane Technology Association conference was used to analyze the current knowledge. Species health and environmental conditions are affected by chemical changes, such as an increase in salinity levels, which may be lethal or detrimental to growth. Desalination process types determine different chemical concentrations and physical characteristics, and depending on the receiving water body, the concentrate needs alteration to be compatible with the receiving water body. Solutions vary by location, but possibilities include beneficial ecological options that restore habitat water volume, economic benefits that use the concentrate, and technical changes that blend the concentrate more effectively in surface water outfalls. Identifying the potential ecological issues from concentrate waste and developing sustainable practices before harm is caused will protect valuable ecosystems that connect all life on earth.

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ABBREVIATIONS

AMTA	American Membrane Technology Association
Ar	arsenic
AWWA	American Water Works Association
B	boron
BWRO	brackish water reverse osmosis
^{o}C	degree Celsius
Ca	calcium
$CaCO_3$	calcium carbonate
Cd	cadmium
CO_2	carbon dioxide
Cr	chromium
Cu	copper
$CuSO_4$	copper sulfate
EC	electrocoagulation
Fe	iron
g	grams
H^+	hydrogen atom (proton)
H_2O	water
hr	hour
km	kilometer
L	liter
m	meter
Mg	magnesium
mg	milligram
mL	milliliter
Mo	molybdenum
MSF	Multistage flash evaporation
NaCl	sodium chloride
NaClO	sodium hypochlorite

$NaHSO_4$	sodium bisulfate
NF	nanofiltration
NH_3	ammonia
Ni	nickel
O_2	oxygen
OrgC	organic carbon
Pd	lead
pH	potential of H^+ atoms available
ppt	parts per thousand
RNG	renewable natural gas
RO	reverse osmosis
shock ED	shock electrodialysis
SO_4^{2-}	sulfate
Sr	strontium
SWRO	seawater reverse osmosis
μL	microliters
W	Kendall's W statistic (Coefficient of Concordance)
ZLD	Zero Liquid Discharge
Zn	zinc
π=MRT	osmotic pressure formula (π = 3.14, M = molarity, R = ideal gas constant, T = temperature in Kelvin)

INTRODUCTION

Many regions in the world take an ample supply of clean freshwater for granted, where water has always been available on demand. In contrast, many regions of the world lack the minimum requirements for clean water, and some 844 million people worldwide are without an available drinking-water service (WHO 2018). Unfortunately, the access to the fresh water situation will worsen. An increasing population is stressing water sources, and climate change is altering the distribution of the hydrologic cycle, the natural movement of water, to make some water sources unreliable (Hagemann *et al.* 2013). Climate change will warm areas to generate more evaporation, and it will reduce rainfall in some areas while increasing it in others (Hagemann *et al.* 2013). In areas predicted to increase in rainfall, tapping into freshwater resources is usually not the problem. In contrast, areas that are predicted to decrease in rainfall face greater challenges in the global problem of water scarcity. The World Health Organization (2018) predicts that by 2025, half of the people on earth will reside in a water-stressed area. Water is a vital resource to facilitate life and is used in excess to raise the standard of living. Without water, all life ceases to exist. Thus, a reduction in water availability not only makes life more difficult, but it may also create conflict to secure such a valuable resource. People need water, and a speedy solution is paramount.

A leading solution to providing freshwater is with desalination technology, which is the process of removing salt from water. There are various processes of desalination that extract drinking water from a saline source, such as the sea. With a large amount of the population living near the sea, and such a vast resource available, desalination of seawater is an obvious solution. Desalination currently only produces about 1% of the freshwater used today, but production will double by 2030, and production growth is expected indefinitely (Voutchkov 2016). Currently, there are over 18,000 desalination plants in operation globally that utilize two main processes, membranes which separate through pressure, and thermal evaporation that uses heat (Voutchkov 2016). The energy required for desalination is a limiting economic factor, but the technology has proven to be a reliable supply of freshwater to areas in need.

Ecological concerns are secondary to providing economically viable water in an extremely competitive industry, and the best solution would produce incalculable profits (Villiers 2000). One of the biggest concerns regarding economic feasibility comes down to energy, and desalination requires an enormous amount compared harvesting from a freshwater source. The energy difference adds greenhouse gas emissions, and trying to solve a related climate change issue, while adding to the cause of climate change, is futile. Therefore, the energy required creates another indirect ecological effect which must be considered, but volumes of other research address this topic. There are other ecological effects from the process of desalination too. The intake system can draw small organisms into the pipe, reducing the bottom of the food chain. Membranes need frequent replacement, which adds to landfill waste and resources spent on production. Future research about effective solutions to these, and other problems need to be addressed, but they are not within the scope of this research.

When fresh water is extracted from saline water, the saline water increases in concentration. This concentrated saline solution, known as concentrate, is generally of little economic or practical use, and it is considered a waste byproduct that needs to be disposed of back into the natural environment. Pretreatment chemicals used in the process may also end up in the effluent waste stream, which creates an additional problem for disposal. Location is key for disposal, and disposal may harm species or degrade the environment. Finding effective solutions for concentrate disposal is vital for local and overall ecological health. Therefore, each desalination plant requires a thorough analysis of disposal options, based on numerous factors, and this research identifies the issues and presents solutions that minimize ecological harm and develops sustainable practices. The issues for decision-makers vary. The private sector may be focused on costs, community members desiring water access, activists concerned with environmental health, and government officials worried about getting reelected, needing the community and the private sectors' support. With a background in environmental science, and through an ecotist lens, which values all species, this research will frame the global issue of concentrate disposal from desalination plants on the environment.

METHODS

A critical literature review was conducted, using electronic database access provided by the University of Washington (UWT). Relevant articles that were peer-reviewed and based on quantitative analysis provided the strongest supportive evidence. Industry-leading books on desalination helped to explain the fine details of the process. In addition, published articles and handouts were analyzed from industry leading organizations, such as the American Membrane Technology Association (AMTA) and the American Water Works Association (AWWA). Also, a case study of Cape Town, South Africa that has turned to desalination was examined, using local news sources, organizations, and government websites to evaluate disposal options.

Conferences and seminars were attended to support research. The 2017 Northwest Climate Conference in Tacoma, WA emphasized changing water availability and adaptation. The AMTA and AWWA held a joint annual conference at West Palm Beach, FL in 2018 that premiered desalination membrane technology, which provided discussions with industry experts, presentations of experiments, and the latest product solutions. At UWT, relevant science seminars also provided insight. The collection of knowledge was organized and analyzed.

The research was performed over the course of a year through the Global Honors Program at UWT. A proposal was submitted, and this was awarded the Bamford Fellowship. Funding was provided through the Bamford Fellowship and UWT's conference and training fund. This research was in collaboration with Krystal Hedrick, that studied restoration of water resources, and Dr. Elizabeth Bruch that advised the collaborators' research, emphasizing a social framework to water access. This research sought to answer the following research questions:

- How is the concentrated byproduct from desalination affecting ecological systems?
- How can any harmful ecological effects be reduced or eliminated?

DESALINATION: PROCESSES, CONCENTRATE, & DISPOSAL

Process Types

There are two main types of desalination: Membranes and distillation (See Appendix A). Both processes need a substantial amount of energy, but they use it in different ways: Membranes use pressure, and distillation uses heat. Determining the desalination process depends on numerous factors, such as the source water, the amount of potable water needed, overall quality desired, energy and chemical availability, and disposal methods available (AMTA 2007c). These factors then influence what pretreatment is needed, and the concentrate's salinity and physical properties will then reflect the process used.

Membrane processes use pressure on a saline solution to diffuse H_2O molecules across a semipermeable membrane while keeping the salts and contaminants in the feed water. Most desalination plants use membrane technology, such as reverse osmosis (RO), nanofiltration (NF), microfiltration (MF), ultrafiltration (UF), and electrodialysis (ED). Membrane processes are less energy intensive than distillation methods. Each type of membrane uses a different membrane permeability, which operates at different pressures, are ideal for various types of source water, and have different ranges of permeate recovery amounts (Voutchkov 2014).

In a thermal distillation plant, heat is applied to boil saline water, evaporating H_2O as vapor and then condensing it into liquid water. The thermal energy required is the main drawback in economic costs and greenhouse gas emissions. Due to the high cost of energy, these systems are common in the Middle East, where oil is abundant. The main distillation methods are Multistage flash evaporation (MSF), Multieffect distillation (MED), and Vapor compression (VC). Each process produces a quality product, but these systems only get about 25-50% recovery rates, the ratio of freshwater extracted (AMTA 2007c).

Concentrate Properties

The concentrate chemical composition from desalination plants varies at each location, as the source water contains its own contaminants. These contaminants may be organic microbes, minerals from local geologic substrates, and pollutants from nearby anthropogenic activities, etc. Pretreatment chemicals include antifoulants, antiscalants, coagulants, and a strong acid or base for cleaning (See Appendix B). The process itself affects the byproduct, such as the saline concentration or temperature of the solution, etc. Even the equipment used may add elements to the concentrate. Chemicals and physical properties have varying effects on the environment. Salinity is the number of salt ions dissolved in a volume of water. The salinity of the concentrate depends on the initial source water concentration and the recovery rate of the process type (recovery rate % = $\frac{\text{volume of fresh water produced}}{\text{volume of intake water}} \times 100$) (Voutchkov 2014). While there is a technological race to increase recovery rate, generating more valuable fresh water product, a higher salinity concentrate is also generated.

The salinity and properties of the concentrate dictate how the waste byproduct interacts with the environment. The higher concentration of salinity, the higher the density, which causes it to sink below a less dense solution. The dense solution sinks to the ocean floor and expands, where dispersion mixing decreases with greater depth (Cooley *et al.* 2013). In contrast, the addition of cooling water from MSF lowers the concentration, and therefore lowers the density, and with the higher temperature of the discharge, the discharge may float on the receiving water surface (Lattemann and Höpner 2003). Changes in temperature affect the amount of dissolved oxygen, with higher temperatures containing less oxygen. The temperature change from RO is negligible since heat is not applied, but the concentrate may be blended with heated water from other industrial processes (Cooley *et al.* 2013). The main concern of temperature differences is with distillation operations that are heat dependent, and the concentrate may be 10-15^oC above the receiving water ambience, which is even after being diluted and cooled (Münk 2008). Naser (2015) found a difference of 14^oC higher than ambience about 400m from an MSF plant. An advanced cooling system that reduces the temperature to the same as the receiving water is a vital solution when considering a distillation operation.

The source water typically undergoes pretreatment to prevent fouling and scaling, which is when the membranes get plugged up from contaminants (Voutchkov 2014). Pretreatment chemicals depend on the process and source water, and these may remain in the effluent plumes. However, advancements of new techniques may greatly reduce the need for pretreatment, such as adding an NF membrane, a shock ED, or using electrocoagulation (EC) (Kabarty 2016, Deng *et al.* 2014). Shock ED separates ions with low voltage electricity rather than pressure (Deng *et al.* 2014). EC creates a chemical coagulant from the metal anode, undergoing dissolution and hydrolysis reactions, that isolates coagulants in several ways (Kabarty 2016). These electrical techniques, if used with renewable power, may be a major technological sustainable solution, preventing chemicals in the environment by not using them initially.

Naturally occurring metals and compounds of seawater, such as Mg, B, Ca, and SO_4^{2-}, that remain in the waste will increase in concentration (Cooley *et al.* 2013). Furthermore, distillation component parts may corrode from seawater, releasing Cu, Zn, and Ni, while stainless steel from the RO process releases metals of Fe, Cr, Ni, and Mo (Cooley *et al.* 2013). Alshahri (2017) researched heavy metals in the Arabian Gulf, comparing desalination outfall locations to nearby natural locations, and found elevated levels of Cu, Cr, Ar, and Sr, while Naser (2015) also found elevated levels of Cu, Cd, Pd, Zn, and NH_3^+.

Disposal Options

All desalination plants create a concentrated byproduct that needs a solution for disposal. Figuring out a viable disposal option is so critical, that Dr. Robert Reiss of Reiss Engineering states, “If you don’t have a concentrate disposal, you don’t have a budget” (informal roundtable discussion, March 10, 2018). There are many factors that determine the best disposal option, but in most locations, not all options are available. The common ways to dispose of concentrate are surface water discharge, sewer disposal, deep well injection, land application, evaporation ponds, zero liquid discharge, and some other lesser used methods (See Appendix C).

Sometimes there is a lack of disposal options, and other times there are several to choose. When more than one option is available, regulations should defer the decision to the least environmentally impactful, or if available, one that may benefit the environment. Typically, there is an extra cost associated with doing what is best for the environment, and regulations should also provide tax incentives to mitigate the difference between options. The initial investment is often a challenge to overcome, especially when already investing in a major desalination plant. A wetland in Mexico, the Ciénega de Santa Clara, is currently used for concentrate disposal, aiding a valuable ecosystem, with no detrimental effects reported (Arizona 2011). All Californian desalination plants in development are designing an ocean or estuary disposal (Cooley *et al.* 2013). Government assistance for an ecological benefit, such as wetland application or adding to an overdrawn river, is more than justified because it also enhances society through recreational activities, property values, and environmental health, such as clean air through increased biomass production.

CASE STUDY: CAPE TOWN, ZA

Cape Town, South Africa is a prime example of drought greatly affecting water access. Conditions have reached critical levels, and the term Day Zero is known as when Cape Town will run out of water. A massive conservation effort has delayed Day Zero till 2019. The government has imposed a limit of 50 L/day of water per person (Evans 2018), while an average person in the U.S. uses about 340 L/day (USGS 2018). Michael Kiparsky, a director of the Wheeler Water Institute at UC Berkeley, proclaims the situation of, "Cape Town as a warning shot for us. What we can see is that it's very possible for water crises, which emerge all the time around the world, to get close to the point of real, massive human disaster" (Simon 2018).

The solution has been a rush to build at least seven SWRO desalination plants, which will generate 2.0×10^{8} L/day by July 2018 (The Source 2018), but this falls well short of a city that had used 1.1×10^{9} L/day (Simon 2018). The plants are designed to use diffusers on the outfall (The Source 2018), but disposal is an expensive part of construction costs, so the diffuser option may be neglected in a rush to get water now and to keep costs down. In addition, modeling analysis and due process are discounted in such situations. Relying only on desalination will not be sufficient, and Cape Town is an example of a place needing to diversify its water sources, because as Lesley Green of the University of Cape Town states, "It doesn't make sense to me to solve one ecological problem by creating a whole lot more" (Simon 2018). A difficult situation is compounded by poor planning and resource use, potentially harming valuable ecosystems.

Cape Town is in the middle of the west coast region, and there are two marine bioregions near the shore of Cape Town (Agulhas, South-western Cape) (Griffiths *et al.* 2010). The seven desalination plants around Cape Town will dispose into either bioregion. The western coastline is shallow, and vast research has identified the west coast with the greatest richness of species because 83% of all marine species are found in less than 100m depth (Griffiths *et al.* 2010). The northward current from Antarctica is frigid, which will require greater osmotic pressure, and therefore, more energy for desalination, as temperature is a variable in osmotic pressure (π=MRT) (Swartz *et al.* 2006). Highlighting source water challenges, the high winds in the area cause up-welling of nutrients, making the water quality not consistent, and this will require higher amounts of chemicals to prevent fouling, while the south and east coast has warmer temperatures and fewer nutrient levels (Swartz *et al.* 2006). Unfortunately, Cape Town's location prevents harvesting from a more reliable and less expensive to process source water, with mountains and distance between this better source water providing too great an obstacle.

Disposal using diffusers still has an ecological effect, and there are regulations in Cape Town that monitor water industry development (Swartz *et al.* 2006). About 23% of the coast in South Africa is considered a protected area, but there is minimal enforcement from the government to protect the marine areas, and only 9% of the protected area receives full enforcement (Griffiths *et al.* 2010). Instead of ocean discharge, Cape Town could use wetland application. Most of the 343 estuaries in South Africa are on the east coast, and the remaining 51 estuaries on the west coast are too far from Cape Town, except for the Diep estuary (Griffiths *et al.* 2010). Desalination plants on the northern side of the city (Granger Bay, Hout Bay) could consider discharge into the Diep estuary to support a vital habitat. The Diep River flows through the estuary and into the sea in the winter, but in summer the river runs dry due to low rainfall, and the estuary becomes landlocked and hypersaline (Milgard and Scott 2010). Even though the Diep estuary is seasonal, the natural hypersalinity by evaporation makes this a potential fit to support species year-round, connecting the estuary back to the ocean, especially with more than one plant discharging into the estuary (See Appendix D).

ECOLOGICAL EFFECTS

How is the concentrated byproduct from desalination affecting ecological systems?

Ecological effects range from anything that reduces at least one individual species fitness to interactions on a global scale (Molles 2016). While change is constant, typically, change happens very slowly in the natural world, such as geologic creations of mountains or evolutionary shifts. Species have evolved over a long period of time, under relatively stable conditions, which has helped species to fulfill certain niches in the food web or location (Molles 2016). Ecologic systems are highly integrated and full of complex interactions. Most studies have found negative impacts to environmental conditions from desalination plants (Cooley *et al.* 2013), and this may come from pollution through pH differences, how the concentrate flows, heavy metals, and deoxygenation, all of which can influence species and overall diversity.

Chemical Factors

pH

pH is the potential of H^+ atoms available, ranging on a scale of 0 (acidic) to 14 (alkaline), and can be found using either ($pH = - \log [H^+]$) or ($[H^+] = 10^{-pH}$). The pH of intake water is often manipulated to make the desalination process more effective when certain particles or temperatures are encountered, such as increasing the pH to 10-11 to make the rejection of boron easier when water temperatures are high (Voutchkov 2014). Before the concentrate is released, the pH is usually adjusted to match the water body (Voutchkov 2014), but it may not be in all locations, nor exactly match the ambient when adjusted. Even a slight pH difference will generate different chemical concentrations that species may be temporarily or constantly subjected to in the outfall location. The ocean has a stable overall pH of 8.1 today, which is down from a historic level of 8.2 due to ocean acidification (NG 2017). Since pH is a log scale, the lowering of 0.1 pH is a 25% difference in H^+ ions (NG 2017). Even this pH change is well known to have detrimental effects on species because required ions, such as calcium from $CaCO_3$ for building shells, are not as readily available (NG 2017). Therefore, the pH differences of concentrate versus the sea represent a problem for species, both in available required chemical compounds, but also in toxic compounds that may be present in much greater concentrations than species have adapted to biologically process.

Concentrate Movement

When emitting the waste back into the ocean, diffusers mix and spread out the waste more equally than emitting from a single point source (Cooley *et al.* 2013). Developers are increasing diffusers into the design of new desalination plants globally (Cooley *et al.* 2013). Blending the waste helps flora and fauna not be exposed to high concentrations of pollutants that could be detrimental to species' health. Despite the benefit from diffusers blending the waste, the concentrate will still create a plume and sink to the ocean floor and expand (See Appendix E). There also remains a possibility of any contaminants in the waste accumulating in the sediment. The toxins that are emitted may not be biodegradable. Toxins may remain in the environment and could eventually elevate in concentrations unhealthy to flora and fauna species.

In Australia, an experiment to determine concentrate movement put dye into the waste. The concentrate was witnessed to initially rise as it exited upward, but then sank towards the seafloor and expanded outward of up to 1.5km (Khan 2007). The concentrate can fill up channels and reduces mixing, causing stratification (Khan 2007).

Reiss explains that deoxygenation does not usually occur in the desalination process, except in the case with excess sodium bisulfite added to remove free chlorine (See Appendix B).

Whatever oxygen content the source water contained remains in the concentrate. However, it is the stratification of layers that causes deoxygenation because O_2 is used in respiration by species, and the prevention of vertical mixing does not allow the replenishment of O_2. The source water may contain rich amounts of organic carbon material, which gets digested in organisms and released as CO_2 gas (OrgC + O2 $\rightleftharpoons$ CO_2 + H_2O) (Hemond and Fechner 2015). Low dissolved O_2 levels have been detected in proximity to outfalls in shallow bays, such as in Perth, AU (Cooley *et al*. 2013). Also, the new constant flow of organic material may cause a bacterial bloom, with the respiration consuming O_2 in the process, and depleting the available O_2 for species naturally present.

Temperature differences can greatly affect the species within an ecosystem. The ecological effect of temperature may change seasonally: A temperature increase in winter may allow species growth, while summer increases are undesired since water temperatures are already elevated (Münk 2008). However, depending on the receiving water, such as in rivers and lakes, species growth in the winter may not be desired, especially when considering that cold winter temperatures reduce mosquitos that carry pathogens.

Heavy Metals

Heavy metals are a potent type of toxic pollutant that will not break down. Another concern is that the heavy metals undergo speciation, that is, an element, such as copper (Cu^{2+}), will immediately react with H_2O to create different hydrolysis compounds, such as $Cu(OH)_2$, $CuOH^+$, $Cu(OH)_3^-$, $Cu(OH)_4^{2+}$, and $Cu_2(OH)_2^{2-}$ (Jensen 2003). The presence of $CO_{2(g)}$ products, such as carbonic acid ($H_2CO_{3(aq)}$), also reacts with copper to form $CuCO_3$, $Cu(CO_3)_2^{2-}$, along with even more compound products (Jensen 2003). For example, $CuSO_4$ is commonly used in RO, and the soluble $CuSO_4$ compound undergoes hydrolysis reactions, resulting in the many copper products mentioned above (Matavos-Aramyan *et al.* 2017). Copper has a low toxicity to species, but it will accumulate, and the higher levels from bioaccumulation will negatively affect species (Chadha 2015). Depending on the pH of the system, the concentrations of each species product can be calculated. However, the copper example provides an insight into the complexities of heavy metal pollution. Each chemical product has varying degrees of tissue absorption and effects on a species. Therefore, the number of chemical products and specific species responses is vast and is beyond the scope of this research.

In the Arabian Gulf, research by Alshahri (2017) studied the concentrations of heavy metals near outtake areas from desalination plants. The data was compared to similar areas in the Gulf, and to standard levels of shale, which is the common local geographic substrate (Alshahri 2017). That research provides strong support for pollution from an anthropogenic source. Heavy metals may be introduced from the metallic parts in the process (Alshahri 2017). Heavy metals can be very toxic to fauna, causing "reduced growth, development, cancer, organ damage, nervous system damage, and, in extreme cases, death" (Ogoyi *et al.* 2011). In flora, heavy metals, such as copper, have also shown reduced growth and lower survival rates (Hanley 2017). One effect that is predictable is the bioaccumulation of toxins through trophic levels, where toxins in water transfer to lipid cells (Molles 2016). In a polluted environment, the primary producers (plants) absorb some toxins into their tissue, and then the primary consumers eat the toxic tissues, accumulating a greater concentration within the consumer's tissue (Molles 2016). At the next trophic level, the secondary consumers feed upon the primary consumers, increasing the toxin concentration (Molles 2016). Each trophic level increases the concentration of toxins within the species, leading to acute or chronic toxicity effects (Cooley *et al.* 2013). An example of this is the commonly known problem of mercury in seafood. The toxic heavy metal mercury bioaccumulates through each trophic level, increasing in concentrations that becomes harmful for top consumers to eat.

Biological Factors

Species Diversity

Some species are specialized in their niches, while others are more general. Removing a single species can have a cascade effect though the food web, either benefiting some or harming others (Molles 2016). Species richness, the amount of species present, and species evenness, how balanced each species is to each other, are calculated to give a diversity score, known as the Shannon-Wiener Index. The Shannon-Wiener Index provides a useful score to grade diversity and allows the effects of concentrate on species to be easily compared. Despite useful tools available for comparison, a challenge with determining ecological effects stems from the lack of data of pre-waste disposal in areas affected (Cooley *et al.* 2013). Additional challenges to knowing the full effects come from studies that are focused on the short term, rather than the long-term possibility of acute and chronic toxicity (Cooley *et al.* 2013).

An experiment by Peterson *et al.* (2016) showed a significant difference in species richness near the outflow compared to the inflow (Chi^2-test, 187, df=6, p=0.001). In research by Jenkins *et al.* (2012), some species may be harmed by only 2-3 ppt salinity change, while other species are more fit to salinity changes. Changes in environmental conditions, such as pollution, or in the species present can greatly affect the food web. Species have life development stages that are vulnerable at each stage, and a disruption in one stage can greatly affect the future of the species (Molles 2016). Often, it is the smaller organisms that are first affected, and if their numbers are reduced, then the organisms that feed upon them are reduced (Molles 2016). However, the food web is so complex, that many effects are not predictable.

Microbes

The diversity of species is less in extreme environments, as these conditions are often for species that are fit for specialized niches. Microbes have been found in the harshest of environments. Microbes are the quickest to respond to unfavorable conditions, and a study by Van der Merwe *et al.* (2014) examined the differences in microbial diversity between RO outfall locations and ambient locations. The outfall point displayed the least number of microbes, and the trend showed an increase in microbe quantity with greater distance from the outfall (Van der Merwe *et al.* 2014). While the researchers conclude the differences not to be drastic, they recognize the limit of their study and recommend pyrosequencing as being necessary to determine species richness and evenness of microbes (Van der Merwe *et al.* 2014). The study is also limited in determining the type of microbes, as various microbes have a range of ecological benefits. The SWRO desalination plant used a common chlorination of NaClO weekly (10 mg/L for 2-3 hr), and then $NaHSO_4$ to de-chlorinate (0.3-0.5 mg/L), along with consistent use of phosphonate as an antiscalant (3-5 mg/L) (Van der Merwe *et al.* 2014). The RO process and chemicals killed all phytoplankton and almost all the bacteria, but 2 events/μL of bacteria were detected in the concentrate compared to 473 events/μL in the feed water (Van der Merwe *et al.* 2014). The small number of bacteria that survive provide a constant propagule pressure of species, considering that they have an advantage in the changed environment and may come from an intake some distance away. The few microbes that survive may drastically reduce the richness and evenness by dominating the new environment. The data does support an effect of mortality on microbe quantity from the concentrate.

Marine Benthos

Marine benthos is those species inhabiting the seafloor. In a study comparing concentrate effects in Bahrain by Naser (2015), there was a significant difference in the macrobenthic community between an MSF and RO plant of similar ecosystems. In the MSF area, 371 individuals of 43 species were identified for a Shannon-Wiener diversity score of 1.5±0.4, while in the RO area, 1403 individuals of 63 species were identified for a Shannon-Wiener diversity score of 2.3±0.2 (Naser 2015). The variance in the species community between the locations was also significant using a non-metric multidimensional scaling analysis (ANISOM: $R=0.541$, $P=0.001$) (Naser 2015). A W statistic measuring disturbance displayed a trend of greater disturbance in the MSF area (Naser 2015). Indicator species are useful for determining environmental conditions. Polychaete species, an annelid worm, are often used as an indicator (Giangrande *et al*. 2005), and presence of these species indicate organic-rich conditions that stem from sewage or oil outfalls (Carregosa *et al*. 2014). In both RO and MSF locations, polychaetes were the most abundant (Naser 2015), indicating poor overall environmental conditions in both locations.

There are a variety of marine ecosystems, such as seagrass and coral reefs, that provide an important habitat for marine species, renewable sustenance, and shelter for numerous species (Naser 2015). The study by Peterson *et al.* (2016) found larger sand grain sizes due to the higher flow from the outtake. A high rate of flow washes away the smaller grain sizes of sand. Flora and fauna species rely on certain sediment conditions during their life cycle. A slow rate of outflow could reduce washing away grain sizes. Maintaining environmental habitats is crucial to maintaining species presence.

DISCUSSION

How can any harmful ecological effects be reduced or eliminated?

The greatest potential for ecological effects of concentrate discharge occur in surface water discharge. Thus, mitigating these effects is of the greatest concern. In a sustainable solution, there is no detrimental change in environmental conditions. Blending the discharge to match salinity, temperature, pH, and dissolved oxygen of the receiving water, while not introducing new pollutants, needs to be the design standard of all plants. Salinity may be matched by blending with other effluents, such as the stream after a waste treatment plant. Temperature differences require greater cooling system designs before releasing the waste. pH can be closely monitored and adjusted, with improved systems using little to no acids or bases in the cleaning process. Dissolved oxygen changes may be prevented with close free chlorine monitoring, as well as screening of organic carbon sources to prevent byproduct reactions from consuming O_2. All aquatic management should be performed in a synthetic system prior to outfall release, and therefore, the most minimal impact to species and the ecological system occurs. To achieve the desired results, quantifiable research is needed to advance designs with room for improvement.

There is no perfect desalination plant that fits all areas and complexities. There are certain aspects of the desalination process that apply to all scenarios. The location of the plant should play a prominent role in determining the disposal method. The concentrate from each process and chemical additives to counter source water conditions results in a range of chemically variable concentrates, and this must be considered for disposal. The key questions to consider when disposing into natural water systems are: Is the environment appropriate for the discharge, and is the wastewater compatible for the environment? Those are the central guiding questions for every situation concerning disposal. For example, freshwater may seem suitable to dispose of anywhere, but freshwater is toxic to organisms in saline environments, and vice versa. Organisms have evolved to exist in the conditions of their habitat. Co-discharge, where concentrate and effluent waste is blended together to make a solution comparable to ocean water or freshwater, depends on the concentrations of the receiving water body. Co-discharge is not common, but some large-scale plants use this practice, such as in Barcelona and Japan, but co-discharge is a likely waste solution for a quarter of new plants in California (Cooley *et al.* 2013). The following guidelines will help to mitigate more costs onto the environment.

The recovery rate is not important if a large volume of source water is available, such as the ocean. While it would require more volume to withdraw, the lower recovery means a less saline concentrate that would be easier to dispose of back into to the ocean. While the technological focus is on efficiency and getting more squeeze out of the source, that may not be the ideal environmental solution. When needing to make the concentrate compatible with the receiving water, more water would be required to dilute the concentrate.

New technology should focus on designing desalination systems with minimal chemical additives which would prevent such chemicals emitted into the environment. The design ties back to the source water, as each site has a unique water chemistry that must be managed. In addition, the desalination plant needs proven products that do not leech metals, especially with distillation processes. Furthermore, newer methods for pretreatment, such as electrocoagulation, should be the pursuit of research. Another focus of the industry should be on redesigning the material of the membranes to prevent many of the fouling and scaling problems.

Desalination adds to climate change through greenhouse gases, which is a reason for the need of more water. Releasing carbon into the atmosphere from a stored source in a linear system is unsustainable and contributes to climate change. First, the energy needed to desalinate water needs to come from renewable and nonpolluting sources, such as solar, wind, or wave energy. Since plants may be regionally isolated, the power needed could be supplied without requiring the infrastructure connection to the electrical grid. Emerging technologies are developing renewable natural gas (RNG), which is methane obtained from biomass. When used with RNG, technology from EFD Corp. is promising. There are also situations where the desalination plant is located next to a power plant or other water user that heats water in its production, and that preheated water can be the intake supply, reducing the energy needed. However, as Spaetzel (2018) explained during a conference talk, the water from power plants is often unpredictable, as chemicals may have been added from the source plant, through cleaning or other means. The unpredictability can be solved by better communication and partnership between the source plant and the desalination plant. Perhaps the power plant needs a chemical additive for cleaning, but then communicates this to the water plant, and the necessary duration of contaminated water can be diverted.

Using the concentrate to produce biofuel is a direct benefit for society, as well as it will not add to environmental degradation. This solution may work for a variety of locations, in open ponds if quick evaporation is not an issue, or perhaps within closed containers in arid locations. Available land is an issue, along with an infrastructure in place to support biomass production, but this solution will absorb CO_2 and use carbon in a cyclical loop.

Evaporation ponds do have the benefit of creating a beneficial product, as this salt can be used as a de-icing agent on roads in freezing locations (Desalitech 2017). This is a low-tech solution that works in arid regions, such as the southwest U.S. and the Middle East. Humid regions, such as Florida, would not work because evaporation rates are slower.

ZLD offers perhaps the easiest of all disposal solutions in a trip to a landfill facility, but endless trips to the landfill is not a sustainable solution. However, if transport vehicles did not emit CO_2, then this solution is acceptable. It is possible to extract metals from the solid which provides an economic benefit, but as each site has a different water source, the product will also produce elements present from the source. For example, limestone is prevalent in Florida, so a high quantity of calcium will present, but a high amount of magnesium will also be included since magnesium is a suitable substitute for calcium in limestone. Note that limestone could be either calcite or aragonite. Both minerals are considered $CaCO_3$, but they differ in their molecular structure, and the compact structure of aragonite allows for more substitution of magnesium for calcium, adding to the complexity of what to expect in the product (Klein and Philpotts 2017).

Wetland applications may be the best ecological solution, as it may directly benefit an ecosystem. It may even be possible to build such an ecosystem in areas with little ecosystem activity, such as an open desert, supporting one of the most important beneficial habitats, and the concentrate can provide the source of water (Arizona 2011). However, natural environment applications need to be concerned with areas that are seasonal, as no movement of water will not mix nor dilute the concentrate for proper disposal.

There are additional disposal challenges, as Reiss explains an impossible discharge scenario is one with a source water that is already contaminated. For example, source water from a tech industry may contain various amounts of toxic metals unsafe for disposal. Those contaminates will not only remain in the concentrate, but it then becomes more concentrated. Adding another challenge to disposal is the shifting of source water extraction. Utility companies will extract water from the least expensive source, such as a near-surface aquifer, as utilities used to extract from in Florida. However, this source became overdrawn and no longer viable, so the next least expensive source was used, a deeper brackish water aquifer. Now there is a source water with much different chemistry that will have a more saline concentrate that cannot be disposed of in the same manner as the previous source.

Modeling is recommended to determine concentrate movement and ideal placement of the outfall. Specific location placement of outfalls in places of "sub-tidal, off-shore environments with persistent turbulent flow" will help dispersion (Roberts *et al.* 2010). Currently, blending of the concentrate into ocean outfalls is optimized at 30-45^{o} angles of discharge (Roberts *et al.* 2010), but new diffuser designs can greatly enhance the blending with surface water discharge, especially an economic option that new and old plants can add.

A solution that may reduce or eliminate surface water discharge issues is developing an outfall system that includes an intake (See Appendix F). The added intake would blend the concentrate before release into the water body. While this would not reach ambient salinity, a 50-50 blend of ocean water and concentrate halves the salinity (e.g. 35g NaCl/L of seawater plus 70g NaCl/L of concentrate (assuming 50% recovery rate) equals a 53g NaCl/L discharge). A second intake system would lower it to near ambient levels (e.g. 35g NaCl/L of seawater plus 53 NaCl/L equals a 44g NaCl/L discharge). An electronic monitoring system can automatically adjust blending amounts. A diffuser emitting the lower saline concentrate would sufficiently blend the discharge. Field studies are needed to determine effectiveness. This solution would require added economic costs, but this would negate any harmful ecological effects.

Further Sustainable Considerations

Economic considerations drive development within the desalination industry. Ecological consideration is made, but it is not the driving factor to technological advancement. While these topics may not be exclusive, such as limiting chemical use saves money and reduces pollutants, the value of environmental capital is not fully embraced. As a pillar of sustainability, it is the environmental capital that all economic capital draws from, and not reinvesting in the environment leads to economic bankruptcy.

Desalination raises many questions of social access to water. Yes, potable water is created, but for whom? The higher economic cost to produce water by desalination means better access for the higher economic status individuals. Many do not have running water, and without investment into distribution infrastructure, then water access remains divided. Who are the decision makers guiding the projects, and is the project focused on economic gain or water availability? Collaboration between policy makers, developers, and the community is key for equal water access to all, and early on everyone should be involved. Desalination concentrate disposal is complex, and hopefully this research helps everyone from policy-makers, average citizens, and to those in the industry better understand the ecological effects and solutions to concentrate disposal.

Future studies should investigate species that are near outfalls and the bioaccumulation of relevant toxins. Continuing the research and development of diffusers is critical. Studies should also focus on the factors of concentrate plume size, temperature, and concentration; Identifying what is the greater impact will allow for the most detrimental effects to be minimized or eliminated.

In conclusion, a long-term solution is reducing the amount of water used and restoration of natural water systems. More efficient technology, better storage, personal choices, and taxes are some ways that will prevent water being needlessly lost, as cheap water does not generate efficient designs (Villiers 2000). Efficient technology is available and continues to be developed, but it needs to replace current inefficient systems. Storage of the water resource when it becomes naturally available would help during dry times. Perhaps the best solution is to remove subsidies and limit water usage from industries that consume vast amounts of water, including fining those responsible for water pollution, such as the meat and dairy industry, which uses around 55% of all freshwater resources and causes most water pollution (PETA 2018). Choice in diet has an enormous water usage difference. Accurate costs of products will generate change, and individuals can make a difference by choosing a vegan diet to save over 4000 L/day of water (PETA 2018). Desalination is a great technology, but it is very energy intensive and can cause environmental harm, so limiting the need is more important than relying on more production. Sustainability needs to be at the forefront of decisions, because tomorrow will soon be today, and carefully planted seeds will bear continuous fruit, or neglect will bear depravity.

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APPENDIX

Appendix A. Overview of desalination processes. For detailed parameters, including pressure, flux, and rejection percentage, see Voutchkov (2014).

Process type	Notes
Membrane	
SWRO (seawater RO ~35,000 mg/L)	• Higher pressure is needed to counter the natural osmotic diffusion • Membrane permeate flux of SWRO is less than BWRO (Voutchkov 2014) • Concentrate from SWRO ranges from 1.5-2 times more concentrated than the source water
BWRO (brackish water 400-10,000 mg/L)	• BWRO waste ranges from 2.5-5 times more concentrated (Voutchkov 2014). • Less expensive than seawater
NF	• Used when source waters are less saline but contains high color, hardwater, or organic content, and will block cysts and viruses • Not used exclusively (AMTA 2007a)
MF	• Used when feed sources contain microbial and turbidity contaminants (AMTA 2007b)
UF	• Used when feed sources contain microbial and turbidity contaminants (AMTA 2007b)
ED	• Utilizes electrochemical properties, where anion and cation membranes separate the salt ions from water
Shock ED	• Emerging technique developed by researchers at MIT • Rather than pressure through a membrane, shock ED runs water over a membrane with a low voltage electric charge applied (Deng *et al.* 2014) • Cations and anions are oppositely directed by the charge and out through the membrane (Deng *et al.* 2014). • Overall electricity needed is less than traditional RO processes • Need for cleaning chemicals that clog membranes may be greatly reduced
Distillation	
MSF	• uses electricity and a thermal source
MED	• uses electricity and a thermal source
VC	• only requires electricity, as the compression of a gas generates heat (AMTA 2007c)
VC (EFD Corp.)	• combined proven technologies of VC and spray drying • produces a crystallized salt (no liquid waste) • proposes the salt can be sold as a product • process uses natural gas, but that is available from a fossil fuel

Appendix B. Overview of pretreatment chemical additives**.**

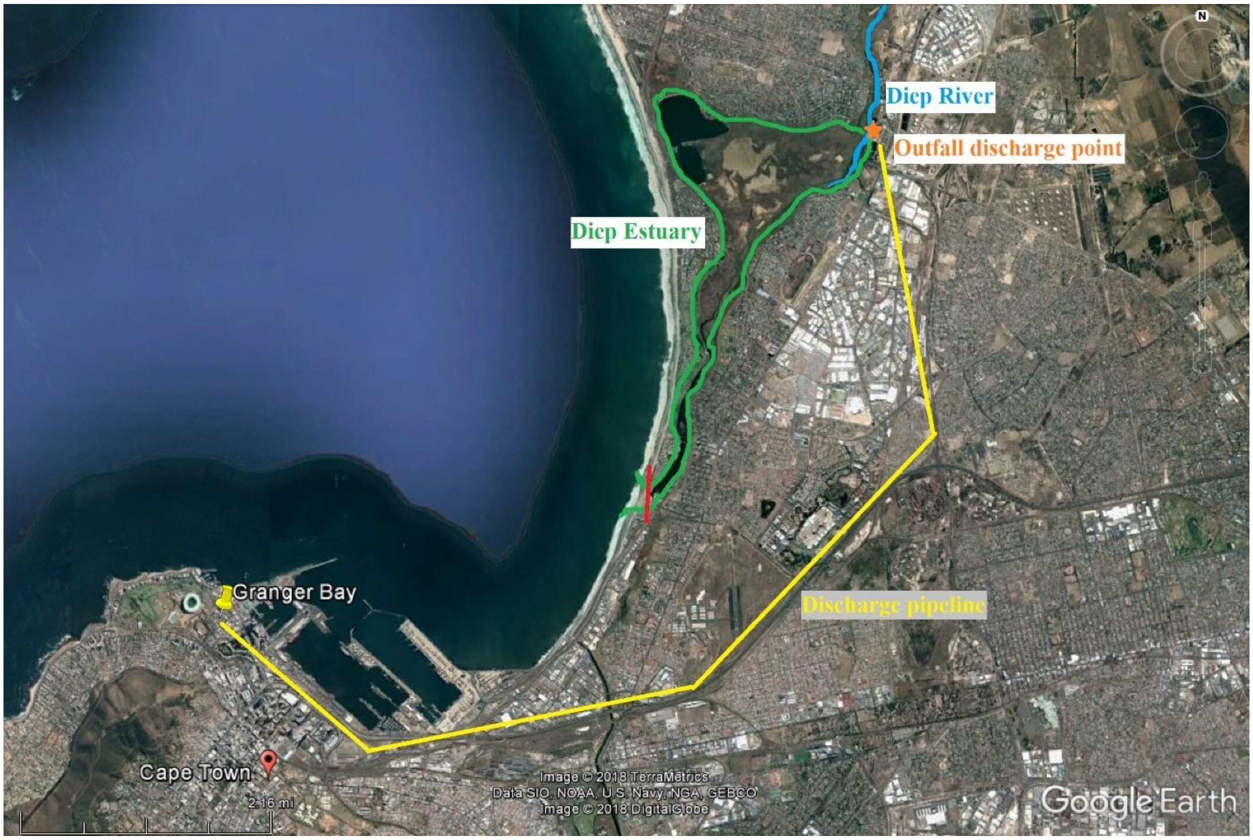
Pretreatment	**Use**	**Concern**
Antifoulants	• Used to prevent fouling of the membranes, usually in RO and MSF processes (AMTA 2007c) • May also require the use of, "biocides, anti-foaming additives, and detergents" (Cooley *et al.* 2013)	• May contain free chlorine • Chlorine ion generates halogenated products • To remove chlorine, sodium bisulfite ($NaHSO_3$) is added • Excess sodium bisulfite may also deoxygenate the water $SO_3^{2-} + \frac{1}{2} O_2 \rightarrow SO_4^{2-}$ • Trace amounts of these chemicals may be harmful to marine species (Cooley *et al.* 2013)
Antiscalants	• Prevent scaling, which are deposits from minerals on the membranes (Voutchkov 2014) • For BWRO, sulfuric acid (H_2SO_4) is added as an anti-scalant (Voutchkov 2014)	• Do not biodegrade well, their effects are not well known, and therefore they continue to accumulate in the environment and in species (Chadha 2015)
Coagulants	• Help remove the suspended solids from the feed water that may clog the membranes in RO systems (AMTA 2007d) • $FeCl_2$, $AlCl_3$, or polyacrylamide mixed in quantities dependent on the ratio of suspended solids (Cooley *et al.* 2013; AMTA 2007d).	• Overdosing can cause discoloration to various colors depending on coagulant • Not as great a concern as other chemicals
Strong acid/base	• Cleaning components • Strong acid (pH 2-3) is applied for a range of "metal oxides, scales, and inorganic colloids" (Münk 2008) • Strong base (pH 11-12) is used for the "removal of biofilms as well as organic and inorganic colloids" (Münk 2008)	• Effects available ions • May not be adjusted to ambient levels before release • Small changes in pH greatly affect species health

Appendix C. Overview of the benefits and issues of disposal methods.

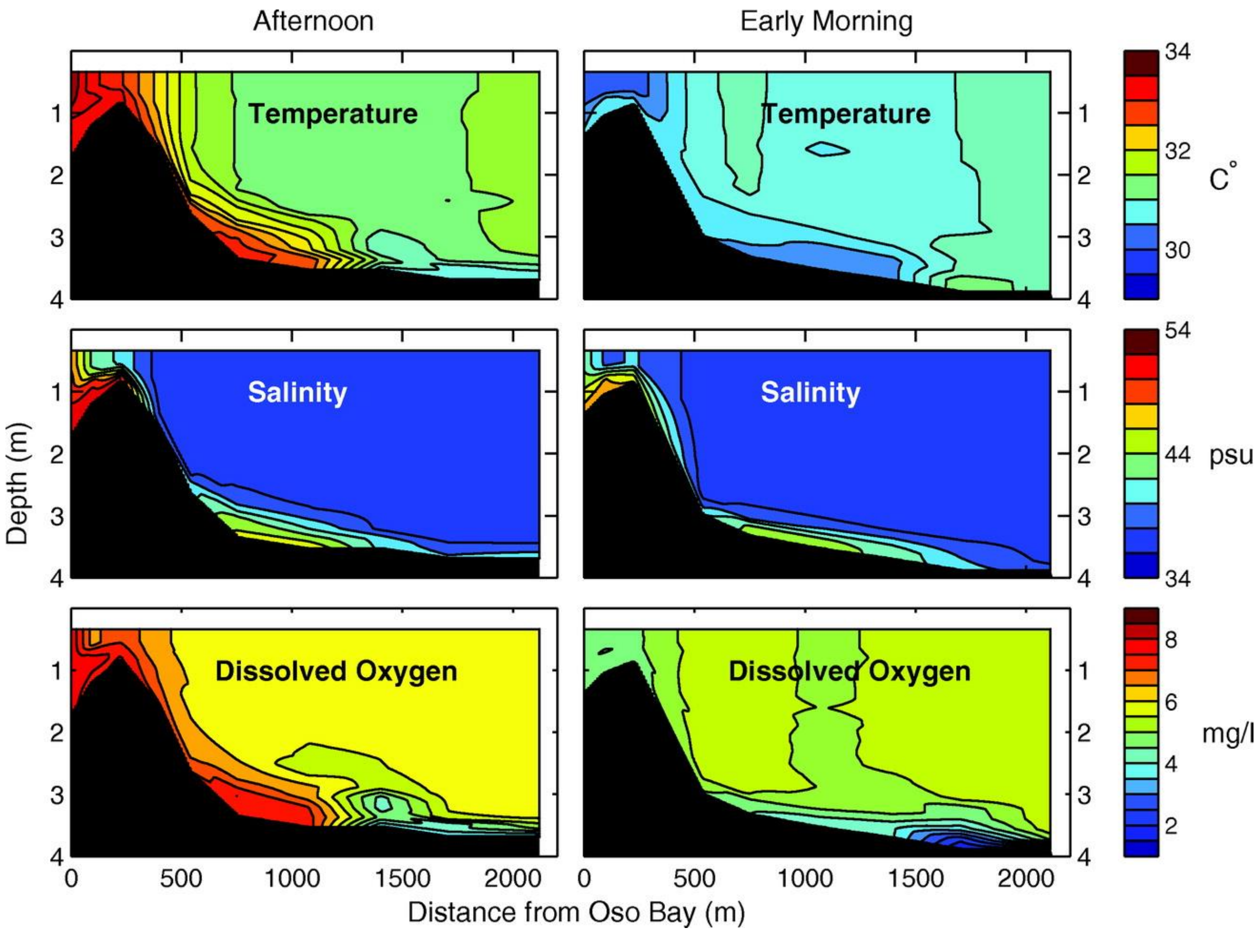
Disposal option	Benefits	Issues
Ocean Surface Water Discharge		
• Leading solution is to discharge the concentrate into surface water bodies (ocean, lakes, and rivers) • Common strategy is to point the outflow pipes upward and in a high flow zone to blend	• Handle large volumes • Inexpensive	• Discharging to a surface water in the U.S. requires a National Pollutant Discharge Elimination System permit (Desalitech 2017) • Many other locations around the world have protection laws that are limited, nonexistent, or unenforced • Even in ideal conditions, the concentrate can still be detected hundreds of meters from the outflow pipe • Inland disposal locations are typically freshwater and incompatible for salinity without blending
River Surface Water Discharge		
• Discharge the concentrate into river	• Adds volume to overdrawn rivers • Slow velocity river removes some pollutants with the sediment settling to the bottom	• Change in volume seasonally • Concentrate will have a much greater effect when there is a low flow in the summer, rather than becoming more diluted with more flow in the winter • Added volume from the discharge to potentially cause flooding • Velocity, bottom roughness, slope, and the width of the river affects the transverse mixing zone of the outfall where species would be exposed to elevated levels of concentrate
Wetland Application		
• Mix concentrate into a salt tolerant wetland ecosystem • Concentrate becomes diluted over a large area, and then returns to the sea	• Provides added volume to production ecosystem • Haven't been noticeably detrimental effects, but long-term effects are still unknown (Arizona 2011)	• Any salt added to the system above the ambient concentration will still raise the overall salinity, even though it may be negligible with such a large volume of receiving water

Sewer Discharge		
• Discharge the concentrate into a local waste treatment plant	• Convenient option and doesn't require much energy or extra costs (Voutchkov 2014)	• The volume of waste that a waste treatment plant will accept is limited, and it also poses potential damage to equipment of the treatment plant (Voutchkov 2014) • Waste must still conform to the requirements set upon the waste treatment plant (Desalitech 2017)
Deep Well Injection		
• Used to dispose of liquid waste deep underground • Waste is pumped into the porous layer.	• Industry preferred option if available • Potts explains, "if you can afford a deep well, [the permit] is there for you"	• Right geological conditions are needed, as the waste requires a porous layer for injection under a confined aquifer (Voutchkov 2014) • Areas vary greatly (Florida may be 1000m deep, while Colorado may be 3000m deep), which greatly alters the cost of construction and maintenance (John Potts, informal roundtable discussion, March 10, 2018) • Requires an EPA permit • Possible for groundwater to be contaminated (Voutchkov 2014)
Land Application		
• Use the concentrate as irrigation water	• Extra source of water for irrigation • No waste	• Need a less saline concentration • Whatever toxins are in the concentrate may accumulate in the soil substrate • Plant species receiving the application need to tolerate a saline solution (Arizona 2011)
Evaporation Pond		
• Concentrate is spread out in shallow ponds • Large surface area and shallow depth allow the solution to evaporate off the water	• Solid salts remain that can be collected and sent to a landfill or suitable location • Federal permit is not needed, but monitoring may be mandatory by certain states (Desalitech 2017)	• Requires large areas of land • Not a solution for large-scale desalination plants, as it cannot accommodate the volume of waste without an enormous size of land allocated (Voutchkov 2014) • Possible contamination to groundwater sources, and a liner to prevent seepage is needed (Voutchkov 2014)

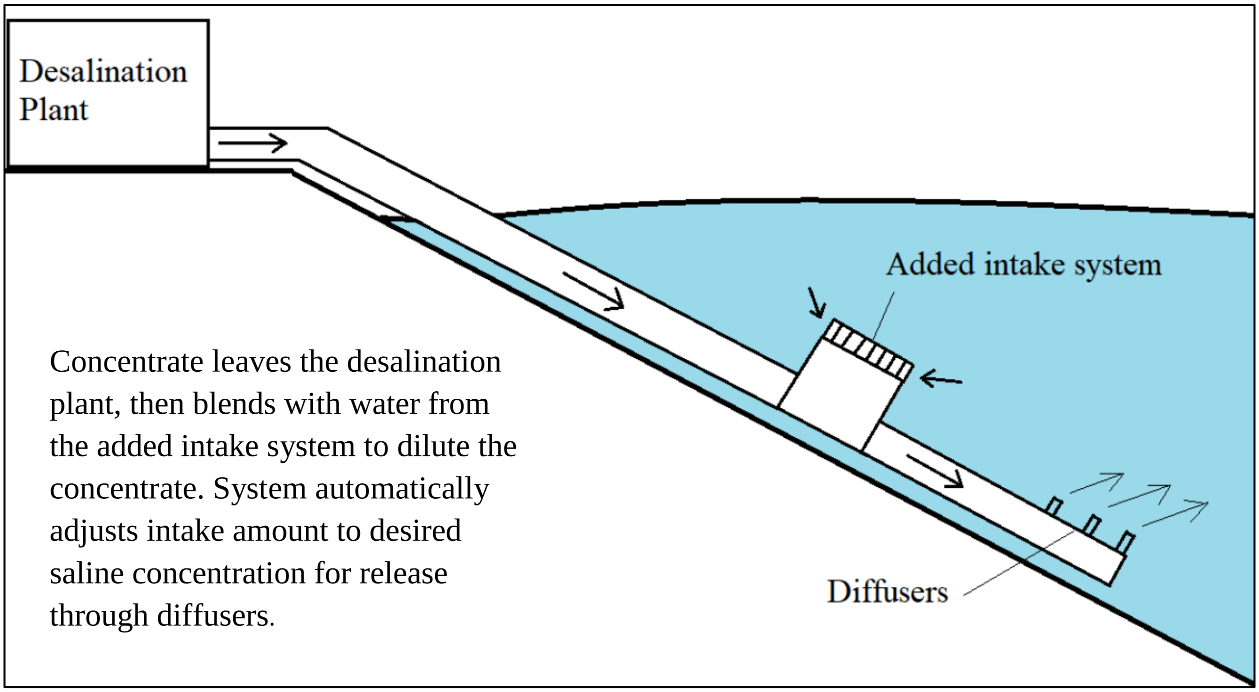
Zero Liquid Discharge (ZLD)		
• Removes all the liquid in the process, and the waste in no longer a liquid but rather a solid	• Can be disposed of in a landfill • Potential for the extraction of metals from the solid product, which would provide a resource from waste • No ecological discharge	• Reiss explains that all current techniques to remove the last amount of water from the waste involves heat, which is extremely costly and resource intensive
Biofuel Production		
• Using the concentrate as a substrate for growing phytoplankton algae	• Concentrate induces a stress on the algae, promoting the manufacture of lipids and fatty acids rather than proteins, which aids production of biofuels (Matos *et al.* 2017) • *Nannochloropsis gaditana* displayed the greatest salinity tolerance (Matos *et al.* 2017)	• Different algae species have various tolerances to saline concentrations, so the species would need to be the right fit for the concentrate • Concentrate cannot be the complete substrate medium, as known substrates need to be added (Matos *et al.* 2017)



Appendix D. Map of Cape Town, ZA with the Diep River (blue) and the Diep Estuary (green) outlined. A proposed discharge pipeline (yellow) from the location of the Granger Bay desalination plant to the beginning of the Diep Estuary at a potential outfall discharge point (orange star). Mouth of Diep Estuary marked where area becomes landlocked in summer (red bar) (Map courtesy of Google Earth).



Appendix E. Concentrate movement in distance from Oso Bay displaying temperature, salinity, and dissolved oxygen differences during afternoon and early morning (Hodges *et al.* 2011).



Appendix F. Cross section diagram of a proposed intake system added on an outfall pipe with diffusers that is discharging into a surface water body.