THESIS

TO TREAT OR NOT TO TREAT: THE EVOLUTION OF WASTEWATER TREATMENT MANAGEMENT APPROACHES

Submitted by

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ABSTRACT

TO TREAT OR NOT TO TREAT: THE EVOLUTION OF WASTEWATER TREATMENT MANAGEMENT APPROACHES

The research presented in this thesis focuses on wastewater management practices to further the understanding of the evolution of wastewater treatment approaches. Within this thesis, wastewater treatment technologies and processes are categorized into four groups: dilution dependent, conventional, alternative, and emerging. The evolution of wastewater treatment technologies is initiated with initial investment by a society to self-organize; transformed when there are alterations in the way the society lives, primarily considering the urbanization and industrialization of societies; and satisfied when the society has incorporated sustainable practices that can ensure water security for future generations. The motivation of this research is to interpret how the concept of conventional wastewater treatment can be driven to encompass more sustainable approaches in both the developed and developing world. In order to facilitate understanding of this, we aim to address the following: what wastewater technologies are available and how practical are they?, what are some significant drivers that have driven the evolution of wastewater treatment up till now?, how do institutional arrangements affect implementation of technologies?, and how does public perception play a role in the adoption or repudiation of wastewater treatment technologies? To investigate these questions, South Africa and the United States were used as primary case studies.

There is an abundance of technologies used in the field of wastewater treatment; however, the resources (natural, financial, and technical) of a society will determine the practicality of implementing certain technologies. The major drivers that lead to the transformation of treatment technologies include the following: population growth and urbanization, public health initiatives, actions to prevent the degradation of the natural environment, capacity building within institutional arrangements such as societal organization and regulation, concerns of climate change, objectives to minimize conflict, the demand on

water from energy and food sectors, and social perception of science. In the United States, "conventional" technologies have been pushed to encompass secondary treatment standards for point source wastewater through policy measures. South Africa, due to its historical Apartheid era, has an additional layer of water management methods that pertains to the access to sanitation services as a human right. In both countries, development of industry has been clashing with preserving the environment and protecting public health. Sustainable, emerging technologies are trying to harmonize economic growth and environmental conservation by treating wastewater as a feed of resources to be recovered.

In the exploratory Wastewater Treatment Survey presented in this thesis, responses from 655 U.S. participants were analyzed to demonstrate the effectiveness of surveys to produce social perception data for water managers. From the survey, it was observed that over 35% of U.S. participants were not at all likely or not so likely able to explain what happens to their wastewater. Even within the STEM field respondents, 30% were unsure what happens to their wastewater. This exemplifies a wide gap in the link between humans and their waste disposal. Of the 655 U.S. respondents, over 90% were moderately to extremely concerned about water pollution. A higher level of concern for wastewater pollution was also correlated with people who believed they had a better understanding of wastewater treatment. Those who were more concerned about water pollution were also more likely to get involved in water resources management activities. The respondents chose protecting public health and the integrity of the environment as the two main reasons why wastewater treatment is necessary. Of the U.S. respondents, around three-quarters of the participants believe that no longer can dilution be treated as the solution to pollution with the majority of the other participants believing that it may only be conditionally sufficient.

Many alternative and emerging technologies are being heavily scrutinized by the public. Public buy-in is necessary to transform the wastewater field and will only be accomplished when societal perception and wastewater treatment technologies are linked. From the survey data, almost 60% of the U.S. participants were willing to increase a utility bill by at least 3 additional USD to pay for improvements in their wastewater treatment plant's treatment capabilities whereas only 46% were willing to pay at least 3 additional USD for improvements in their wastewater treatment plant's energy efficiency. In the real world,

these improvements for a treatment plant may not be mutually exclusive; however, this type of information may help a water manager build public buy-in for the project. Only 14.35% of U.S. respondents were completely willing to drink direct potable reuse water, with an additional 22.29% very willing to drink it.

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CHAPTER 1. INTRODUCTION

1.1 Background

The research in this thesis will illustrate the evolution of wastewater treatment practices through the link water creates between people, political structures, public health, and the natural environment. With global population rising, trends toward migrating to the urban areas progressing, and access to a clean, sustainable water resources becoming more limited, it is not surprising that obtaining water security has become a major undertaking to overcome. According to the United Nations, the planet has a sufficient amount of freshwater to sustain human life; however, the uneven distribution and poor, unsustainable management of the freshwater has led to the resource being wasted, polluted, or inequitably accessed (UN, 2014). This results in water scarcity, or in other words, the inability to meet demands for freshwater. Mara (2003) reports that "over half the world's rivers, lakes and coastal waters are seriously polluted by untreated domestic, industrial and agricultural wastewaters." United Nations Environment Programme (UNEP) and United Nations Human Settlements Programme (UNHabitat) (2010) estimate that in developing countries, an overwhelming ninety per cent of all wastewater is discharged into rivers, lakes or the oceans untreated. When considering that most human activities that use water produce wastewater, it becomes clear that managing water quality is an immensely large task (UN, 2017). Lack of financial resources tend to be cited as the main factor prohibiting the building and/or improvement of sanitation infrastructure. Eighty per cent of countries reported that current levels of financing are insufficient to meet their targets for drinking-water and sanitation (World Health Organization [WHO], 2014).

By reviewing the components of wastewater, wastewater treatment (WWT) approaches, WWT technologies, and policy, the drivers that shape watershed management plans and WWT treatment technologies in certain regions can be identified. Exploration of alternative water treatment technologies and comparing it to the "conventional" treatment methods will be vital in appealing to adopt wastewater sanitation more universally. The research will bring together interdisciplinary topics (e.g. wastewater treatment technologies and processes, roles and structures of governance systems, and societal context) in a way that can help guide regions in exploring different options that will drive them toward a more sustainable and water secure future.

The incessant degradation of water quality around the world poses many significant environmental, economic, and social implications. The purpose of the research is to synthesize the benefits and drawbacks of the different technologies, processes, and institutionalized management approaches currently utilized around the globe. The South Africa and the United States will be presented as case studies to expand on trends observed in the water quality management sector in both the context of a developing and developed region setting. Providing domestic and international perspectives of wastewater treatment will expose the effects that differences in population, location, climate, policy, and culture can have on wastewater management. This thesis is a combination of a robust literature review which included analyses of wastewater treatment technologies, the water quality nexus, institutional arrangements, and background information on the specific case studies. Qualitative interviews and a trial survey also revealed drivers of the evolution of this field.

1.2 Objectives

The objectives of the research presented in this thesis include:

- investigating the role wastewater treatment plays in the water, food, energy, and public health nexus by
    - understanding the composition of wastes ending up in our waterways thus contributing to the widespread and costly problems of pollution around the world and
    - identifying key policy at different management levels (i.e. international, national, regional and local) that have contributed to the adoption of wastewater management practices;
- constructing a framework in which to analyze the evolution of wastewater treatment approaches and comparing management approaches in the developed versus developing world and the rural versus urban landscapes;
- analyzing and comparing case studies of wastewater management approaches in South Africa and the United States

- connecting the evolution of wastewater management approaches to social perception with the support of a survey.

1.3 Organization of Work

Chapter 2 depicts what constitutes wastewater and highlights the importance of using systems thinking in order to comprehend the contributions proper wastewater management can have on society as a whole. The discussion of wastewater in this section is formulated by creating a holistic picture of the essential role wastewater management plays in the water, food, energy, and public health nexus. This will include an investigation of the wastes that are actively polluting waterways around the world as well as the role policy plays in shaping the field of wastewater management.

In Chapter 3, the evolution of wastewater management approaches will be identified. The wastewater management technologies will be categorized into four classes: no treatment at all, conventional treatment technologies, alternative treatment technologies, and emerging treatment technologies.

Chapter 4 presents a case study of wastewater management in the KwaZulu Natal Province of South Africa. It will consider both managerial and technical aspects of how the province handles wastewater treatment. The case study will expose unique challenges a government of developing regions faces in order to provide basic services to their constituents. In this particular case study, the implications of a free basic water policy can be examined. Within the province of KwaZulu Natal is the eThekwini Municipality. This case study will explore the impact of deep sea outfalls, such as those utilized in Durban, and prospective alternatives to their current practices. The case study will include information from observations during fieldwork visits, interviews with figures working for the eThekwini Municipality, and analysis of their policy concerning wastewater treatment management.

Chapter 5 considers how surveys can be used to collect social perception data. Public buy-in is necessary to promote a smooth transitioning of wastewater treatment practices from conventional methods to more practical and sustainable methods.

Chapter 6 will address the main conclusions established from the research presented and consider future work to be done in order to further advance the field of wastewater treatment management.

CHAPTER 2. LITERATURE REVIEW

2.1 The Waste

The waste in wastewater can be described as the components added by human activity to waterbodies that make the water impure from its natural composition and perhaps even insanitary. The waste can be classified by where it originates from. Typical categories of wastewater involve domestic, industrial/commercial, and agricultural wastewater, as well as stormwater and sewer inflow and infiltration. Another means of organizing waste is how it propagated into the environment. A common way this is done in practice is labeling waste as either point source pollution or non-point source pollution. The Clean Water Act (Section 502-14, 1987) defines point source pollution as

> *"any discernable, confined and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel or other floating craft from which pollutants are or may be discharged."*

It then goes on to exclude "agricultural stormwater and return flows for irrigated agriculture." Perhaps the most recognizable trait of point-sources is that they have an identifiable single- or multiple-point location where pollutants are discharged (Novotny, 2003). All other sources are then grouped as nonpoint sources. Figure 2.1 provides a list of different sources that fall within each category. Although non-point source pollution is of major concern, the research in this thesis will concentrate primarily on best management approaches and treatment technologies for point source pollution.

When the waste is not removed from the water before it enters the environment directly or indirectly, then the wastewater is designated as water pollution. Water pollution can be the result of a sudden outbreak or ongoing leak of pollutants as well as an accidental or deliberate release of pollutants to water without treatment. Wastewater treatment is designed to remove pollutants to meet water quality standards set by policy. Typical pollutants comprise of an excess of nutrients, organic and inorganic material, pathogens and toxins, heavy metals, pharmaceuticals, and thermal pollution. Various types of wastewater vary by their composition (e.g. physical, biological and chemical pollutants), therefore differing means of removing the waste through treatment processes is dependent on the composition of wastewater. Camp and

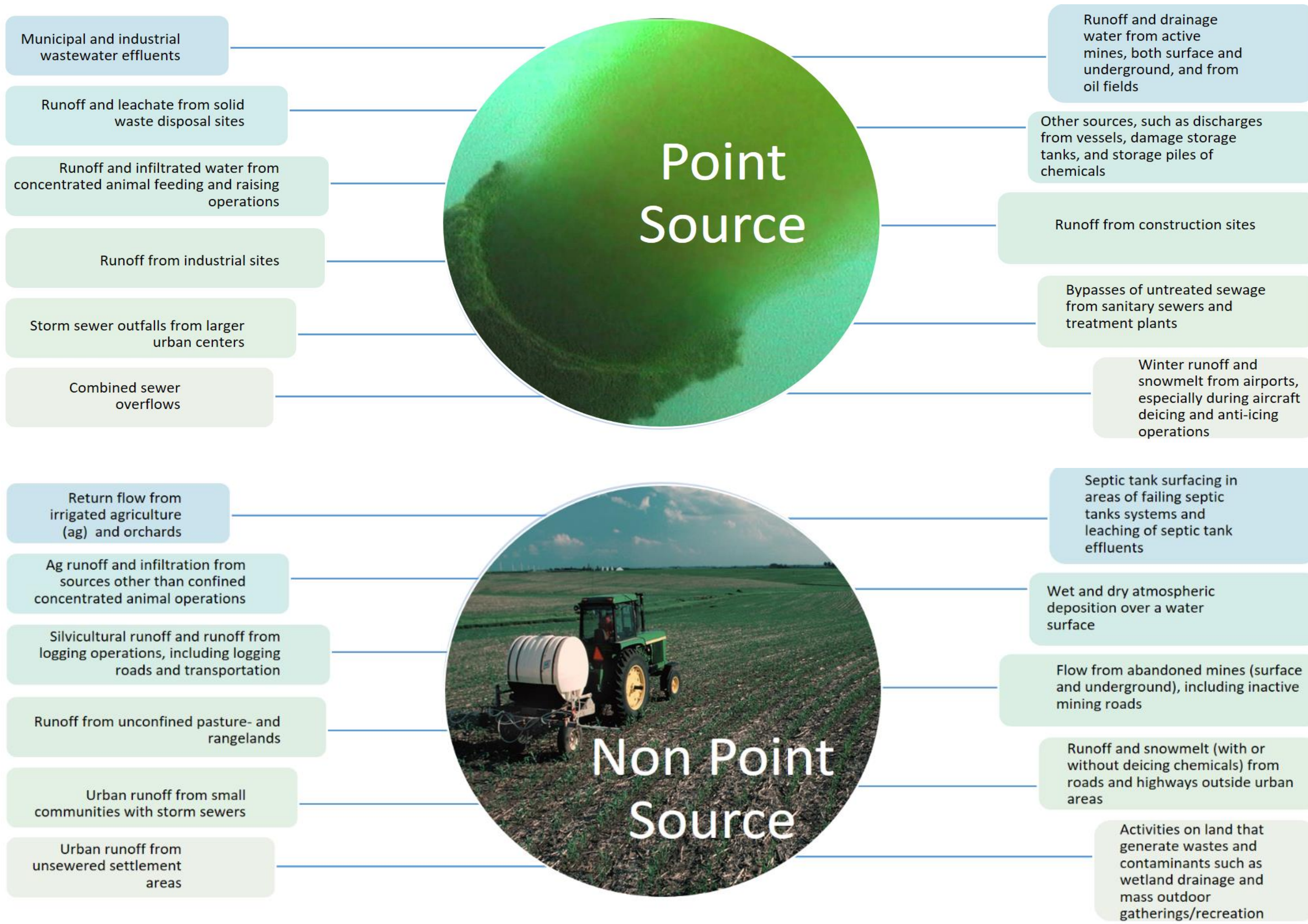


Figure 2.1: Sources of point source and non-point source pollution. Adapted from Novotny (2003).

Messerve (1974) classify pollutants into the following four categories for the purpose of water-quality management:

1. settable impurities,
2. suspended impurities,
3. colloidal impurities, and
4. dissolved impurities.

These classifications will be discussed further in Chapter 3 on Wastewater Treatment.

Water can also be classified by what type of pollutants it has come in contact with or where the water is found in nature. It is common to hear water being referred to as gray, black, blue, green, or even white water. Table 2.1 defines the nuisances between these different designations of water. Black water and greywater are common terms in the field of water reuse which will be explained further in Chapter 3 on Wastewater Treatment.

Table 2.1: Water designations based on the components in the wastewater or where the water is found in the environment. Adapted from The Water Network, 2017.

Type	Definition
Black Water	Sewage water flushed in the toilets. It was in contact with fecal matter containing harmful bacteria and disease-causing pathogens. Typically not reused due to risk of contamination.
Blue Water	The freshwater: surface and groundwater. It is stored in lakes, streams groundwater, glaciers and snow.
Green Water	The soil moisture from precipitation, used by plants via transpiration. It is part of the evapotranspiration flux in the hydrologic cycle.
Grey Water	Polluted water which was not in contact with fecal matter. Grey water is the product water of domestic activities: bathing, laundry and dishwashing or polluted water due to pesticides in agriculture and nutrients from fertilizers. Contains soap and fat particles, even hair. It can be recycled and reused, not for drinking, but for irrigation if the chemicals content is not too high. Water was not in contact with human waste.
White Water	Clean water.

The major role of sanitation is to manage the wastewater in order to benefit public health, the environment, and a productive economy (see Figure 2.2). The adverse repercussions of water pollution have led to a deeper analysis of the wastes society creates. Some wastes bioaccumulate in the environment and wildlife, some interact with other wastes creating more potent forms of pollution, and many are very technically difficult to remove even when attempted. The feasibility for a water or wastewater treatment plant to be able to monitor for all the different kinds of wastes created by humans with municipal, commercial, industrial, and agricultural uses is low due to both technical and financial capabilities available. The development of societies has led to brand new hosts of wastes accruing in the natural environment. The field of studying emerging contaminants is growing rapidly as we seek to understand what "wastes" are in our wastewater and how they impact the earth.

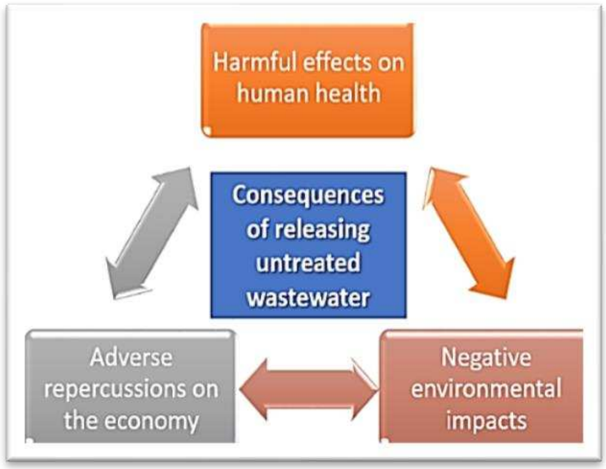


Figure 2.2: Consequence of releasing untreated wastewater. Adapted from U.N., 2017.

2.1.1 Common Pollutants

Common pollutants are those added components that are typically observed in wastewater or contaminated natural waters. The concept of "common" pollutants will always be relative to a specific area because the characteristics of that area (e.g. land use, water use, industry/production, ecosystem services, cultural context) will differ greatly, leading to a distinct set of prevalent pollutants for that given area. The scope of this thesis is not to list every pollutant plaguing the earth's water resources but rather to give examples of the types and groups of pollutants water management infrastructure and organizations, such as wastewater treatment plants, are designed, or not designed, to handle. Some pollutants change the way the water looks (e.g. dissolved and suspended particles and increased levels of phosphorous and nitrate leading to algal blooms), smells (e.g. sulfur bacteria and hydrogen sulfide gas), and tastes (e.g. minerals like calcium and magnesium) while other pollutants may not be able to be observed by the human senses (e.g. microbial and organic contaminants). Some contaminants affect body functions (e.g. fecal coliform bacteria and heavy metals such as lead and mercury) while others bioaccumulate in fish (e.g. persistent organic pollutants such as dioxins and polychlorinated byphenols). Novotny (2003) lists the traditional point source pollutants of concern as

- suspended solids and their organic (volatile) content,
- biochemical oxygen demand (BOD_5),
- chemical oxygen demand (COD).
- pathogenic microorganisms,
- nutrients (nitrogen and phosphorous),
- toxic compounds, both organic and inorganic.

Finding the roots of pollution can bring to light the different types of common pollutants. Table 2.2 considers different causes of water pollution and its corresponding common pollutants.

Table 2.2: Examples of common pollutants from various sources.

Source	Pollutants	Associated Problem
Industrial Discharges	Ammonia	Toxic to fish. [1]
	Cooper	Too much can lead to cooper poisoning in humans. Acute copper poisoning can cause symptoms of nausea, vomiting, diarrhea, gastrointestinal illness, abdominal and muscle pain. Severe cases of copper poisoning have led to anemia, liver poisoning, and kidney failure [1]
Sewage and WW	Chloramines	Trihalomethanes (THMs) can be created when aqueous chlorine reacts with certain organic materials. These disinfection byproducts (DBPs) have been linked to cancer and infant delivery problems. [1]
	Bacteria and Viruses	Not all waterborne microbes are "bad" or cause illness. However, microbial contaminants such as E. coli, Giardia, and Cryptosporidium can cause gastrointestinal problems and flu-like symptoms [1]
	Lead	Typically caused by corrosion of lead containing materials that contact water (eg service connections). Can cause lead poisoning. The most severe form can lead to death. [1]
Mining Activities	Mining Drainage (e.g. sulfuric acid, iron, copper, lead, mercury, selenium)	Mining drainage has substantial impacts on both the environment and humans. Problems related with mine drainage include contaminated drinking water, disrupted growth and reproduction of aquatic plants and animals, and the corroding effects of the acid on parts of infrastructures such as bridges. [2]
Marine Dumping	Dredged material, sewage sludge, and fish wastes	The slew of pollutants dumped into the ocean lead to adverse impacts on both the environment and humans when exposed to the waste. These specific contaminants listed were not banned by the London Protocol which only was established in 2006. [3]
Oil	Bromide	When combined with chlorine can form THMs. These DBPs are toxic to humans. In fact, they have higher health risks than chlorinated DBPs). [4]
Burning fossil fuels	Arsenic	Toxic to humans (e.g. chronic arsenosis which can lead to death in its most extreme form). [1]
Radioactive Waste	Uranium	Toxic to humans including ingestion leading to kidney inflammation and changes in urine composition. Uranium can decay into other radioactive substances, such as radium, which can cause cancer with extensive exposures over a long enough period of time. [1]

[1] Water Quality Association, n.d.; [2] USGS, 2017b; [3] EPA, n.d.; [4] USGS, 2017c

Non-point source pollution is a large contributor to the pollution that ends up in waterbodies. Non-point pollution is a sum of many diffuse sources versus one single source of pollution. The pollutants will typically end up in the water supply of downstream users, eventually leading back to a point source discharge; therefore, it is almost impossible to uncouple treatment needs for point source and non-point source discharges of pollutants. Table 2.3 describes common types of diffuse pollution and examples of environmental problems that persist when that pollution enters the natural environment untreated.

Table 2.3: Diffuse pollution of concern. Source: D'Arcy et al. (2000).

Pollutant	Example Sources	Environmental Problem
Oil and hydrocarbons	Car maintenance. Disposal of waste oils. Spills from storage and handling. Road runoff. Industrial runoff	Toxicity. Contamination of urban stream sediments. Groundwater contamination. Nuisance (surface waters). Taste (potable supplies).
Pesticides	Municipal application to control roadside weeds. Agriculture. Private properties.	Toxicity. Contamination of potable supplies.
Sediment	Runoff from arable land. Upland erosion. Forestry. Urban runoff. Construction industry.	Destruction of gravel riffles. Sedimentation of natural pools and ponds. Costs to abstractors (e.g. fish farms, potable supplies).
Organic Wastes	Agricultural wastes (slurry, silage liquor, surplus crops). Sewage sludge. Industrial wastes for land application.	Oxygen demand. Nutrient enrichment.
Fecal Pathogens	Failures of conventional sewerage systems (wrong connections in separate sewer systems). Dog feces in towns and cities. Application of organic wastes to farmland.	Health risks. Noncompliance with recreational water standards.
Nitrogen	Agricultural fertilizers. Atmospheric deposition.	Eutrophication (especially coastal waters). Contamination of potable supplies (rivers and groundwaters). Acidification.
Phosphorous	Soil erosion. Agricultural fertilizers. Contamination of urban runoff (detergents, organic material).	Eutrophication of freshwaters (ecological degradation, blue green algae, increased filtration costs for potable reservoirs/rivers).
Trace Metals	Urban runoff. Industrial and sewage sludges applied to land. Contaminated groundwater.	Toxicity.
Iron	Water table rebound following mining (especially coal).	Toxicity. Aesthetic nuisance.
Acidifying Pollutants	Car emissions (traffic) point source discharges to atmosphere. Fires.	Low pH in sensitive catchments - acid rain. Contribution to eutrophication.
Chemicals	Domestic and industrial wash off.	Toxicity, endocrine disruption. Contamination of potable supplies.

Waterbodies and their interactions with the surrounding environment establish very unique sets of physical, biological, and chemical attributes or processes. Many of these environments are based on a fragile set of conditions, all of which can be easily altered by human activity, climate change, and/or major natural disasters. Releasing an abundance of nutrients into the waterways, especially an excess of nitrogen and phosphorous, result in high dissolved oxygen consumption, also known as eutrophication, and subsequently lead to the creation of dead zones. Hypoxia is another common term used to describe the oxygen deficiency created by algal blooms consuming oxygen before they also die/decompose due to oxygen starvation (EPA, 2017b). Their death/decomposition also promotes bacterial growth in the waterbody.

A current example of an ecological disaster caused by eutrophication is the formation of the largest dead zone ever recorded in the United States (8,776 mi^2) located in the Gulf of Mexico due to the excess of nutrients in the spring time watershed drainage of the Mississippi River Basin (Gallegos, 2017). The size of the dead zone will fluctuate annually based on precipitation and runoff (composed of synthetic fertilizers and animal manure, human and industrial waste) from that year. Figure 2.3 illustrates the location of the dead zone in the Gulf of Mexico. According to Gallegos (2017), nearly 100,000 square miles of the world are covered by dead zones. To put that into perspective, the state of Colorado is a little over 104,000 square miles and the United States as a whole has 264,837 square miles of water area representing 7% of its total area (United States Geological Survey [USGS], 2016). The mitigation of dead zones requires "wastewater treatment, sediment and stormwater controls, soil management practices and more selective and precise applications of fertilizer" (Gallegos, 2017).

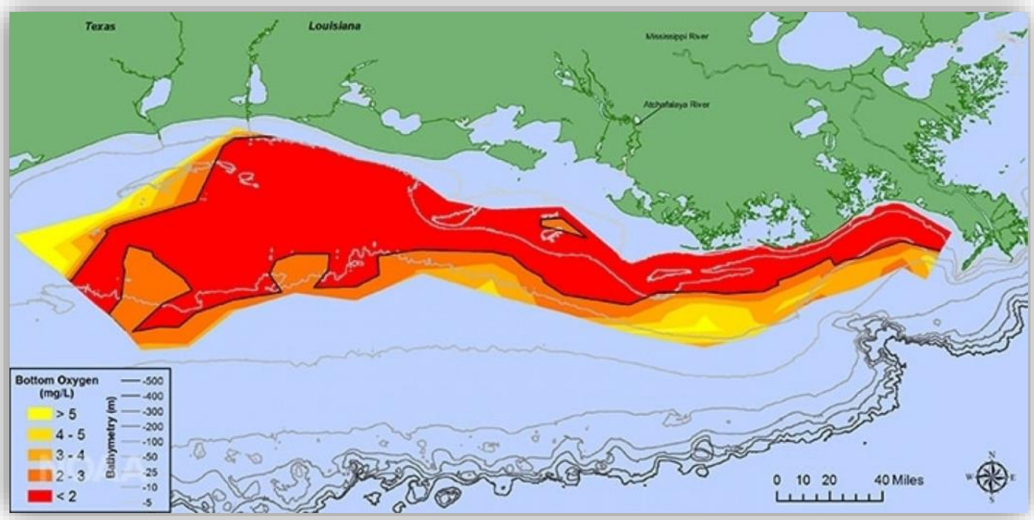


Figure 2.3: The dead zone in the Gulf of Mexico. Source: Gallegos, 2017.

Increased turbidity due to various types of loadings (e.g. sediment, organic material, wastes) create stress in the physical environment as it tries to survive within different environmental conditions. A change in turbidity effects the amount of light that can penetrate down, effectively being able to change the temperature of the water and the biological activity/productivity (e.g. photosynthetic cycle) in the water (Meyer & Heritage, 1941). Inputting new discharges can also cause major changes in temperature and composition (e.g. dissolved oxygen concentrations, chemical constituents and reactions, nutrient loadings) of a waterbody. Industrial/commercial wastes are responsible for another layer of contaminants, many of which are highly toxic, capable of impairing wildlife populations whether it be directly (e.g. buildup of toxins in tissue due to direct exposure) or indirectly (e.g. changing of the ecosystem and/or toxins moving up the food chain).

Analytical methods for characterizing the constituents of wastewater can be found in the *Standard Methods for the Examination of Water and Wastewater* (1999) by the American Public Health Association, American Water Works Association, and the Water Environment Federation.

2.1.2 Emerging Concerns with Micro-Pollutants

As stated earlier, with an evolving society, there is constantly a new array of wastes released into the environment or a bioaccumulation of waste over time that begins to be detected in a waterbody. With the relentless pursuit of research, new concerns are also emerging with known contaminants. All of these different scenarios are instances in which the term "emerging contaminants" is typically utilized, demonstrating that emerging does not always refer to a chemical or compound that has recently been introduced into the environment. Rather the term emerging is often referring to an author believing their detection of a pollutant or their finding new consequences of a given contaminant to be novel (Kummerer, 2011). Kummerer (2011) argues that the term micro-pollutant, rather than emerging contaminant, is a more scientific expression to describe the pollutants construed in this section. Luo (2014) defines micro-pollutants as a "vast and expanding array of anthropogenic as well as natural substances" that exist in waters at trace concentrations up to several µg/L. According to Naidu *et al.* (2016), the detection of these contaminants is the result of "better methods for detecting low level of concentrations of contaminants" and "some recognition that additional substances should be monitored." This comes with acknowledging that new chemicals are used as well as old chemicals being used in new ways.

Contaminants, such as pharmaceuticals, personal care products, hormones and stimulants, and drugs of abuse, have begun to receive more attention due to their growing presence in the environment and the possible detrimental impacts they may be causing (Tran *et al.*, 2018; Talib, 2017; Baalbaki *et al.*, 2016; Naidu *et al.*, 2016; Verlicchi & Zambello, 2015; Verlicchi *et al.*, 2012; Pruden *et al.*, 2006). One example includes linking traces of antibiotics and antimicrobial agents in the water supply with the development of antibiotic resistance genes (Tran *et al.* 2018; Pruden *et al.*, 2006). Another example is the implications of the environment's chronic exposure to caffeine, with studies by the National Coffee Association (2017) reporting that 62% of Americans drink coffee, a caffeinated beverage, on a regular basis. After consumption of a caffeinated product, such as coffee, tea, chocolate, and pharmaceutical products, about 5% is excreted unchanged in urine (Rodriguez-Gil *et al.*, 2018). In many freshwater environments, caffeine concentrations have been found to be approaching the threshold toxicity for aquatic biota (Bruton *et al.*, 2010). The presence of caffeine in waterbodies has also been utilized as an anthropologic marker, or in other words, an indicator of human contamination of the environment (Rodroguez-Gil *et al.*, 2018; Paiga, 2017; Viviano *et al.*, 2017; Bruton, 2010).

Tran *et al.* (2018) identify the following ways contaminants of emerging concern (CECs) are introduced into the aquatic environment:

- direct discharge of raw or treated wastewater from municipal, hospital, and industrial wastewater treatment plants,
- sewer leakage/sewer overflow,
- landfill leachate,
- and surface runoff from urban or agricultural areas where treated wastewater/sludge or manure waste is applied for irrigation purposes.

Due to the continuous input of CECs into wastewater, the raw influent and treated effluent from wastewater treatment plants are the focus of most literature on CECs (Tran *et al.*, 2018; Baalbaki *et al.*, 2016; Verlicchi *et al.*, 2012, Luo *et al.*, 2014). Tran *et al.* (2018) reviewed monitoring data from literature and came up with a list of primary families of CECs featured in Table 2.4 based on the following criteria: high consumption worldwide, high detection frequencies in wastewater, potential risks to ecosystems and human health, and the availability of the analytical data.

As previously stated, a common characteristic of CECs are their *potential* adverse effects they impose on the environment and human health. Deriving the predicted-no-effect-concentration (PNEC) is generally part of a risk assessment procedure for understanding the impact of different chemical substances in tandem with the probable or measured contamination level (Roman *et al.*, 1999). Risk assessment will be defined in greater detail in Section 2.2.7. The PNEC can be calculated based on either acute (i.e. single time exposure) toxicity or chronic (i.e. long-term exposure) toxicity. The PNEC is an estimate, typically based on either applying an assessment factor to the lowest observed effective concentration (LOEC) or on statistical distribution of ecotoxicity data, of the concentration of a chemical at which above the limit implies adverse effects are experienced (Roman *et al.*, 1999). In Table 2.5, the PNEC limit for the same CECs described in Table 2.4 are recorded. For many CECs, PNECs are yet to be derived, making them difficult to manage.

Table 2.4: Examples of contaminants of emerging concern (CECs) and their uses.

Family	Example	Use
Antibiotics	Amoxicillin	A penicillin-type antibiotic that stops the growth of bacteria. Typically prescribed to fight bacterial (not viral) infections such as tonsillitis, bronchitis, pneumonia, gonorrhea, and infections of the ear, nose, throat, skin, or urinary tract. [1]
Antifungal/ antimicrobial agents	Miconazole	An antifungal medicine that fights infections caused by fungus. Typically prescribed to treat infections such as athlete's foot, jock itch, ringworm, yeast infections, and pityriasis. [1]
Nonsteroidal anti-inflammatory drugs (NSAIDS)	Ibuprofen	A nonsteroidal anti-inflammatory drug commonly used to relieve pain such as from muscle aches, headache, dental pain, menstrual cramps, or arthritis. It is also used to reduce fever and aches from the common cold or flu. [1]
Anticonvulsants/ antidepressants	Carbamazepine	An anticonvulsant or anti-epileptic drug used to prevent and control seizures and to also relieve certain type of nerve pain. [1]
Artificial sweeteners	Sucralose	This artificial sweetener is 600 times sweeter than sugar. Typically used for cooking and sold under the brand name Splenda. [1]
Beta-adrenoceptor blocking agents	Propranolol	A beta blocker is typically prescribed to treat hypertension (high blood pressure) and congestive heart failures. Propanolol effectively reduces the heart rate, blood pressure, and strain of the heart. [1]
Lipid regulating drugs	Bezafibrate	A lipid modifying drug used to lower levels of cholesterol and other lipids (fats) such as triglycerides in the blood. The drug is used to reduce the likelihood of heart disease, heart attacks, or stroke. [1]
Steroidal hormones	Ethinylestradiol	This steroidal hormone is an Estrogen, widely used in oral contraceptives (birth control pills), contraceptive patch, and menopausal hormone therapy. [2][3]
X-ray contrast media	Iohexol	A medication used before X-ray imaging tests (e.g. CT scans) in order to enhance the image obtained. It adds contrast to body parts and fluids in the imaging. [1]
UV filters	Oxybenzone	An aromatic ketone used as a typical constituent of sunscreen, used to protect the skin from harmful ultraviolet solar radiation. [1]
Stimulants	Caffeine	A stimulant to the central nervous system. It has been observed to increase memory, decrease fatigue, and improve mental functioning. Common sources of caffeine include beverages such as coffee, tea, energy drinks, soft drinks; food such as chocolate; medications, diet pills, and supplements. [1]
Anti-itching drugs	Crotamiton	A medication typically used to treat scabies, a skin infection caused by mites. [1]
Insect repellents	Diethyltoluamide (DEET)	A chemical used as the active ingredient in many insect repellant products, available in a variety of forms (e.g. liquid, lotions, spray, and impregnated materials). [2]
Plasticizers	Bisphenol A (BPA)	An organic compound that serves primarily as a building block of plastics and plastic additives. [2]

[1] WebMD, n.d.; [2] PubChem, n.d.; [3] Caldwell *et al.*, 2008

Table 2.5: Predicted-no-effect-concentrations (PNEC) of CECs for resistance selection of bacteria and for ecological toxicity to aquatic organisms. Adapted from Tran et al. (2018).

CECs	PNEC (resistance selection) (ng/L)	PNEC (ecotoxity) (ng/L)
Amoxicillin	100/250	-
Miconazole	-	800
Ibuprofen	-	10
Carbamazepine	-	25
Sucralose	-	-
Propranolol	-	244/<100
Bezafibrate	-	230
Ethinylestradiol	-	<1
Iohexol	-	>1.0 107
Oxybenzone	-	1,6000 (LOEC)
Caffeine	-	5.0
Crotamiton	-	21,000
Diethyltoluamide (DEET)	-	5,200
Bisphenol A (BPA)	-	60

2.1.3 Water Cycle: The Ultimate Transport of Wastes

Water is a major mechanism for transport; therefore, when considering water pollution, the transport of the waste is a dominating topic in the field of water resources management. For example, in the United States, water quality standards take into account downstream users of the water. The hydrologic cycle depicted in Figure 2.4 illustrates the processes involved that move water (and whatever it can carry) in nature. Specific examples of how pollution is transported by the water cycle include atmospheric deposition, infiltration or seepage interactions of surface water sources with groundwater resources, surface runoff, and streamflow. Mitigating waste from contaminating groundwater resources adds another layer of complexity, linking the surface interactions with below ground, to watershed management planning. Since 30% of the earth's freshwater resources are located underground (Gleick, 1993), protecting groundwater from contamination is vital to achieving water security. Both non-point and point source origins of pollution are capable of degrading groundwater quality.

Tracking the movement of wastes in the environment is a major undertaking. Modeling is a powerful tool used in the field of water resources management to simulate reality (see examples of models in Table 2.6). This tool has been used in the creation of water quality standards by creating fate and transport models of contaminants. An understanding of the sinks and flows of water, the transport promoting mechanisms (e.g. weather, elevation change, soil permeability, land use, streamflow), and how humans and wildlife utilize the environment (e.g. wastes produced) is necessary to create a representative model. As with models used in all research applications, assumptions are inherent in models. Understanding and quantifying uncertainty of a model makes the tool useful.

For a more extensive list of water management models with detailed information about the type of model, level of complexity, timestep, hydrology, water quality quantification capabilities for specific target pollutants and expressions, the assumptions used to create the model, model's strengths and limitations, and application history, access the report entitled *TMDL Model Evaluation and Research Needs* by Shoemaker & Koenig (2005).

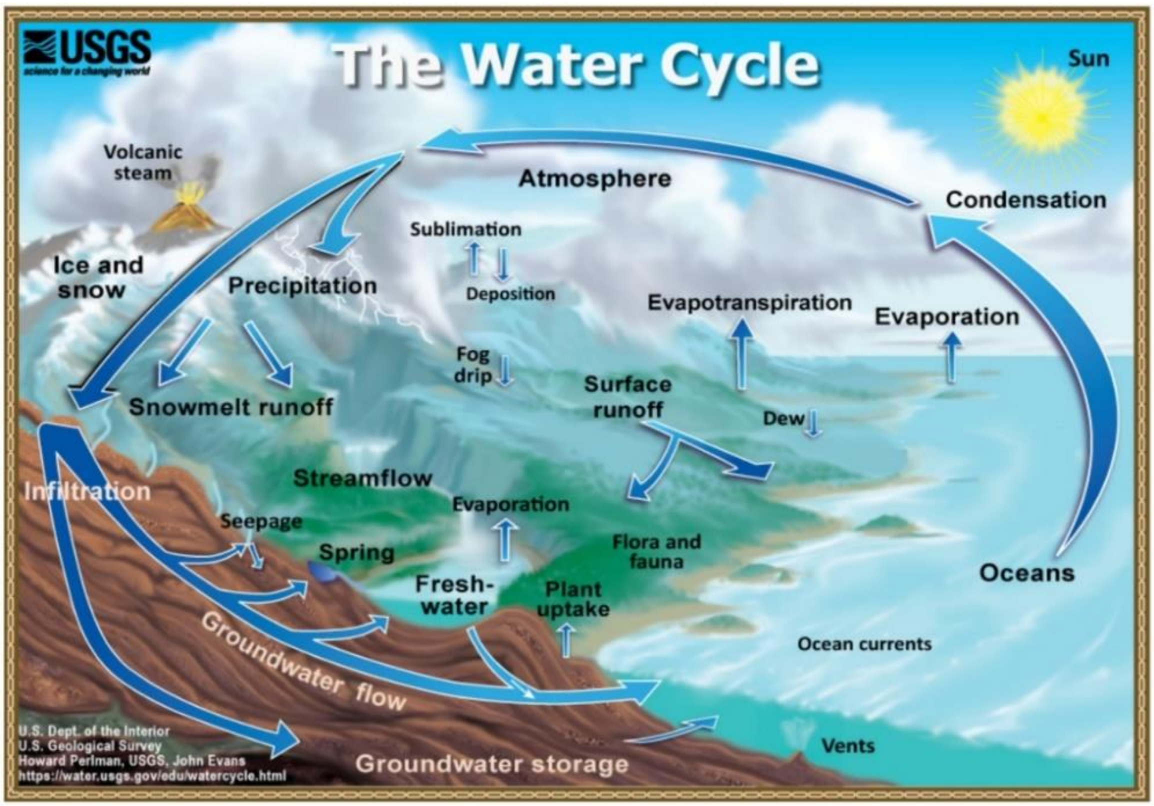


Figure 2.4: The water cycle. Source: USGS, 2017.

Table 2.6: Examples of water resource models currently used in practice.

Examples of Models Able to Quantify Water Quality		
Product	**Description**	**Maintained By**
AQUATOX	This simulation model focuses on the fate of various pollutants and how it affects aquatic life such as fish, invertebrates, and aquatic plants. This includes how contaminants make it up the food chain. Potential applications for this application include water quality criteria and standards, total maximum daily loads (TMDLs), and ecological risk assessments of aquatic systems. [1]	U.S. EPA CEAM
Better Assessment Science Integrating point & Non-point Sources (**BASINS**)	This watershed management model was developed by the US EPA to aid regional, state, and local agencies to perform watershed and water quality based assessments. Example uses of this model is TMDL development, National Pollutant Discharge Elimination System (NPDES) permitting, and nonpoint source programs. BASINS uses GIS to integrate information such as land use, point source discharges, and water supply withdrawals. [1]	EPA/ CEAM
Environmental Fluid Dynamics Code (**EFDC**)	This single-source-code three-dimensional modeling system links together hydrodynamic, water quality, eutrophication, mixing zone dilution, sediment transport, and toxic contaminant transport. The code utilizes finite difference spatial representation. Its general purpose is to create hydrodynamic and transport models able to simulate tidal, density, and wind driven flow, salinity, temperature, and sediment transport. [2] This model is part of the TMDL Modeling Toolbox. [1]	EPA/ CEAM and TetraTech
Hydrologic Simulation Program—FORTRAN (**HSPF**)	This model joins the Stanford Watershed Model (SWM), watershed-scale Agricultural Runoff Model (ARM), and Nonpoint Source Loading Model (NPS) into an integrated basin scale model. It unifies watershed processes with in-stream fate and transport in one-dimensional stream channels. This is one of the few watershed models that is capable of simultaneously simulating land processes and receiving water processes. Newer versions of this model are distributed as part of the BASINS system. [2]	EPA/ CEAM
QUAL2K	This stream water quality model utilizes the advection-dispersion-reaction equations with external sources and sinks to simulate nutrient dynamics, algal production, and dissolved oxygen with the impact of benthic and carbonaceous demand in streams, sediment processes, pH, and alkalinity. [2] This model is part of the TMDL Modeling Toolbox. [1]	EPA/ CEAM
Quantitative structure–activity relationship **(QSAR) Toolbox**	This model assesses potential impacts of chemicals, materials, and nanomaterials on human health and the ecological systems with regression or classification models. [3] It focuses on the intrinsic properties of chemicals (mode of action and ecotoxicological effects).[4] Used to create predictive models for regulatory purposes. [4]	OECD
Storm Water Management Model (**SWMM**)	This dynamic rainfall-runoff simulation model is part of the TMDL Modeling Toolbox. [1] Flow routing can be simulated for surface and sub-surface conveyance and groundwater systems. Quality simulations include traditional buildup and washoff formulation as well as rating curves and regression techniques. Common applications of SWMM modeling include urban hydrologic quantity/quality problems, sewer overflow mitigation, pollution mitigation studies, and stormwater management studies [2]	U.S. National Risk Management Research Laboratory
Water Quality Analysis Simulation Program (**WASP**)	WASP is one of the most widely used water quality models in the world This model can simulate time varying processes of advection, dispersion, point and diffuse mass loading and boundary. [1] The WASP model utilizes three components: WASP for mass transport; EUTRO for dissolved oxygen, nutrients, and algal kinetic; and TOXI for toxic substances. [2] This model is part of the EPA TMDL Modeling Toolbox and can be linked with other hydrodynamic and sediment transport models. [1]	EPA/ CEAM
Water Evaluation And Planning system **(WEAP)**	This model strives to incorporate supply, demand, water quality, and ecological considerations into one integrative water resources planning tool. Within WEAP are built in models for rainfall runoff and infiltration, evapotranspiration, crop requirements and yields, surface and groundwater interactions, and instream water quality. WEAP has been utilized to analyze waterbodies all around the world. [5]	Stockholm Environment Institute
Wellhead Analytic Element Model (**WhAEM2000)**	This is the U.S. EPA's groundwater flow model designed to support the State's Wellhead Protection Programs and Source Water Assessment Planning for public water supplies in the U.S. [1]	EPA/ CEAM

[1] EPA, 2018 ; [2] Shoemaker & Koenig, 2005 ; [3] Cherkasov *et al*., 2014; [4] Organisation for Economic Co-operation and Development & European Chemicals Agency (OECD), 2012; [5] Stockholm Environment Institute, 2018

2.2 The Water Quality Nexus

Water is the ultimate link to sustainable development. All living organisms require water in order to perform functions such as survive, grow, and reproduce (Regional Aquatics Monitoring Program, n.d.). Nutrition's physiological process and waste removal from cells of all living things depends on the utilization of water. (American Geological Institute, 2002). The water in an aquatic environment connects living organisms to an oxygen source (i.e. dissolved oxygen) and food (i.e. suspended particles of organic matter) (Regional Aquatics Monitoring Program, n.d.). Although water is a renewable resource, water is not always present where and when it is needed and the quality of the water may not be sufficient for its intended use (American Geological Institute, 2002). Therefore, information on both the quantity and quality of water is necessary to characterize water resources.

Sustainable development was interpreted by the World Commission on Environment and Development in 1987 as "development that can meet the needs of the present generation without compromising the ability of future generations to meet their own needs." The primary goal of water resources management is water resources sustainability (Mays, 2011). Mays (2007) defines water resource sustainability as:

> *"the ability to use water in sufficient quantities and quality from the local to the global scale to meet the needs of humans and ecosystems for the present and the future to sustain life, and to protect humans from the damages brought about by natural and human-caused disasters that affect sustaining life."*

This section of the thesis will relate the different services provided by water resources to the importance of water resource management.

2.2.1 Degrading Water Quality – A Systemic Global Dilemma

Globally, societies are debating over how to best allocate and manage their water resources. Brondo and Woods (2007) assert that "varying values and expectations of stakeholders often break down the interdependence between environmental sustainability, economic, and social development." Due to the mechanisms that promote the transport of water, local water management can affect water at larger scales, such as within regional catchment areas and national operations (i.e. transfer schemes, industry and trade).

The problem can become even more complex when waterbodies cross over political borders. When changes to the water regime occur, it can cause major impacts on human habitation, agriculture, sensitive ecosystems, economic development, and land use decisions (American Geological Institute, 2002). For water, energy, and food security to be achieved, the problems that persist in water quality must be attacked at a systems level, recognizing the cross-sectoral influences. It requires understanding how systems are embedded within each other and how they interact.

Defining a system is the first step in analyzing a complex problem. Understanding the network, comprised of a wide breadth of interactions which links the system to its surroundings, is what makes looking at water quality such an arduous exercise for research. The vast role water plays in connecting all things in the natural world illustrates how investigating water quality can quickly become a sizable task. As experienced in most engineering research, creating boundaries in which to investigate a problem, in this case deteriorating water quality, tends to create the largest difficulty. Water quality fits within the popularized water, food, energy nexus. In the context of this thesis, the nexus of water and people as well as water and public health is also explored. The water quality nexus is depicted by Figure 2.5.

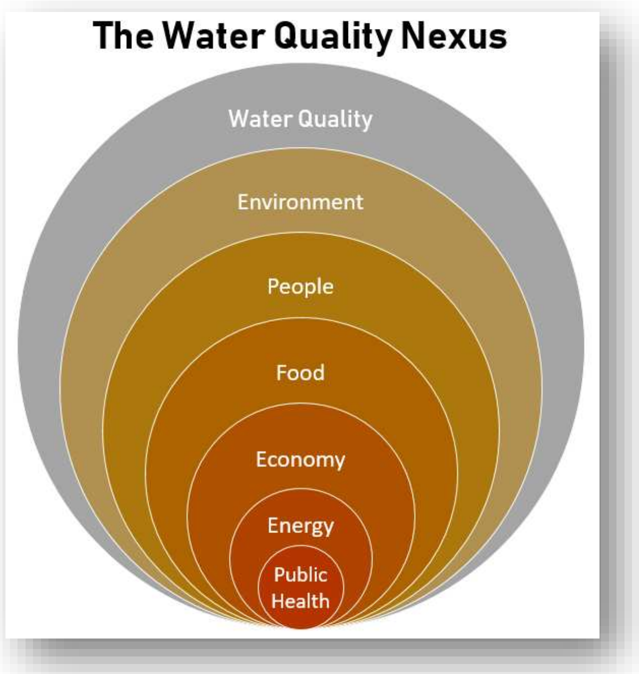


Figure 2.5: The water quality nexus.

The following sections in this chapter are designated to highlight only some significant themes found in water resources management, not to provide an intensive and complete review of what the water quality nexus covers. This thesis seeks only to provide the reader with a demonstration of how to unravel some of the intertwined topics embedded within the water quality nexus.

2.2.2 Water and the Environment

Water covers three-fourths of planet Earth's surface. Although water is typically thought about when it is on the surface (i.e. oceans, rivers, streams, lakes, ponds, estuaries, wetlands, springs, icecaps, glaciers), water is also present underground (i.e. groundwater) and in the atmosphere. Of the Earth's water, approximately 97.5% is salt water and 2.5% is freshwater. The distribution of the planet's water is depicted in Figure 2.6. Within our solar system, the Earth is known for how the abundance of liquid water has shaped life. Water serves many functions. In the ecosystem, water is a medium in which sedimentation and erosion processes can occur. These mechanisms have shaped the landscape and created waterbodies (i.e. flood plains, deltas, beaches) (American Geological Institute, 2002). These waterbodies have served as aquatic

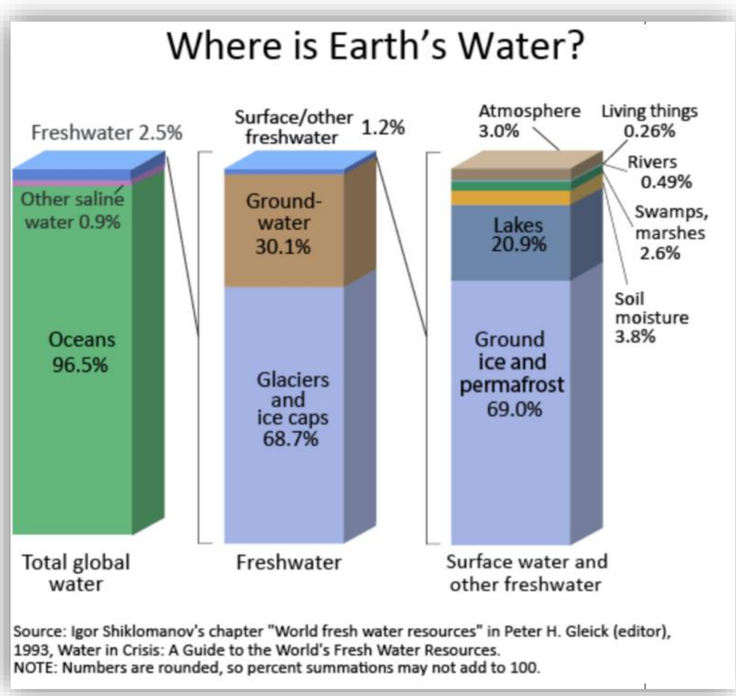


Figure 2.6: Distribution of Earth's Water. Figure from USGS, 2016. Data from Gleick, 1993.

habitats, promoted biodiversity, effected the local climate, provided disturbance regulation (i.e. flood protection, forestalling effects of drought), and created a source of sustenance for living organisms.

Climate, characterized by the amount and timing of rainfall and the temperature in a given location considered over a long period of time, will determine the type of ecosystem (i.e. desert, grassland, rainforest) and what can inhabit it. In terms of precipitation, if there is an event transporting large amounts of water, it may result in flooding and if there is a prolonged dry period characterized by the absence of water, it may result in a drought. The environment also has effect on water regime. The atmosphere and the ocean are intrinsically linked. In tandem they move energy/heat and freshwater globally. The ocean's capacity to store a large amount of heat correlates to its ability to have major effect on the climate (NOAA, n.d.). Nature is also capable of assimilating waste (i.e. pollution control, detoxification); therefore, changing the quality of water. This is an example of an ecosystem service. However, humans are producing more waste than nature can assimilate. Mara (2003) reports that "over half the world's rivers, lakes and coastal waters are seriously polluted by untreated domestic, industrial and agricultural wastewaters."

According to U.N. Water (n.d.), "water is the primary medium through which we will feel the effects of climate change." Recent climate change has caused less predictable weather conditions, more extreme weather events (i.e. increased incidences of floods and more severe droughts), and higher temperatures. These factors will greatly impact the availability, distribution, and quality of water around the world (U.N. Water, n.d.). Contributing to climate change is the lack of wastewater treatment. This absence of treatment exposes the environment to emissions of methane and nitrous oxide which are known to be gases that can greatly contribute to climate change effects (Corcoran *et al.*, 2010). A fifty percent increase in methane wastewater related emissions and a twenty-five per cent increase in nitrous oxide wastewater related emissions is expected to occur between 1990 and 2020 unless action to mitigate contaminating waterways is taken (UNEP, 2010). UNEP and UNHabitat (2010) estimate that in developing countries, an overwhelming ninety per cent of all wastewater is discharged into rivers, lakes or the oceans untreated. The American Society of Civil Engineers (ASCE, 2017) estimates that between 23,000 to 75,000 sanitary sewer overflows occur each year in the U.S. This contributes to 3 to 10 billion gallons of untreated wastewater being released in the U.S. from sewage treatment plants per year (Evans, 2015). Large uncertainty in the estimate provided by Evans (2015) highlights the insufficient monitoring and management of wastewater experienced even in a developed country.

Figure 2.7 depicts temperature and precipitation data between the years 1901 to 2015 to provide insight on the effects of climate change experienced in the United States and South Africa. In both countries, a trend in rising temperatures is observed, as well as a variation in precipitation patterns. The case study of KwaZulu, Natal, South Africa will be presented in the following chapter.

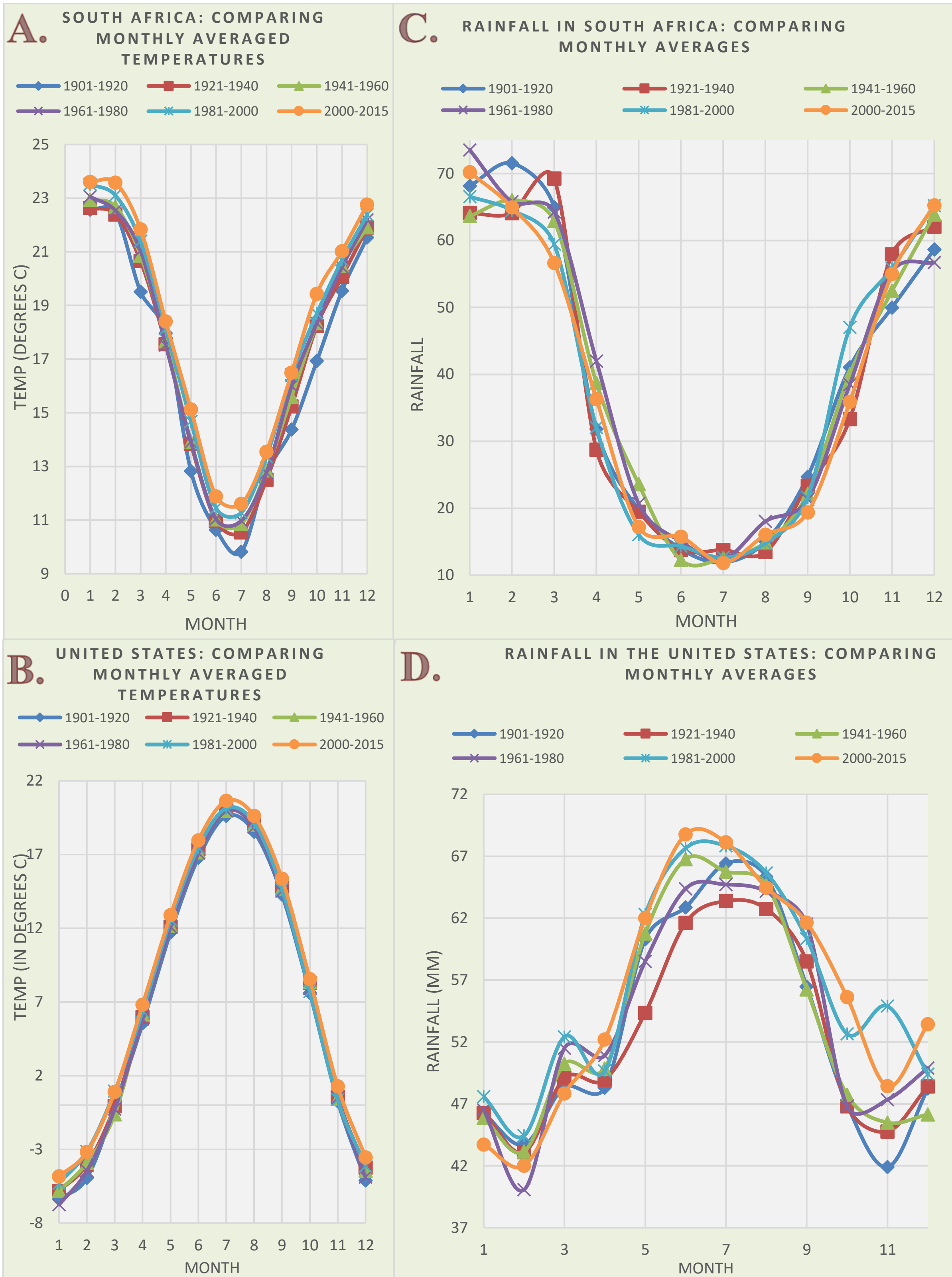


Figure 2.7: Representing climate change effects, temperature data in South Africa and U.S. displayed in plot A and B respectively and precipitation data for U.S, and South Africa displayed in plots C and D respectively. Data sources from World Bank Group, 2016.

2.2.3 Water and Public Health

The Millennium Ecosystem Assessment (MEA, 2005) observes that the health of the ecosystem has many noticeable ties to human health and wellbeing; therefore, taking care of the environment in terms of water resource management is in the best interest of public health. Public health is typically characterized in water resource management in the terms of risk management. Risk considers the load and persistence of pollutants known to cause harm to the health of humans found in a waterbody (i.e. pesticides, fecal matter) and the probability of exposure to that pollutant. According to Bain *et al.* (2014), an estimated 1.8 billion people still drink from water sources threatened by fecal contamination. Wastewater treatment becomes a major proponent of protecting further contamination of this vital resource. The United Nations (2016) cites that in 2015, 4.9 billion people (sixty-eight per cent of the global population) used an improved sanitation facility but that an estimated 2.4 billion people still lacked proper access to these improved facilities. The lack of water or the poor quality of water is a cause of diarrhea which kills around 2.2 million people every year (U.N. Water, n.d.).

The recorded improvement in sanitation coverage does not always correlate with improved wastewater management or public safety. The UN (2017) determined that "only 26% of urban and 34% of rural sanitation and wastewater services effectively prevent human contact with excreta along the entire sanitation chain and can therefore be considered safely managed." Even with the wide coverage provided by the network of U.S. drinking water and wastewater systems, the Centers for Disease Control and Prevention (CDC) estimated the acute gastrointestinal illness per year due to public drinking water systems to be roughly around 4-32 million cases (CDC, 2016c). Gargano *et al.* (2017) identified thirteen diseases caused by pathogens that can be transmitted by water (although they can also be transmitted by other routes such as contaminated food or contact with a sick person) and of which caused almost 7,000 annual total death: acute otitis externa, Campylobacter, Cryptosporidium, Escherichia coli (E. coli), free-living amoeba, Giardia, Hepatitis A virus, Legionella (Legionnaires' disease), nontuberculous mycobacteria (NTM), Pseudomonas-related pneumonia or septicemia, Salmonella, Shigella, and Vibrio). The Gargano *et al.* study found the fecal-oral transmission to only cause 7% of deaths in the United States. The largest waterborne disease outbreak in United States history occurred in 1993 in Milwaukee, Wisconsin. The parasite Cryptosporidium was found in the city's drinking water supply. Over 400,000 people had cases of diarrhea (CDC, 2016b).

2.2.4 Water and Food

With the world population expected to increase from 6.9 billion in 2010 to 8.3 billion in 2030, serious questions are arising about whether there is enough water available to support feeding the world (U.N., n.d. c). Both crops and livestock require water to grow. Globally, the agricultural sector is responsible for 70% of water withdrawals (U.N., 2017). Since 1960, abstractions for irrigation have increased by over 60%. Figure 2.8 illustrates the proportion of total water withdrawn for agriculture. Currently, the food system is extremely inefficient. About 1.3 billion tons, or 30%, of food produced is either lost or wasted each year (U.N., n.d. c). This equates to water being wasted by virtue of the input of water to produce the wasted food.

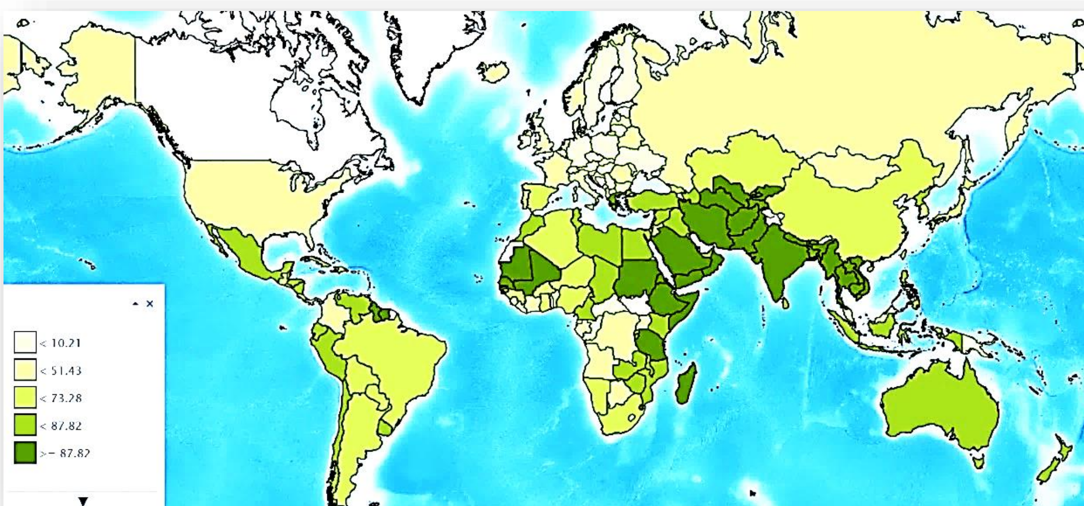


Figure 2.8: Proportion of total water withdrawn for agriculture (%). Source: FAO, 2016.

A growing agricultural sector also has effects on land use. Agricultural fields have been constructed at the cost of clearing forests, draining wetlands, and removing native vegetation which effectively changes infiltration and runoff and the use and distribution of water in a catchment. Land use change of irrigated land in the United States is depicted in Figure 2.9. The figure depicts an increase of irrigated fields of just under 1.3 million acres from 2002 to 2007. Return flows from agriculture typically contain salts, pesticides, and/or increased concentrations of nutrients such as nitrate and phosphorous (American Geological Institute, 2002). These contaminants can impair water quality and affect future water use. The agriculture sector is also responsible for adding to global greenhouse gas emissions, therefore, affecting climate change and the hydrologic cycle (U.N., n.d. c). Climate change will then add stress to food production and water availability in certain areas. The U.N. (n.d. c) predicts that the most vulnerable regions to climate change-related food shortages by 2030 will be South Asia and Southern Africa.

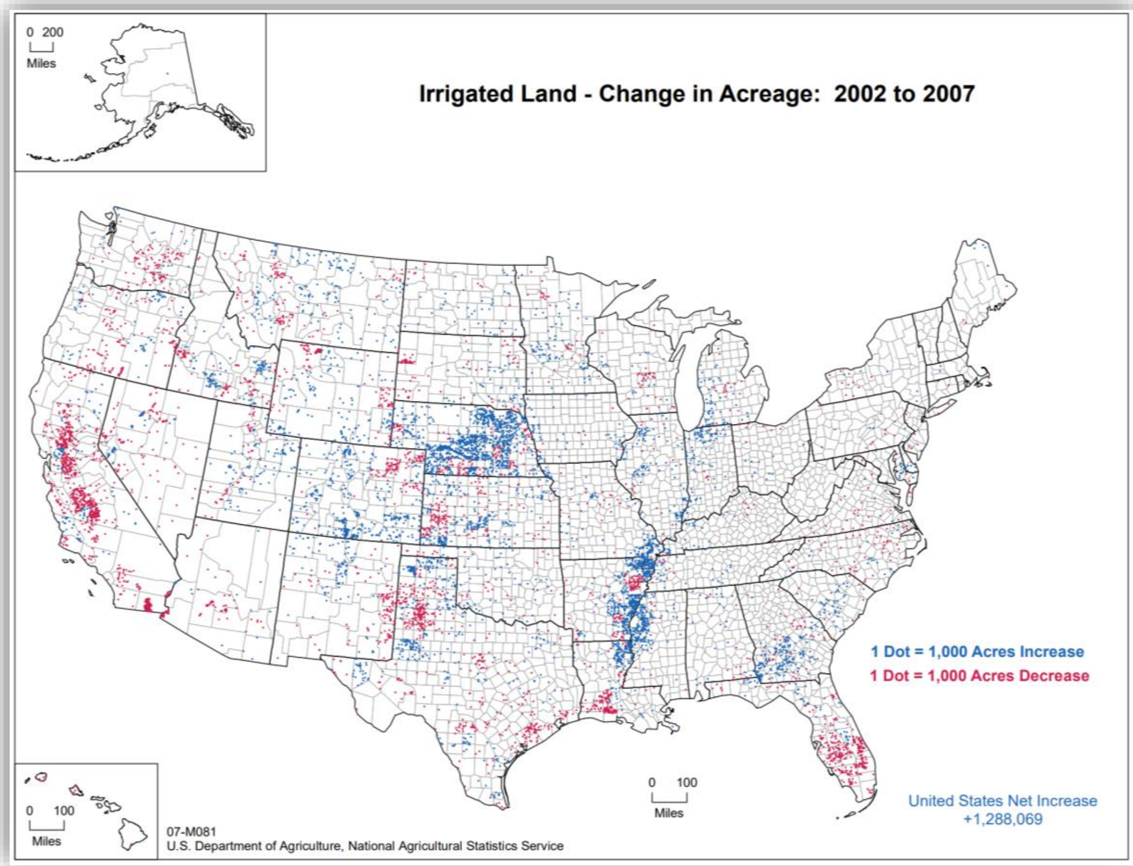


Figure 2.9: Irrigated land use change from 2002 to 2007. Data from 2007 Census of Agriculture Data. Source: USDA, 2017.

2.2.5 Water and Energy

Traditional energy sources have primarily been made up of fossil fuel such as oil, gas and coal. Abas *et al.* (2015) and the World Energy Council (2016) estimate that 86% of total energy produced globally are from these nonrenewable resources. Alternative energy resources, such as nuclear, hydro, geothermal, biomass, solar power, and wind power make up around 14% of the global energy portfolio. Figure 2.10 depicts the energy mix of the global energy supply from 2005 to 2015. Figure 2.11 shows the energy portfolio for the United States and South Africa. Water resources management and energy production are interdependent. When considering all sources of energy, they all utilize water within their production process. Examples where water is vital to energy production include the extraction of raw materials, the cooling of thermal processes, cultivation of crops for biofuel production, and the powering of turbines. Globally, the water withdrawals for energy production is around 15% (U.N., n.d. d). On the other hand, energy is necessary to make water resources readily available for different uses. For example, pumping, transportation, treatment, and desalination are all energy intensive processes (U.N., n.d. d).

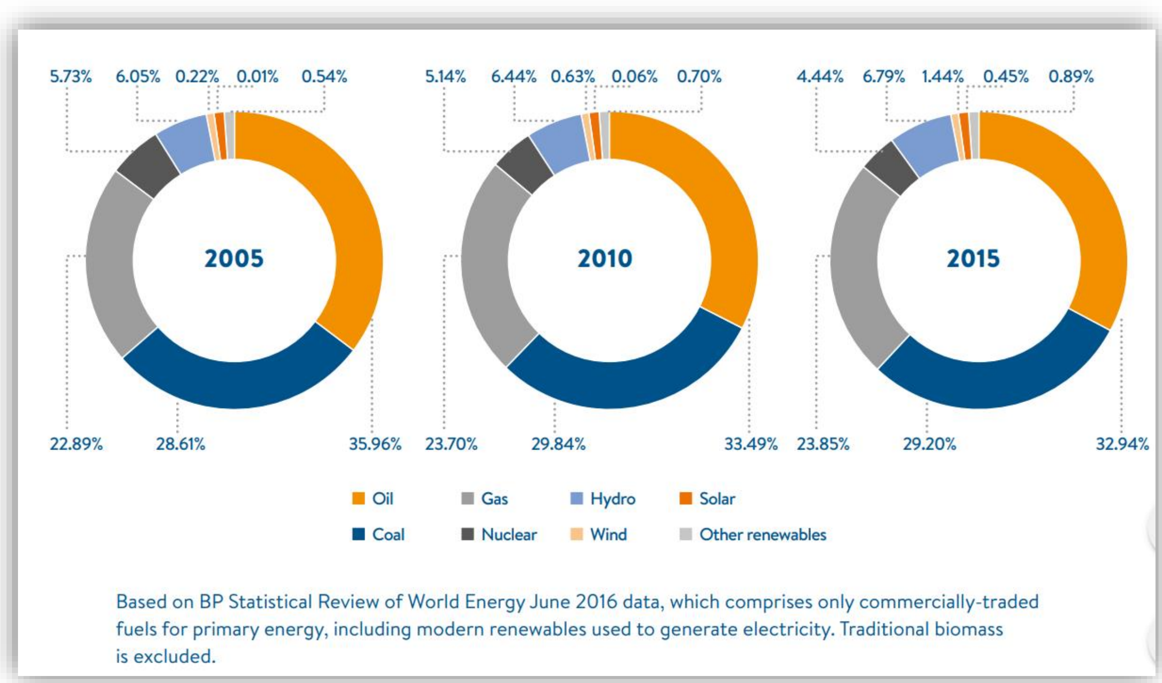


Figure 2.10 Comparative primary energy consumption over the past 15 years. Source: World Energy Council, 2016.

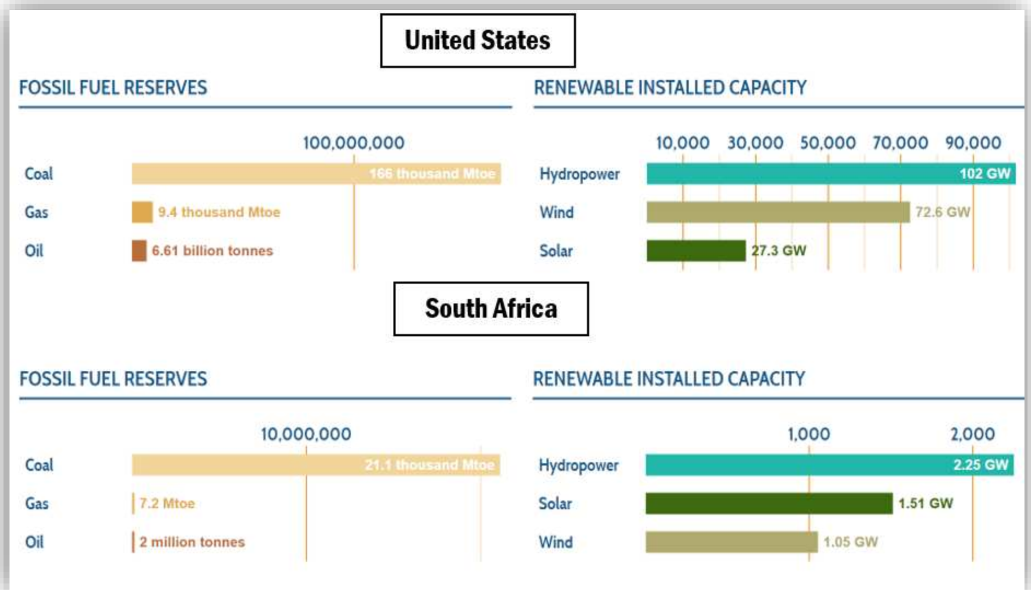


Figure 2.11: Energy resources for South Africa and the United States. Source: World Energy Council, 2016.

Figure 2.12 introduces key facts about the water-energy nexus. The challenge moving forward in the energy field will be providing energy to meet an increasing demand while decreasing water consumption in providing those services and adhering to new, cleaner energy practices in order to mitigate environmental degradation. This generally aligns with a change from conventional sources and technologies to alternative or emerging sources and technologies, echoing the theme portrayed in this thesis on wastewater management. With both the United States and South Africa relying heavily on coal mining and coal powered energy, water quality is heavily impacted in the region if discharged water is not properly treated. Discharged waters from mining operations typically contain high loads of total suspended solids, total dissolved solids, hardness, heavy metals, sulphate, oil and grease, and nitrate (Tiwary, 2001). Sources of water pollution in coal mining areas include (Tiwary, 2001):

1. drainage from mining sites including acid mine drainage and mine water,
2. sediment runoff from mining site,
3. oil and fuel spills/workshop effluents,
4. leaching of pollutants from OB dumps, and
5. sewage effluent from site.

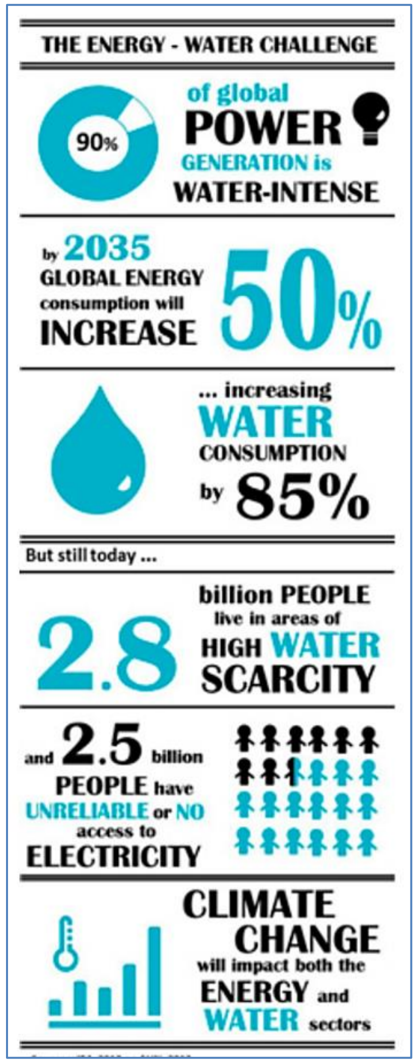


Figure 2.12: The Energy-Water Challenge. Source: U.N., n.d. d.

In addition to waste from the mining, there is high water pollution risk from coal-fired power plants. According to the Natural Resources Defense Council (2014), coal-powered plants account for 72% of toxic pollutants in the United States' waterbodies This is partly attributed to acid rain consisting of harmful pollutants (e.g. sulfur dioxide, nitrous oxides, and mercury) emitted from a plant. Another contributor to water pollution from power plants include water used to manage ash, such as in wet surface impoundments, that if not managed properly can result in runoff into surface water or leaching into groundwater (Natural Resource Defense Council [NRDC], 2014). Process water utilized for cooling thermoelectric plants is also notorious for being discharged at elevated temperatures to the waterbody (Madden *et al.*, 2013). Such as the example provided above for environmental concerns related to utilizing coal as an energy source, each of the different energy sources, including the alternative sources, have their own specific environmental concerns.

Various alternative energy sources utilize energy from water directly (e.g. allowing water to flow through a turbine connected to a generator to produce electricity), using water to cultivate biomass (e.g. growing corn to produce ethanol fuel), or recovering resources from wastewater (i.e. biogas for combustion), Hydropower is the primary alternative energy generation source used globally. In 2015, hydropower accounted for 71% of all renewable electricity (World Energy Council, 2017). In terms of wastewater treatment, energy can be recovered from the wastewater and biosolids it creates. Saad (2017) recognizes that currently in wastewater treatment, biogas is the most prominent form of energy recovered. Biogas is typically combusted on-site for heat or electricity generation, cleaned and sold to local natural gas providers or as fuel for vehicles (Saaad, 2017). In low-income countries, a conventional technique is creating dry fuel bricks from fecal sludge and other organic waste (Saad, 2017).

The World Water Council (2018) utilizes the Energy Trilemma Index Tool to rank countries based on their abilities to provide sustainable energy through the following 3 avenues: (1) energy security, (2) energy equity which entails both accessibility and affordability, and (3) environmental sustainability. Overall, the United States and South Africa achieved an index rank of 15 and 82 respectively in 2017 out of 125 countries. A lower rank (e.g. 1) is indicative of a better score. As Figure 2.13 illustrates, U.S. scored relatively well in energy security and energy equity; however, the United States scored not as well in the area of environmental sustainability. Not only is South Africa ranking not ranking well compared to the United States, but their ranking relative to the other countries has not been improving except within the category of energy security.

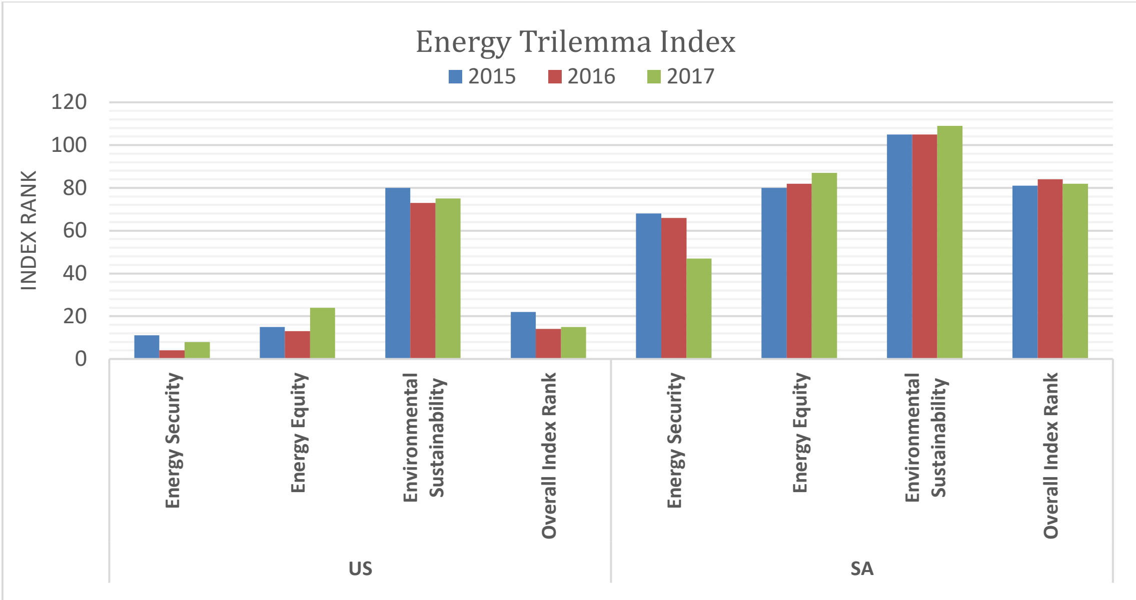


Figure 2.13: Energy Trilemma Index Country Rankings for the United States and South Africa in 2017. Source: World Energy Council, 2018.

2.2.6 Water and the Economy

The market does not reward an investment in public goods (e.g. public infrastructure such as wastewater treatment plant); however, the public goods realm creates civilization (Freeman, 2017). Water is generally categorized as an impure public good. A pure public good is nonrival and nonexcludable, or as defined by Kaul *et al.* (2003), "provide(s) benefits not confined to a single individual and once provided can be enjoyed by many people for free." On the other hand, water is similarly nonexcludable in most societies (e.g. treated as a public commons) however rival in consumption, especially under the conditions of water scarcity (Kaul *et al.*, 2003). With a market failure, there is a net social welfare loss. The market failure is linked to externalities. Economic externality represents a failure of a typical market economy to encompass the full costs of damages to the environment when valuing the production of economic goods (Notovny, 2003). An example of the externality occurring is when the wastes created by producers and consumers affects the cost of the water resource for downstream users. Figure 2.14 illustrates a negative externality, or in other words, when the social marginal costs is greater than the private marginal cost for production. Policy can be used to correct for market failure. Privatization of water and sanitation services

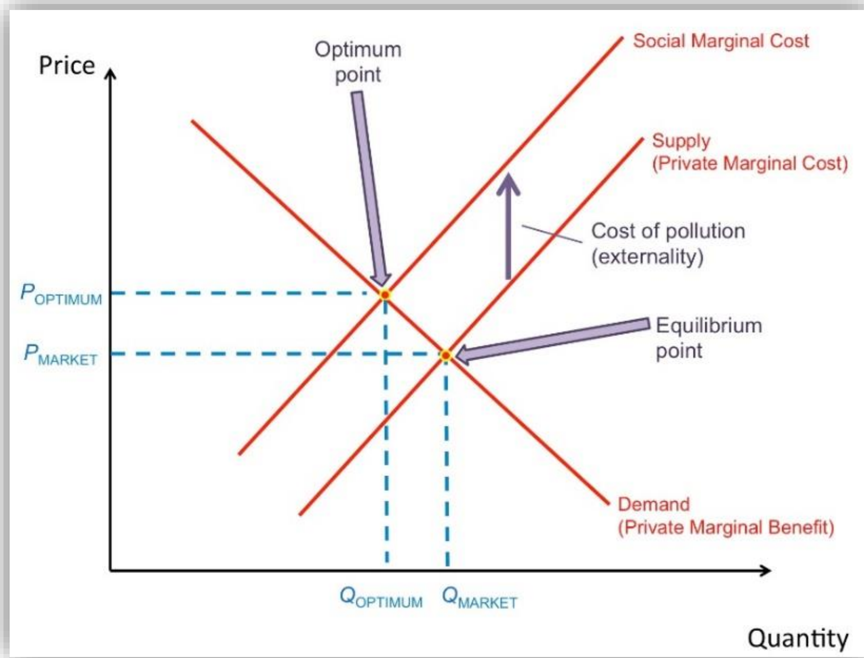


Figure 2.14: Depiction of a negative externality which can lead to market failure. Source: Revisionguru, 2018.

challenges the concept of water as a public good. Water privatization is becoming ever more prevalent around the world. Governments have turned to privatization with the prospect of increasing quality and efficiency of services. Some contentions with privatization of water include concerns of increased fees and unequitable access to services.

The market also severely undervalues the environment, especially in terms of the ecosystem services it provides. In 1997, Costanza *et al.* estimated that ecosystem services were worth at least 33 trillion USD annually. More specifically, 2.3 trillion USD per year valued for waste treatment, 17 trillion USD per year valued for nutrient cycling, and 20.9 trillion USD per year valued for marine activities. To illustrate this, the value of the marine environment will be expanded upon. Over 500 sea outfalls discharge effluent of varying levels of treatment into the sea (International Association for Hydro-Environment Engineering and Research [IAHR] & International Water Association [IWA], 2014). The Institute for Advanced Sustainability Studies (IASS, 2017) reported that around US$1.5 trillion to the global economy can be attributed to ocean-based industries. According to the U.S. Global Change Research Program (USGCRP, 2014), 58% of the United States gross domestic product (GDP) is generated by coastal and ocean activities, such as marine transportation of goods, offshore energy drilling, resource extraction, fish cultivation, recreation, and tourism. According to the UN (2016), over three billion people depend on marine and coastal resources for their livelihoods. The coasts typically attract tourism which largely contributes to the economy of a country. For South Africa, tourism accounted toward 2.9% of the GPD (Statistics South Africa, 2015). Domestic tourism in Durban accounts for an estimated 8% per annum of the region's GDP (eThekwini Municipality, 2011).

Grasping the importance of protecting the ocean environment will occur when the scale of pollution potential at the coasts is translated into how it will impact the economy. A great economic dependence is observed on the ocean resources to the global economy; therefore, it is important to value its environmental health so the resource can continue to be a public benefit. A public benefit implies equity among social groups. Promoting equity by protecting sustainable livelihoods is paramount to the concept of sustainable development. Twelve percent of the world's population's livelihoods are supported by fisheries and aquaculture operations (IASS, 2017). With an investment in wastewater technology and infrastructure, it is an investment in the economy supported by both tourism and marine and coastal resources. Understanding the options available to a coastal community for wastewater treatment can be the difference between a community advocating for wastewater treatment versus accepting the status quo of a sea outfall.

Investing in water, sanitation and hygiene yields more than just a reduction in pollution of water resources but also reduces expenditures on healing impaired health effects due to dirty water, restoring water ecosystems, and repairing the negative impact felt by inland and coastal fisheries. Treatment of wastewater even has the potential to produce capital based on the emerging concept of resource recovery. The ability to expand and preserve tourism and to take advantage of nutrient reuse which can take the form of fecal sludge used as fertilizer or biogas generation are just two examples of how wastewater treatment can create capital benefits (UN-Water, 2014). The World Bank Group (n.d.) reported that the economic benefits of reaching the MDG sanitation target (fifty percent reduction in the proportion of people with lack of access to sanitation) was on the magnitude of $63 billion per year with most of the benefits coming in terms of time savings. According to the Gargano *et al.* (2017) study (introduced in Section 2.2.3), a total cost of $3.8 billion USD was associated with 477,000 annual emergency department visits documented for the selected 13 diseases caused by pathogens that can be transmitted by water. Having communities understand that for every US$1 spent on sanitation, the estimated return to society is US$5.5 may make people concede to the initial investment of putting a wastewater treatment management plan in place (UN, 2017). This is not to say that implementing water, sanitation and hygiene (WASH) will be a financially easy task. Figure 2.15 represents the estimated annual expenditures needed to implement the WASH Sustainable Development Goals (SDGs).

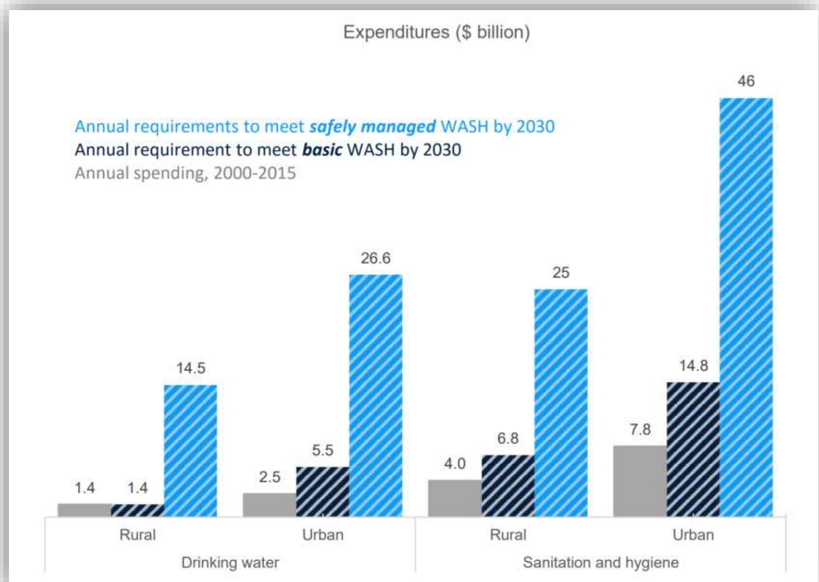


Figure 2.15: Financing needed to meet the SDGs. Figure from World Bank and UNICEF, 2017. Data credited to Hutton and Varughese (2016).

2.2.7 Water and People: Structuring Water Governance

The uniqueness of communities can be characterized by their location, climate, reserve of natural resources, populations demographics, culture, and structure of their institutional arrangements. These attributes directly affect the way people experience the world and how they manage their available water resources. According to The Food and Agriculture Organization (FAO, 2016), about 2,000 to 5,000 liters (approximately 530 to 1320 gallons) of water is said to be used to produce a person's daily food and meet the daily drinking water and sanitation requirements contingent on diet and lifestyle. Rising global population relates to an increase in water demand, as depicted in Figure 2.16. The distribution of water resources does not always align with where demand is located. This is further exasperated with the urbanization trend occurring globally. Figure 2.17 depicts the growth of some of South Africa's most prominent coastal cities. The U.N. (2017) reported that two thirds of the world's population currently live in areas that experience water scarcity for at least one month a year. Approximately 500 million people live in areas where water consumption exceeds the locally renewable water resources by a factor of two (UN, 2017). Saad (2017) remarks that "wastewater is the only source of additional water that actually increases in quantity as population and water consumption grow."

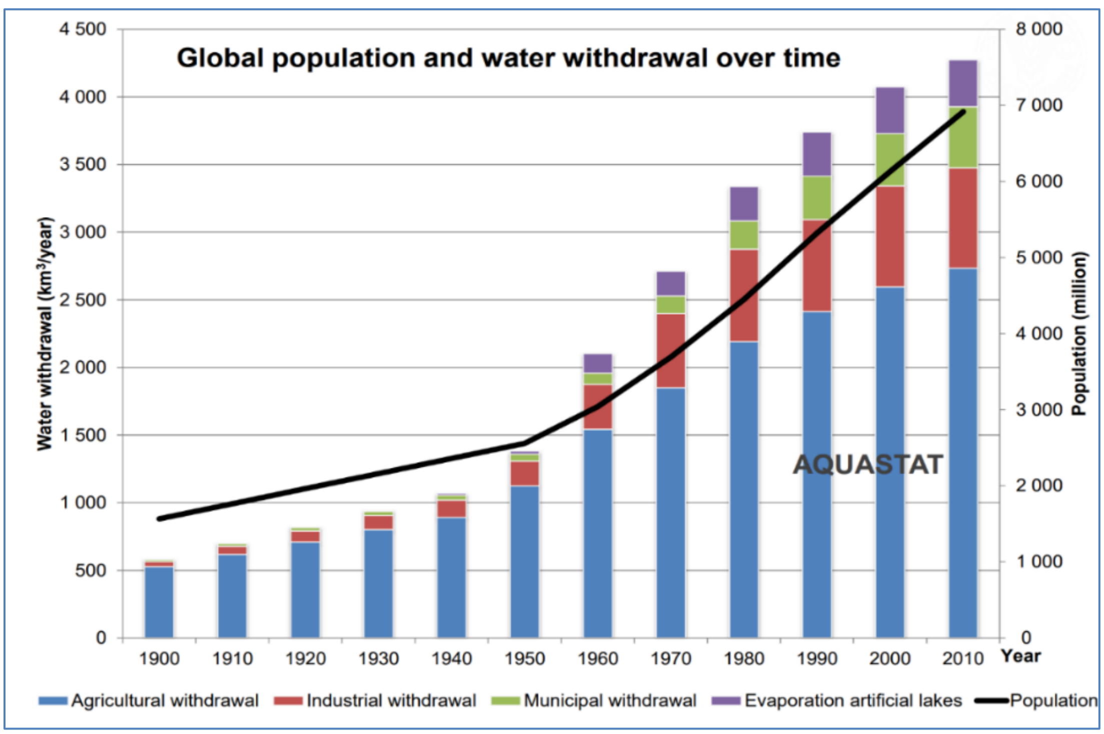


Figure 2.16: Global population and water withdrawal over time. Source: FAO, 2015.

	1995 Population	2015 Population	2030 Population (expected)	% Growth from 2015-2030
East London	204,000	319,000	397,000	24%
Durban	2,081,000	2,901,000	3,349,000	15%
Cape Town	2,394,000	3,660,000	4,322,000	18%
Port Elizabeth	911,000	1,179,000	1,390,000	18%
Total		8,059,000	9,458,000	17%

Figure 2.17: Population growth of some of South Africa's most prominent coastal cities. Population data from Writer, 2015. Map image from Google Maps, 2017.

According to the U.N. (2014) water scarcity can be either the consequence of altered supply patterns (e,g, climate change) or social construct (e.g. society's customs and values). Water scarcity is defined by the U.N. (2014) as "the point at which the aggregate impact of all users impinges on the supply or quality of water under prevailing institutional arrangements to the extent that the demand by all sectors, including the environment, cannot be satisfied fully." This definition provides that water scarcity is a relative concept (U.N., 2014). The concept of global water scarcity is disqualified in the name of the conservation of mass; however, there is an increase in the number of regions that are experiencing chronic water shortages (U.N., 2014). As eluded to above, demand is driven by lifestyle, or in other words, driven by affluence and customary behaviors of a society. Ultimately, the relationship a society cultivates with water and the environment will be analogous to how the society will manage their water resources. Subsequently, societal perception becomes a powerful mechanism for either promoting or depressing evolution of water management practices. Drechsel (2015) observes that ignoring broader social issues that impact the adoption of sustainable solutions prolongs global environmental problems as well as unjust public health and social conditions. Access to education is a leverage point that has the ability to influence social perception of a society.

Risk is “a measure of exposure to possible danger or harm” (Grigg, 2005). The magnitude of frequency of human and ecological exposure are a major component of risk assessments. An environmental risk is due to some physical, chemical, or biological stressor to the environment that may prompt detrimental impacts (EPA, 2017c.). Correspondingly, a human risk is due to some stressor that may prompt detrimental impacts to public health. The risk of an event occurring is the combination of both its probability of happening and the consequences if the event occurred. Risk assessment such as these unveil a society’s vulnerabilities. Figure 2.18 depicts the overall water risk around the world based on attributes such as physical risk quantity, physical risk quality, and regulatory and reputational risk. The status of these attributes is representative of poor management practices of water resources by humans. Both regions in South Africa and the U.S. are determined to be at fairly high water risk (WRI, 2014). In order to put the map (Figure 2.18) into a larger context, Figure 2.19 depicts population density around the world. When the figures are compared side by side, it can be observed that many of the population dense areas are at higher water risk.

Water quality effects quality of life in many regards such as health, livelihood, and recreational and environmental amenities. Sustainable water resources management plays a large role in poverty reduction and enhancing equity. Typically, global assessments, such as the Millennium Development Goals (MDGs) and Sustainable Development Goals (SDGs), use access to water services as an indicator of living standards. National policy has been used to expand WASH services in some cases while in other instances, policy has been used to create inequities. The latter creates distrust for government, typically also fueled by societal fear of corruption. The lack of confidence in the government by the public creates an unhealthy dynamic that can lead to conflict and impede the government’s ability to function. This will become evident in Chapter 4 considering the Apartheid era in South Africa. Access points and incentives for people to participate in policymaking can build a stronger sense of belonging and national identity (Thomas Slayter,

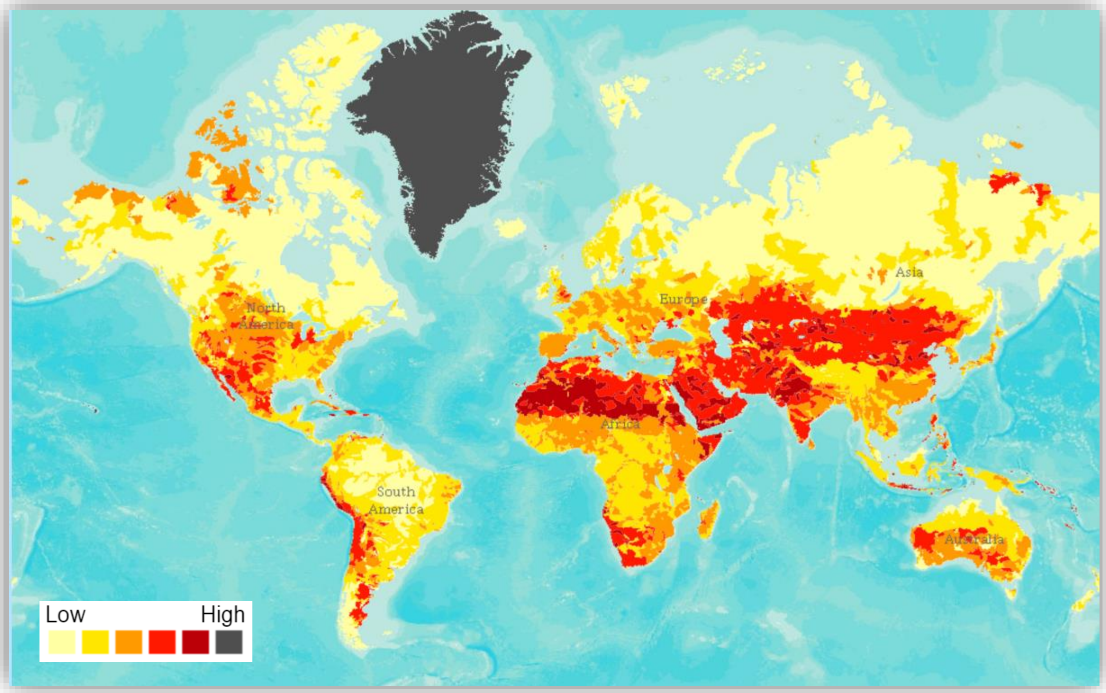


Figure 2.18: Water risk atlas. Source: World Resource Institute, 2014.

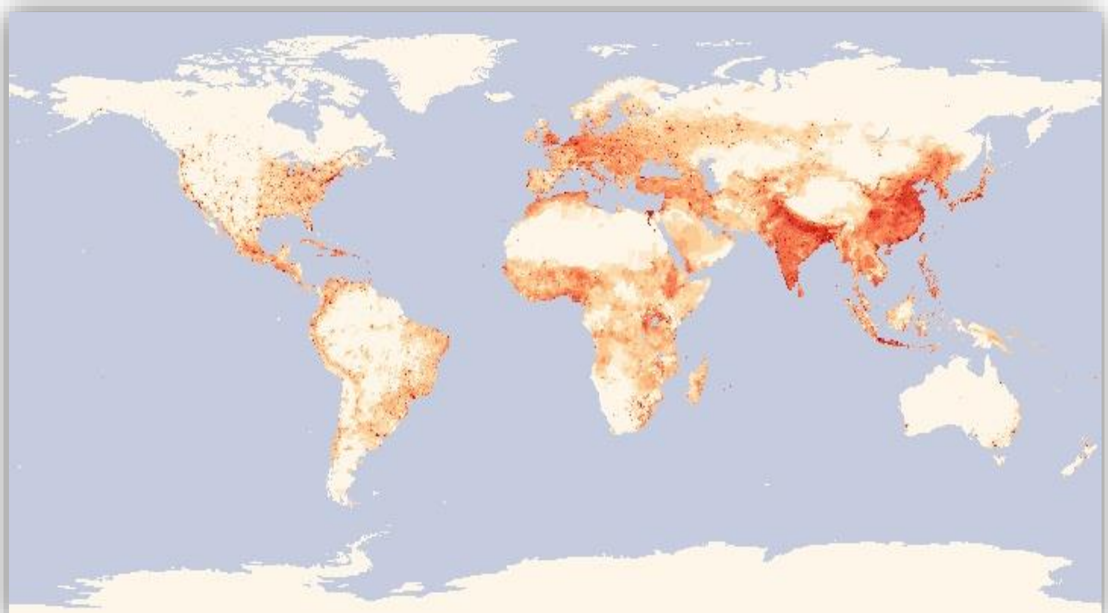


Figure 2.19: Map of population density. Source: NASA, 2000.

2003). Building national identity can help create resilience in the societal system. Gaining a sense of community identity within a society can empower people to strive to further improve the society in which they live.

Preventing pollution, or in other words, eliminating the production and discharge of pollutants, is considered the idealistic strategy to protect waterbodies from contamination; however, cultural values, economy development, and population growth make this strategy alone impractical. The U.S. Department of the State (2016) describes water as “a fundamental cornerstone to maintaining global peace, security and prosperity.” Water resources planning is defined as an integrative problem-solving process that generally involves making plans and collaborating to solve problems using collective action. Aspects of water resource planning include policy development, river basin coordination planning, infrastructure planning, operations planning and assessment, financial planning, conflict management, and public health action (Grigg, 2005). Basic water resources planning originates, as fundamental principle of basic societal planning, to meet societal demands. Drivers, such as population growth, urbanization, public health concerns, and a degrading environment, advance the development of water resources management for a society. Figure 2.20 illustrates examples of how the evolution of wastewater treatment practices can transpire in conjunction with the development of water resources management. This progression of water resources planning and management, specifically considering the transformation of wastewater treatment, will be described in greater detail in Chapter 3 and further illuminated in Chapter 4 in the eThekwini Municipality, South Africa case study. In order for a society to transition to more effective and efficient wastewater treatment technologies and practices, water managers must seek buy-in for the project from the community.

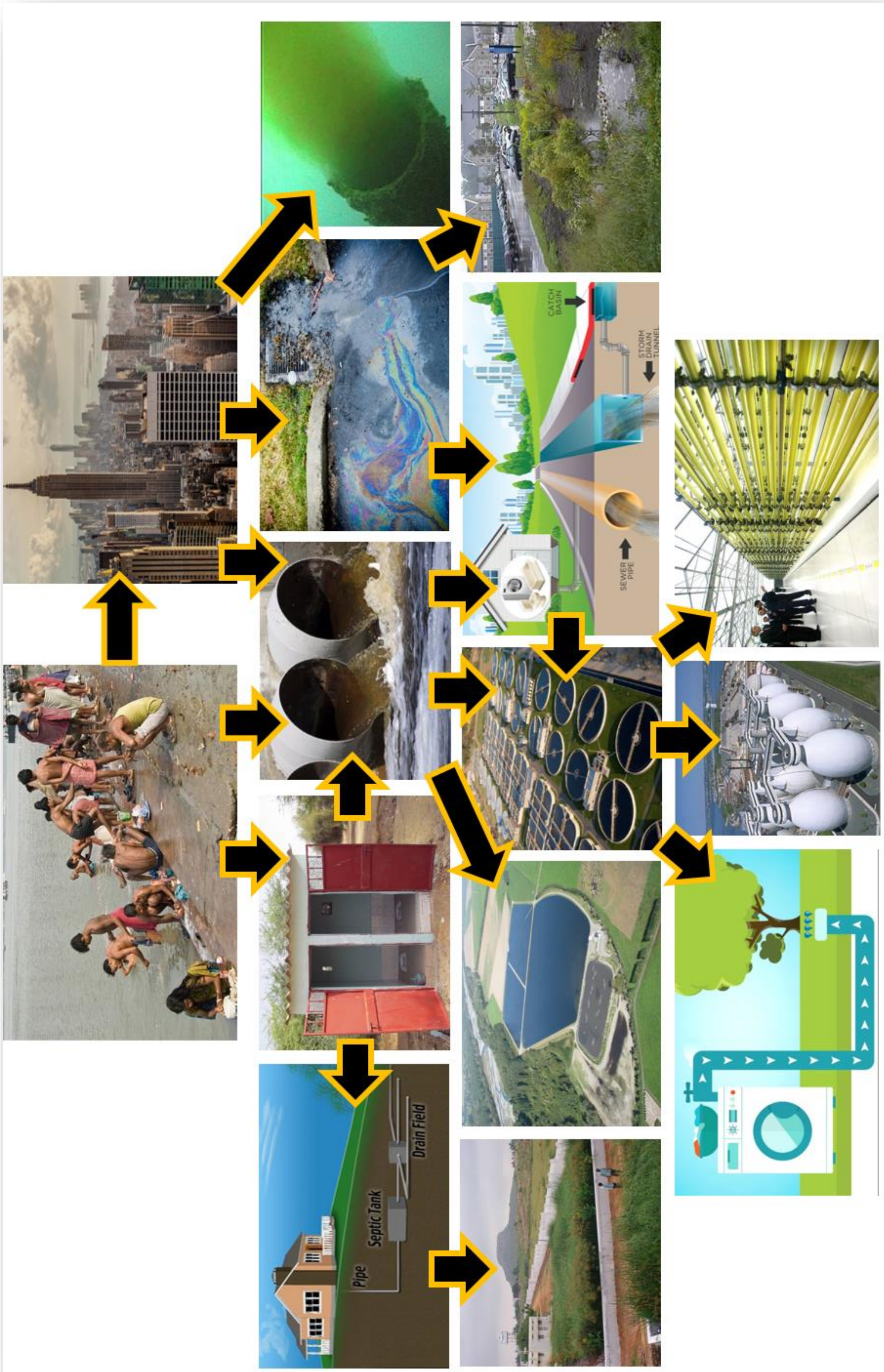


Figure 2.20: A depiction of the evolution of wastewater treatment practices.

CHAPTER 3. THE EVOLUTION OF WASTEWATER TREATMENT

3.1 Introduction

This section of the thesis will outline different classes of technologies used to treat wastewater. The following classes of technologies depict a general evolution of wastewater treatment technologies: dilution technologies, conventional technologies, alternative technologies, and emerging technologies. See Figure 3.1 for an illustration of the evolution of wastewater treatment technologies. Chapter 4 will go into further detail on the evolution of wastewater treatment technologies utilized in South Africa.

The primary motivations and intervention chosen for treating wastewater will vary at a local level. This will be explored further in Section 3.5 on the factors that contribute to the adoption of certain technologies over others in developed regions versus developing regions and rural areas versus urban areas. Although treating water is managed at a local level, the significance of treating wastewater is of global interest. Some of the reasons discussed previously that make protection of water quality significant on a larger scale include water's ability to travel beyond communities and political borders and the implications poor water quality has on societal development which can inhibit

1. the growth of world markets and international trade,
2. the progress of global public health benchmarks,
3. the advancement of human rights,
4. the mitigation of climate change
5. the establishment of water security that can prevent displacement of people (e.g. climate refugees), and
6. the avoidance of international conflicts.

The technologies explored in this section do not represent all technologies utilized in the field of wastewater treatment. The technologies provided in this section do however portray a conceptual framework for the evolution of the wastewater treatment field.

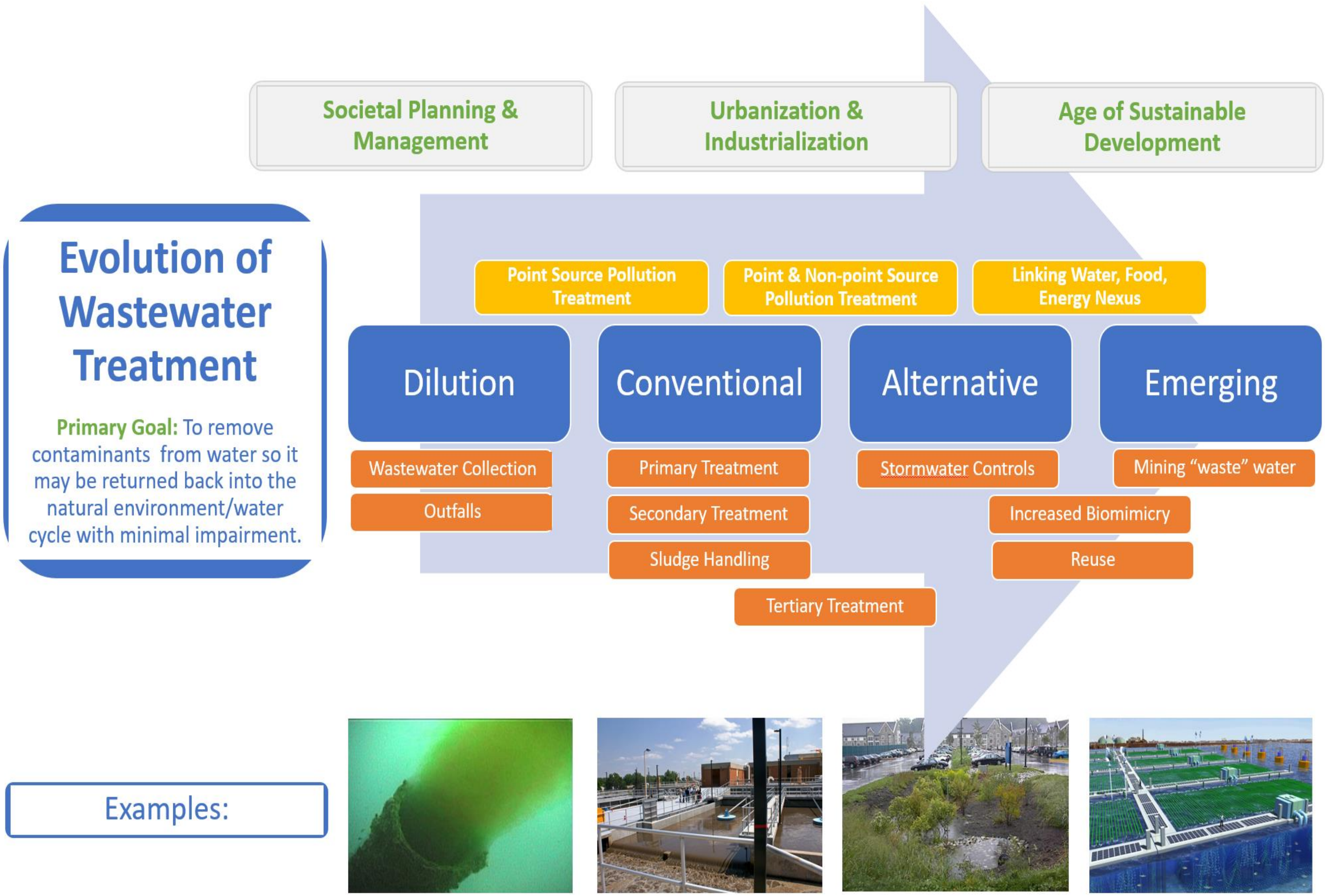


Figure 3.1: The evolution of wastewater treatment field.

3.2 Dilution

In the context of this thesis, dilution practices represent no to very minimal application of technical wastewater treatment and the most primitive methods for managing wastewater. These practices rely heavily on the environment to assimilate waste. Dilution practices include open defecation, latrines, and wastewater conveyance systems that lead to the disposal of contaminants into the environment, such as into the ocean, irrigation fields, and surface water bodies. Figure 3.2 depicts dilution practices in terms of centralized and decentralized practices and illustrates different disposal routes of the waste into the environment.

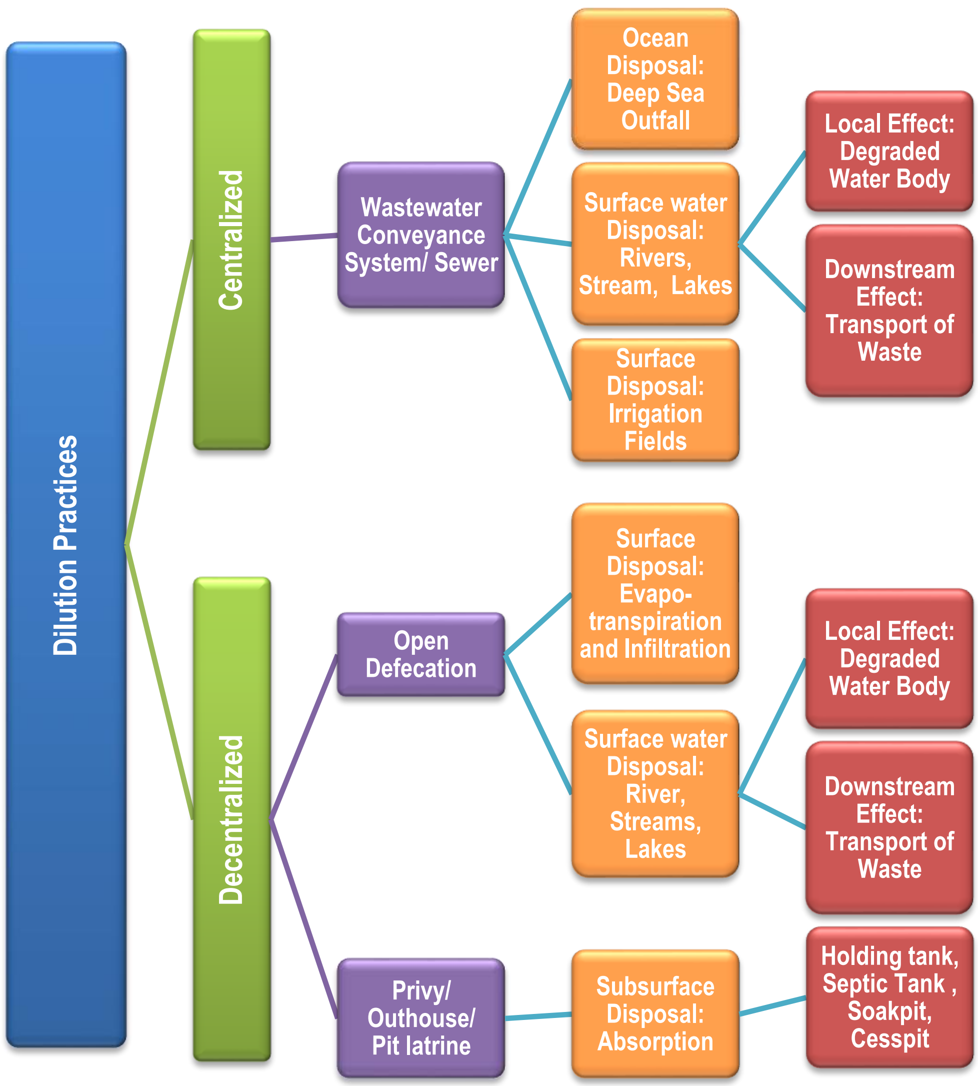
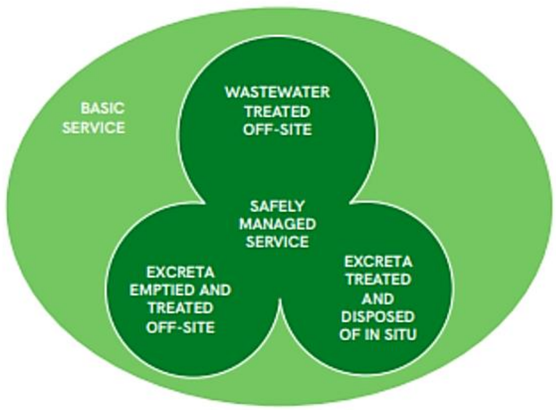


Figure 3.2: Dilution practices for wastewater.

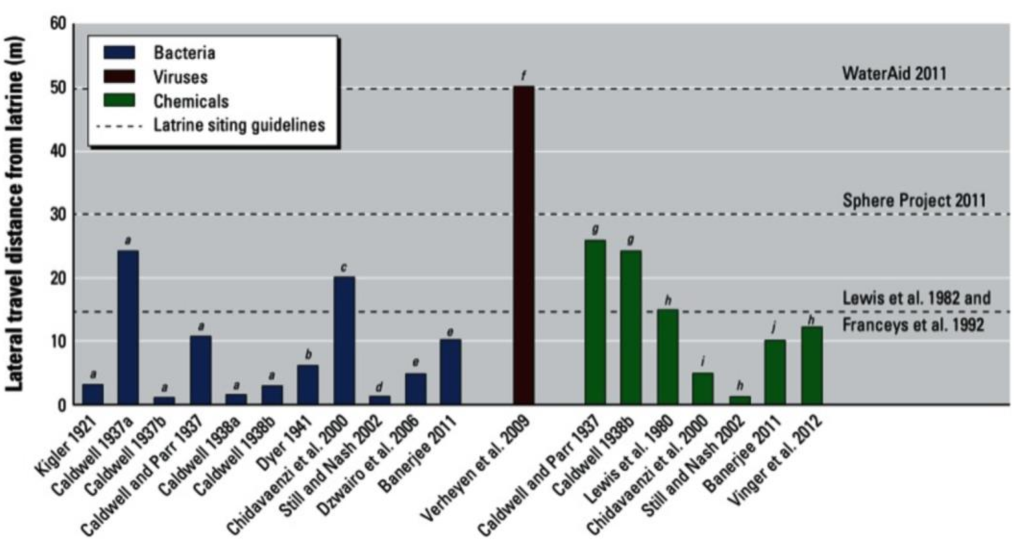
On a timeline representing methods of human waste disposal, open defecation would be the first and most basic scenario. Even though the method may seem primal, nearly 1 billion people worldwide still practice open defecation (U.N., 2017). It does not rely on technology. As insinuated by having the lowest service level ranking in Figure 3.3, the practice is not deemed appropriate at the international scale; however, the practice of open defecation hinges on society dynamics and acceptance, or in other words, cultural relativism. When this practice is not challenged by public shaming, a link between decreased public heath due to poor sanitation practices, or external intervention, then the practice becomes the status quo for a community.



SERVICE LEVEL	DEFINITION
SAFELY MANAGED	Use of improved facilities that are not shared with other households and where excreta are safely disposed of in situ or transported and treated offsite
BASIC	Use of improved facilities that are not shared with other households
LIMITED	Use of improved facilities shared between two or more households
UNIMPROVED	Use of pit latrines without a slab or platform, hanging latrines or bucket latrines
OPEN DEFECATION	Disposal of human faeces in fields, forests, bushes, open bodies of water, beaches or other open spaces, or with solid waste
Note: *improved facilities include flush/pour flush to piped sewer systems, septic tanks or pit latrines; ventilated improved pit latrines, composting toilets or pit latrines with slabs.*	

Figure 3.3: The Joint Monitoring Program (JMP) ladder for sanitation services. Source: WHO and UNICEF, 2017.

When open defecation is challenged by one of those conditions, a more involved method of waste management is typically subsequently initiated. To address controlling human exposure to waste and increasing privacy, constructing privies is generally the first sanitation intervention method utilized. It is estimated that 1.77 billion people use a type of pit latrine as their primary sanitation means. Common contaminants from excreta in these onsite sanitation systems are of microbial (e.g. bacteria, archaea, microbial eukarya, viruses, protozoa and helminths) and chemical (e.g. nitrate, phosphate) concern. Within several months of using a latrine, a biologically active "scum mat" can form around a latrine pit that can mitigate the movement of fecal material by filtration and predation by antagonist organisms. A systematic review by Graham & Polizzotto (2013), based on 24 studies considering transport of microbial and chemical contaminants from pit latrines, found that groundwater contamination was frequently observed downstream; however, the distance of which the contaminants transported were extremely variable. Figure 3.4 displays the lateral distance of different contaminants of the studies considered in the review. The dashed lines in the diagram illustrate recommendations for latrine siting guidelines from different organizations. (Graham & Polizzotto, 2013).



[a]B. coli; [b]total coliforms; [c]coliforms; [d]fecal coliforms; [e]total and fecal coliforms; [f]adenovirus and rotavirus; [g]chemical stream (nitrate, nitrite, and chloride); [h]nitrate; [i]nitrogen; [j]salt tracer.

Figure 3.4: Lateral travel distances of different contaminants emanating from pit latrines in relation to select latrine/water-point siting guidelines. Verheyen et al. (2009) and Vinger et al. (2012) used existing wells to approximate distances, whereas all other studies used test wells to measure distances.

The service level designations given in Figure 3.3 can be achieved though different design parameters for privies (see Figure 3.5 for various types of latrines). Design parameters and technological upgrades to pit latrines affect the containment of contaminants, the degree of treatment of waste that occurs which is primarily based on retention time in the system, and the servicing needs of the latrine. Graham & Polizzotto (2013) observed:

1. liners are able to minimize seepage to groundwater,
2. raised latrines can increase vertical separation and promote aerobic digestion of waste,
3. upgrades such as urine-diverting methods, painted ventilation tubes, and chemical amendments to latrines can minimize nitrate formation and its eventual leaching to groundwater, and
4. upgrades such as composting toilets and ecological methods can reduce the microbiological risk and chemical leaching from latrines.

Jointly, the design and society's interaction with the technology effectively determines whether it will create beneficial or detrimental outcomes, or whether the technology is even accepted into society. In order for dry sanitation systems to stay in commission, manual collection of waste is necessary whether it be by the community, government, or service authority. If managed properly by the community, the excreta stored onsite can be used as a means of resource recycling of organic material. When latrines are not properly maintained, they can overflow leading to nonpoint source pollution. Due to the dependency of pit latrines on permeability of soil, too many latrines in a small area (i.e. high density urban areas) can lead to overloading the infiltration capacity of the area (Rose, 1999). For more information on the different types of latrines, specifically the principles of operation, the operational and institutional requirements, costs, and their experience in South Africa, refer to the *Sanitation for a Healthy Nation: Sanitation Technology Options* by the South African Department of Water Affairs and Forestry (2002).

When a society begins to grow in population and develop greater capacity for societal planning and management (e.g. organizational structure, availability of funding and technical resources), communal infrastructure such as centralized conveyance systems is typically the next technological jump. The purpose of a conveyance system is to remove the waste from where people live. A cluster system represents a system that serves up to 100 homes whereas the conventional centralized system represents larger systems (Massoud *et al.*, 2008). Cluster systems can direct wastewater to decentralized on-site systems for

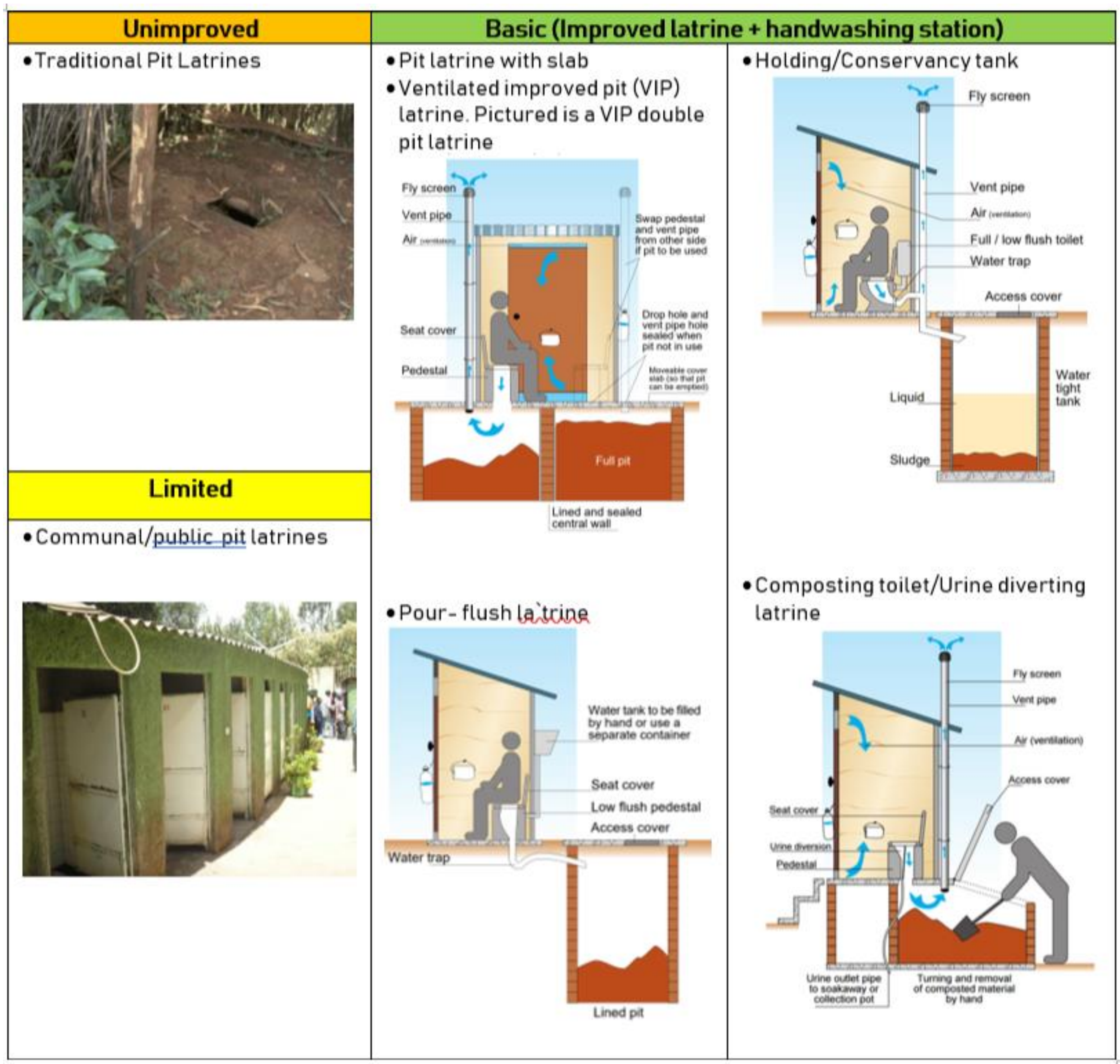


Figure 3.5: Types of latrines and their respective level of service.
Pictures in Unimproved and Limited Latrines categories from the Open University (2016). Pictures in Basic Latrine category from the South African DWAF (2002).

treatment, such as to large septic tanks and absorption fields, or to more centralized off-site systems, such as conventional treatment technologies that will be discussed in the following section. Larger centralized sewerage systems may also lead the wastewater to off-site conventional treatment systems. On the other hand, both types of sewer systems have also been observed to lead untreated wastewater to a surface water body such as a river that sends the contaminated water downstream, a lake that degrades due to exceedance of its assimilative capacity for waste, or the ocean through an outfall. For instance, a billion liters of sewage is dumped into the ocean everyday by Sydney, Australia (Barlow, 2009). In Latin America, less than fifteen per cent of the wastewaters collected in cities and towns with sewers is treated prior to discharge (Mara, 2003).

The old philosophy of relying solely on dilution practices, represented with the memorable phrase “the solution to pollution is dilution," is even now perpetuated by cultural norms and enshrined into policy. This philosophy is still represented in most countries regulating policies. For instance, In the *South African Water Quality Guidelines for Coastal and Marine Waters*, it states that it “recognised that the marine environment has a certain capacity to assimilate waste without detrimental effect” (South African Department of Water Affairs and Forestry, 1995). Mara (2003) prescribes a dilution of greater than 500 in the receiving watercourse in consideration of not treating wastewater as acceptable, describing that this dilution factor can make the pollution negligible. Dilution cannot be a complete response to wastewater management due to

1. the growing amount of waste being produced which is exceeding the environment’s capacity to handle as demonstrated by the number of degraded waterbodies;
2. the types of waste being produced that the environment is not able to assimilate; and
3. the uniqueness of flow, ecological, and climate conditions of regional areas.

For example, dilution is not the solution to chemicals that bioaccumulate. Observations of this have been recorded via studies of fish with varying levels of organic contaminants and pharmaceutical chemicals such as the study completed by Maruya *et al*. (2012) near the outfalls of discharging treated wastewater effluent. A long outfall does not always account for currents and internal waves that push polluted water back toward the shores where important ecological structures such as coral reefs and grassbeds generally form and where people generally interact directly with the water (DeGeorges, Goreau, Reilly, 2010). Between ten to twenty-five percent of the bathing zones in the North Sea do not adhere to standards enforced by the EU (GESAMP, 2001). Over 3 billion people depend on marine and coastal resources for their livelihoods (UN, 2016). These livelihoods are being put at risk provided that over 500 outfalls discharge effluent into sea (IAHR/IWA, 2014)

Education, especially on the implications of not treating wastewater, will play a major factor in transforming cultural norms to safer and healthier practices for both people and the environment. As will be discussed, regulation has a large impact in evolving the wastewater management practices, especially in terms of requiring levels of treatment. Mara (2003) observes that all too often, decision makers become complacent with the status quo of discharging untreated wastewater. Therefore, large amounts of untreated wastewater continue to be discharged into the natural environment, especially in developing countries or developed countries that utilize combined sewer systems that consistently overflow.

3.3 Conventional Wastewater Treatment Technologies

The term "conventional" in the context of this thesis is relative to societal development and location. Conventional wastewater treatment technologies encompass the implementation of technologies and practices commonly utilized and regulated to treat wastewater in order to meet water quality objectives set by government institutions. Based on this definition, pit latrines and septic tanks can be classified as both dilution practices and conventional wastewater treatment technologies. A typical wastewater treatment system is comprised of 3 basic components: collection, treatment, and disposal (Massoud *et al.*, 2008). The section above on dilution practices focuses primarily on the collection of waste. With collection practices in place, adding more technical treatment and disposal components is the concentration of conventional wastewater treatment technologies. Including treatment into the wastewater management strategy for a society is usually a reaction to urbanization and/or industrialization leading to an increase of public health issues in a region. This section will highlight processes and technologies based on conventional centralized practices of developed regions and appropriate treatment options for less developed regions. The factors that are considered for implementing technologies in a developed or less developed region is illustrated in Table 3.1. Implementation of appropriate technologies will be discussed in greater detail in section 3.6.

Table 3.1: Comparison of Factors of Importance in Wastewater Treatment in Industrialized and Developing Countries. Source: Mara, 2003.

Factor	*Industrialized countries*	*Developing countries*
Efficiency	C•••••	••••
Reliability	C•••••	C•••••
Sludge production	•••	C•••••
Land requirements	C•••••	••
Environmental impact	••••	••
Operational costs	•••	C•••••
Construction costs	••	C•••••
Sustainability	•••	C•••••
Simplicity	•	C•••••

Notes: C, critical; •••••, extremely important → •, no impact
Source: adapted from von Sperling (1996a*)

The conventional process of treating wastewater in a centralized wastewater treatment facility is generally categorized in four stages: pretreatment, primary treatment, secondary treatment, and the sludge handling. Tertiary or advanced treatment is an additional treatment step; however, this step is less commonly utilized then the other steps preceding it (Mara, 2003). During the pretreatment, equalization to even out organics loading to avoid shocking the system and grit removal to remove the large inert materials occurs. Primary treatment builds on the pretreatment by removing suspended inert materials through clarification. Secondary treatment generally consists of an activated sludge system that oxidizes biological carbon and nitrogen for the removal of BOD. Further clarification removes suspended biological materials. In tertiary treatment, nutrient removal to reduce the concentrations of phosphorous and nitrogen occur as well as filtration and disinfection. Filtration removes any remaining particulate matter and disinfection deactivates the remaining pathogens. The final step is handling the sludge removed from the wastewater. Digestion and dewatering are used to reduce sludge volume, generate methane, and then make the solids more compact for transport.

Mara (2003) considers the following as appropriate wastewater treatment options for developing regions: waste stabilization ponds (WSPs), wastewater storage and treatment reservoirs (WSTR), constructed wetlands (CW), often simply called ‘reedbeds’, upflow anaerobic sludge blanket reactors (UASBs), biofilters, aerated lagoons, oxidation ditches, and lime-assisted primary sedimentation. Most of these technologies embody natural treatment processes and are less energy intensive processes. In order to perform, they require sufficient land availability; therefore, land availability and cost of land can play a large role in deeming if such a technology is feasible for a community. This technology, usually considered as “low tech”, has less operation and maintenance costs when compared to a “high tech” centralized wastewater treatment plant. This is especially apparent in the electrical energy costs that are necessary to meet the pumping requirements for a centralized system (Mara, 2003). Based on the concept of conventional and appropriate technology, Figure 3.6 illustrates technologies that are used in developing and developed settings.

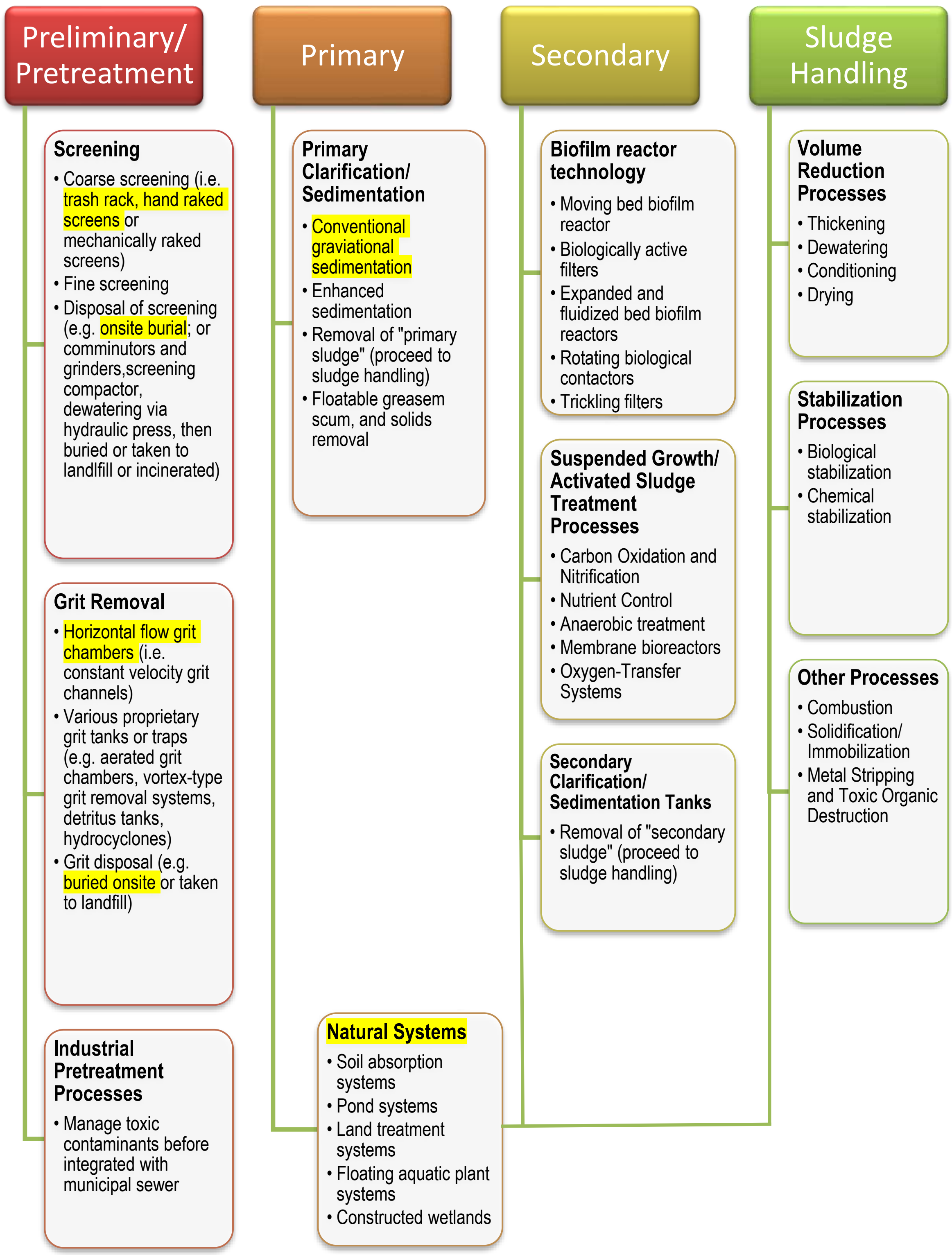


Figure 3.6: Treatment Technologies. Technologies highlighted in yellow signify that they may be used as an appropriate option for a developing region. Information from EPA (2003), Mara (2003), and Water Environment Federation (WEF) (1998).

3.3.1 Preliminary Treatment

Although domestic wastewater is typically comprised of 99.9% water as depicted in Figure 3.7 (Tebutt, 1988), the small percentage of solids in sewage can disrupt the subsequent treatment processes. The screening to remove coarse solids (e.g. large solids, debris, rags) and the grit removal to separate heavy and inorganic solids reduces adverse effects such as increased wear and maintenance on wastewater treatment equipment; however, preliminary treatment has very little effect on the water quality (EPA, 2003).

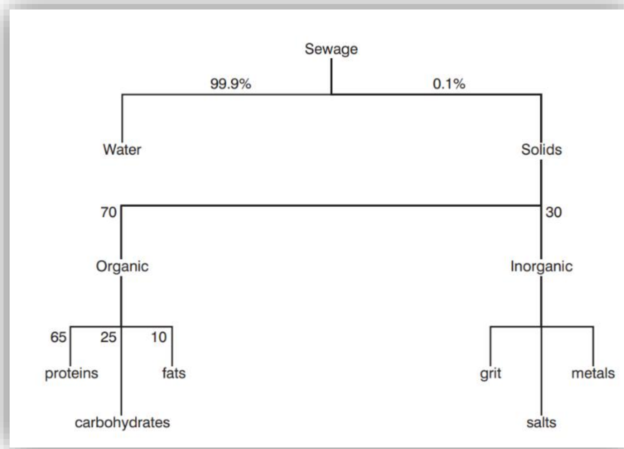


Figure 3.7: Composition of domestic wastewater.
Source: Tebbutt (1988)

Fine screens can be used to remove finer suspended solids. When fine screens (0.2 to 1.5 mm) are placed after course screens, suspended solids can be reduced to levels that almost match the efficiency of primary clarification. Depending on the material in which fine screens are made, cleaning oil and grease from the screens can be extremely difficult. Comminutors and grinders, typically utilized in smaller plants (less than 5 MGD), prevent jamming and wear of downstream treatment operations by shredding coarse solids. Due to the energy requirements for a comminutor/grinders, mechanically cleaned screening systems and grit removal systems, they are less desirable for implementation in a developing region. Manually cleaned screens require very little maintenance; however, labor costs are associated with the labor required. On the other hand, the mechanically cleaned screening improves flow conditions and screening capture. Grit removal technologies can increase the headloss of a system which in turn can increase the need for pumping. (EPA, 2003).

3.3.2 Primary Treatment

Within a conventional wastewater treatment plant, primary treatment typically results in about a one third reduction in total BOD and a greater than 50% reduction of suspended solids by sedimentation. The reduction of BOD and other components found in wastewater, such as nutrients, pathogenic organisms, trace elements, and toxic organic compounds, are either in the form of settable solids or sorbed to the solids. The residue, made up of a concentrated suspension of particles, collected from primary treatment are known as the "primary sludge." (National Research Council, 1996).

Clarifiers can be rectangular, circular, stacked, and plate-and-tube settlers. The most common configurations of clarifiers for wastewater treatment are rectangular or circular (see Figure 3.8). The circular primary clarifiers for Darvill Treatment Works in Pietermaritzburg, South Africa are illustrated in Figure 3.9. The design criteria of a clarifier considers the following parameters: wastewater characteristics (e.g. settleability of suspended solids), extreme flow conditions (e.g. wet weather), surface overflow rate, hydraulic detention time, depth, surface geometry, and weir loading rate. Enhanced sedimentation relies on preaeration to increase the settling parameter or chemical flocculation to create more settleable flocs in

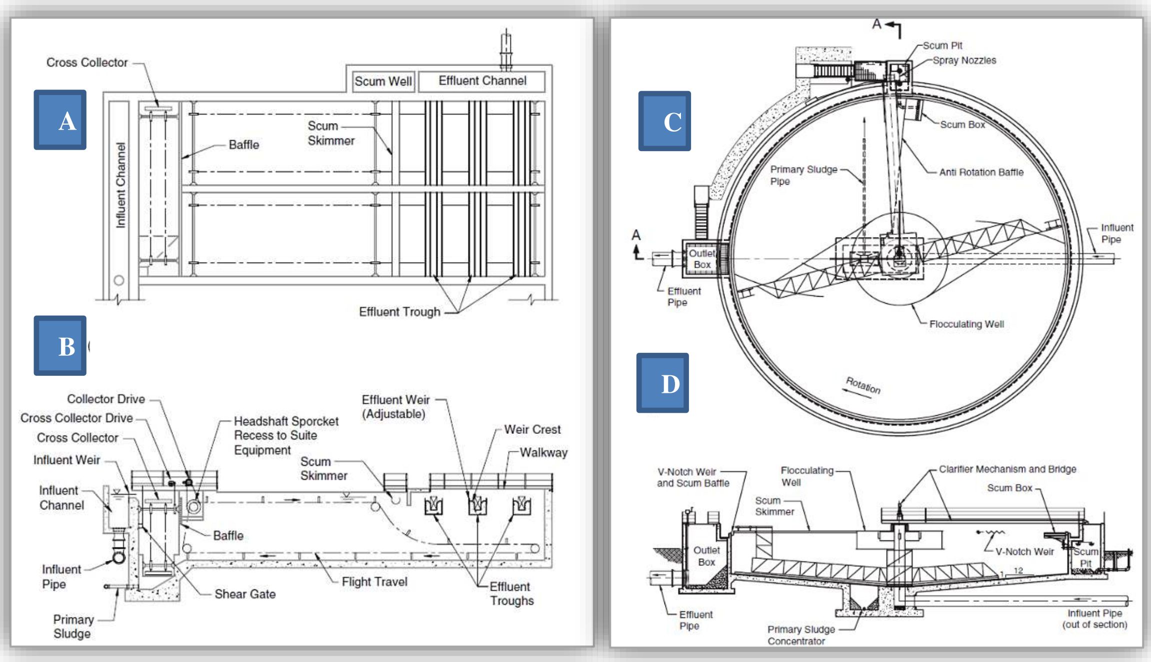


Figure 3.8: (A) plan and (B) section view of typical rectangular primary sedimentation tank. (C) plan and (D) section view of typical circular primary sedimentation tank. Source: Metcalf and Eddy, 2014.

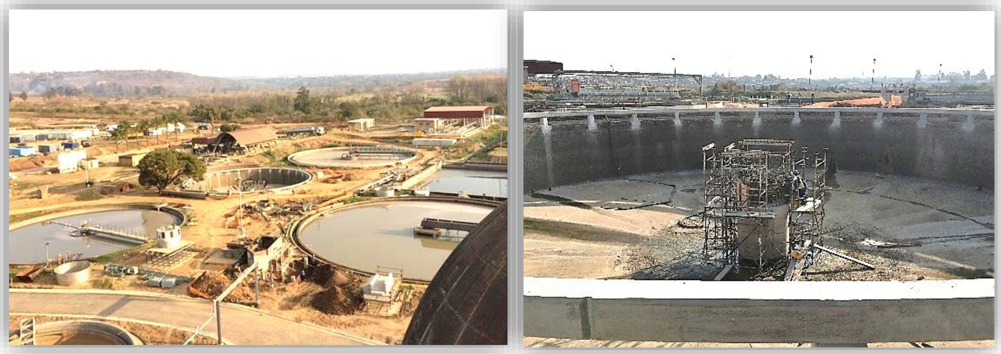


Figure 3.9: Clarifiers at Darvill Treatment Works from site tour in 2017.

order to achieve increased suspended solids, COD, BOD, and phosphorus removal efficiencies. To improve reliability of a wastewater treatment system, having more than one clarifier is important because the plant can stay in operation when a clarifier is being serviced. To improve odors emitting from the raw sewage, methods such as source control, chemical treatment, preaeration and containment covers can be utilized. Added benefits of preaeration include scum flotation improvement, scrubbing of VOC odor components, and prevention of septicity. A disadvantage of utilizing preaeration is the increased energy requirements for inputting air that increases operations costs. The inherent tradeoff for chemical flocculation allowing for a clarifier's reduced footprint and performance is an increase in operation costs and the increased mass of primary sludge that may also be harder to thicken and dewater due to the addition of coagulants. Removal efficiencies of conventional sedimentation versus enhanced sedimentation is given in Table 3.2. (Water Environment Federation [WEF], 2018).

Table 3.2: Removal efficiencies of conventional sedimentation versus enhanced sedimentation. Data sourced from WEF, 2018.

Type of Primary Treatment	TSS Removal	COD or BOD Removal	Phosphorus	Bacteria Loading
Conventional Sedimentation	50% to 70%	25% to 40%	5% to 10%	50% to 60%
Chemically enhanced primary treatment	60% to 90%	40% to 70%	70% to 90%	80% to 90%

Within the primary sedimentation tanks, the sludge may be allowed to thicken (e.g. can be operated to produce thickened solids concentration of 3% to 6%), or operated to allow for continuous withdrawal of a more dilute primary sludge may be sent to downstream processes that provide thickening and stabilization operations. A solids concentration of greater than 6% can cause issues as a result of a greater viscosity when transporting the thickened sludge to downstream processes (WEF, 2018). Section 3.3.4 will go into more detail on sludge handling, including floatable solids (e.g. fats, oil, grease, and other floating materials responsible for increasing organic load) management. Whereas many communities only utilize primary treatment before releasing primary effluent into waterbodies, primary treatment is utilized in other locations as a necessary, economically beneficial precursor to secondary treatment and other downstream processes (National Research Council, 1996). A depiction of primary treatment and possible subsequent treatment processes are depicted in Figure 3.10.

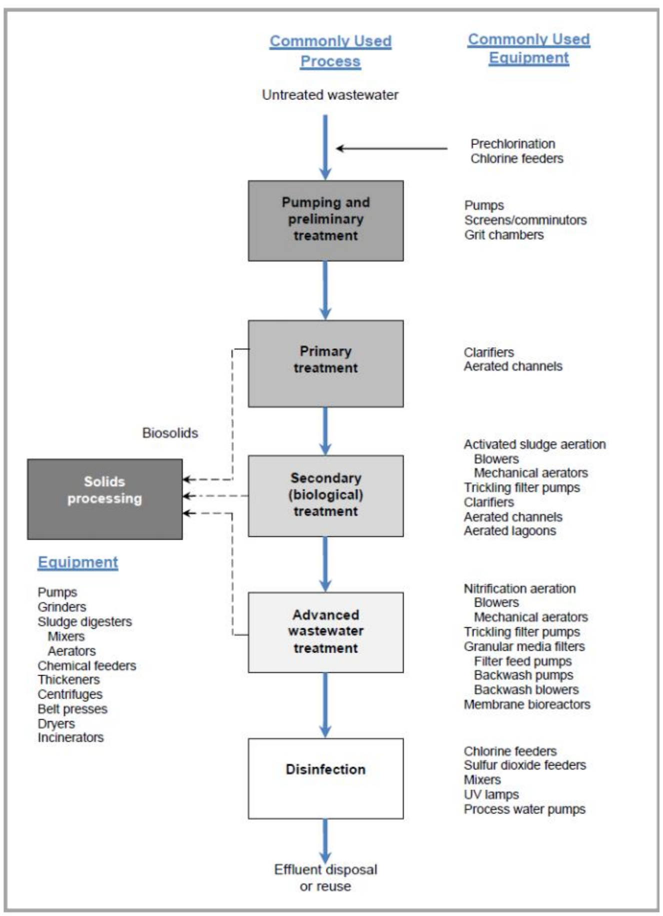


Figure 3.10: Processes and equipment commonly used in wastewater treatment. Source: Water Environment Research Foundation (WERF), 2011.

In rural or developing regions, natural systems may be deemed the more appropriate technology if land is available and affordable and the community has no or little access to a reliable energy supply. Natural processes, such as WSPs, do not rely on significant energy inputs to process wastewater treatment, making the operations more cost effective and practical for a rural or developing region. See section 3.3.5 for detailed information on natural treatment processes.

3.3.3 Secondary Treatment

Conventionally, secondary treatment utilizes biological treatment processes with the objective of removing suspended solids and residual organics (FAO, 1992). When microorganisms are in suspension, it is typically recognized as an activated sludge process. When the microorganisms are attached to a surface, the process is typically recognized as a biofilm reactor. Ponds and other processes can also be utilized in order to remove biodegradable material. The conventional secondary treatment process is generally characterized in the following steps (National Research Council, 1996):

1. wastewater is introduced to the microorganisms, whether in suspension or attached to media,
2. some of the organic material is oxidized by the microorganisms which results in the production of carbon dioxide and other end products,
3. the remainder of the energy is utilized to support the community of microorganisms,
4. the microorganisms biologically flocculate and wastewater constituents (e.g. pathogens, trace elements, organic compounds) also sorb onto the flocculants or create their own agglomerate particles,
5. the flocculants settle, typically in sedimentation tanks following the biological process, and
6. the "secondary sludge" (e.g. waste activated sludge, trickling filter humus) proceeds to sludge handling processes.

An 85% reduction of BOD_5 and suspended solids in the wastewater can typically be observed when high-rate biological treatment systems are used in tandem with primary sedimentation (FAO, 1992). Wastewater characteristics, effluent standards, associated energy costs of technology, and land availability are examples of parameters that will dictate the technologies that are implemented. Figure 3.11 depicts secondary treatment infrastructure (aeration tank and aeration blowers) recently installed at Darvill Treatment Works in Pietermaritzburg, South Africa in order for the facility to expand its capacity.

If tertiary treatment is not present, then the final stage of treatment for secondary effluent is typically disinfection. The WEF (2018) states that disinfection is the most significant component of

Figure 3.11: Recently installed (A) coarse-bubble air diffuser in aeration tank and (B) aeration blower at Darvill Treatment Works in Pietermaritzburg, South Africa. Pictures from site tour in 2017.

wastewater treatment when considering public health protection. Typical disinfection involves adding chlorine solution (common doses around 5 to 15 mg/l but dependent on wastewater characteristics) to the secondary effluent in a chlorine contact basin (FAO, 1992). Examples of other disinfection alternatives include UV disinfection and ozone disinfection. Due to the toxic effects of residual chlorine effluent, dichlorination may be utilized to remove the remaining chlorine from final effluent. (WEF, 2018).

Reliability of treatment design and operations relies on features in a system such as alarm systems, standby power supplies, treatment process duplications, emergency storage or disposal of inadequately treated wastewater, monitoring devices, and automatic controllers are important (FAO, 1992). These features add complexity in the construction, operation, and technical support of these large centralized systems, as well as increase the energy demand. As mentioned with primary treatment, natural low rate biological treatment systems can offer an alternative to highly mechanized systems.

3.3.4 Sludge Handling

According to National Research Council (1996), most priority pollutants will accumulate in the sludge making the sludge treatment process a vital component of wastewater treatment systems. Sludge treatment encompasses various engineered process with the objective of treating sludge to an appropriate level which is determined by its final endues or disposal options (IWA, 2014). Conversely, types of solids produced by a treatment system (e.g. sludge, biosolids, ash) decides what its beneficial use and disposal options are (WEF, 2018). Processes that typically constitute sludge handling include volume reduction, stabilization, inactivation of pathogenic organisms and viruses. Other varieties of processes may entail solidification/immobilization, metal stripping and toxic organic destruction, and combustion processes (National Research Council, 1996). See Figure 3.12 for a diagram depicting sludge management processes.

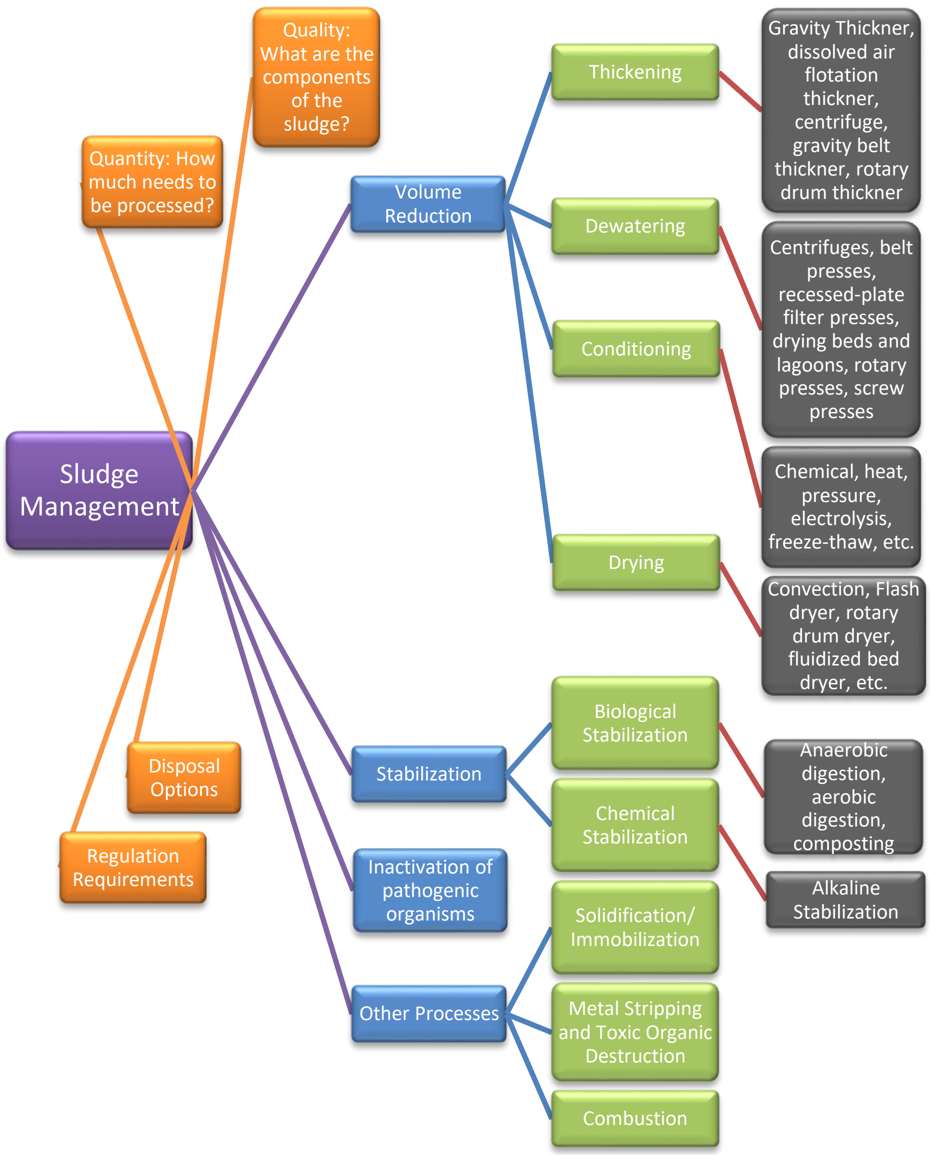


Figure 3.12: Sludge management diagram of considerations (orange boxes), processes (blue and green boxes), and various technologies (gray boxes).

Sludge management will look different for a developed versus developing or a rural versus urban community. Picking a method of handling sludge in a developing or rural region relies on

1. treatment objectives such as meeting specific regulations,
2. technologies that will produce end products that will be beneficial to the society (e.g. soil conditioning, irrigation, building materials, biofuels/cooking materials),
3. space limitations,
4. minimal or no energy requirements, in contrast to most of the mechanized technologies presented in Figure 3.12, or
5. whether there is collection of their onsite sludge to be treated offsite.

For example, common dewatering techniques seen in these regions include gravity settling, filter drying beds, and evaporation/evapotranspiration. Examples of stabilization techniques utilized include deep row entrenchment, co-treatment in WSPs, lime/ammonia addition, composting, solar drying, and plant drying beds. (IWA, 2014). Depending on the technology utilized for sludge treatment, the type of solids produced will determine what happens next whether it be a beneficial use or disposal. Table 3.3 outlines the options available for the following common solid products: sludge, biosolids, or ash. Deep row entrenchment was utilized in the U.S. in the 1970s for wastewater treatment and has been since adapted for fecal sludge management (see Figure 3.13) for forestry and land rehabilitation purposes by Durban, South Africa (Still *et al*., 2012). In the U.S., greater than half of biosolids created by WWT facilities are applied to land as a soil conditioner or fertilizer while the remaining portion is landfilled or incinerated (EPA, 2004).

Figure 3.13: Study in Durban, S.A. investigating the potential of deep row entrenchment. Source: Still et al, 2012.

Table 3.3: Disposal or beneficial options for solid products of wastewater solids in the United States. Adapted from WEF, 2018.

Solid Product	Description	Disposal or beneficial use options
Sludge	Raw, unstabilized, primary, and secondary solids.	In many states, dewatered, unstabilized sludge has two major end-use options: incineration and landfilling. All other end-use options, such as land application, require that solids must first meet the U.S. Environmental Protection Agency's (U.S. EPA's) requirements in 40 CFR Part 503
Biosolids	Any solids that have been stabilized to meet the criteria in the Part 503 regulations	Depending upon state requirements, can be beneficially used (e.g. land applied) or landfilled. Only the highest quality biosolids are suitable for commercial marketing and distribution.
Ash	Product of incineration	Historically was landfilled, but in recent years, there has been more emphasis on finding beneficial uses for this material (e.g., as landfill cover, a soil amendment, an ingredient in concrete, a fine aggregate in asphalt, a flowable fill material, and an additive in brick manufacturing).

3.3.5 Natural Treatment Processes

Natural treatment technologies are "designed and managed to mimic the physical, chemical, and biological processes ongoing in the plant-soil system and in wetland or hyporheic environments" (WEF, 2018). Natural systems can be designed and operated to manage hundreds of gallons per day to many millions gallons per day. The following are examples of common natural treatment processes and technologies utilized in both developing and developed regions: soil absorption systems, pond systems, land treatment systems, floating aquatic plant systems, and constructed wetlands. See Figure 3.14 for a depiction of natural treatment processes. (WEF, 2018).

Natural treatment systems have been designed to provide treatment for a variety of pollutants deriving from municipal, industrial, residential, and agricultural activities (WEF, 2018). Land is availability and land associated costs are a major factor that sometimes prohibit the implementation of these systems. As an example, for domestic wastewater, typically anaerobic technologies (e.g. anaerobic ponds) and photosynthetic technologies (e.g. facultative and maturation ponds) are used in series, requiring a substantial amount of land (Mara, 2003). However, energy requirements are much lower for these system, as depicted in Table 3.4. Table 3.5 also demonstrates the performance and economic factors that make natural systems such as WSPs an extremely relevant and appropriate technology for future applications.

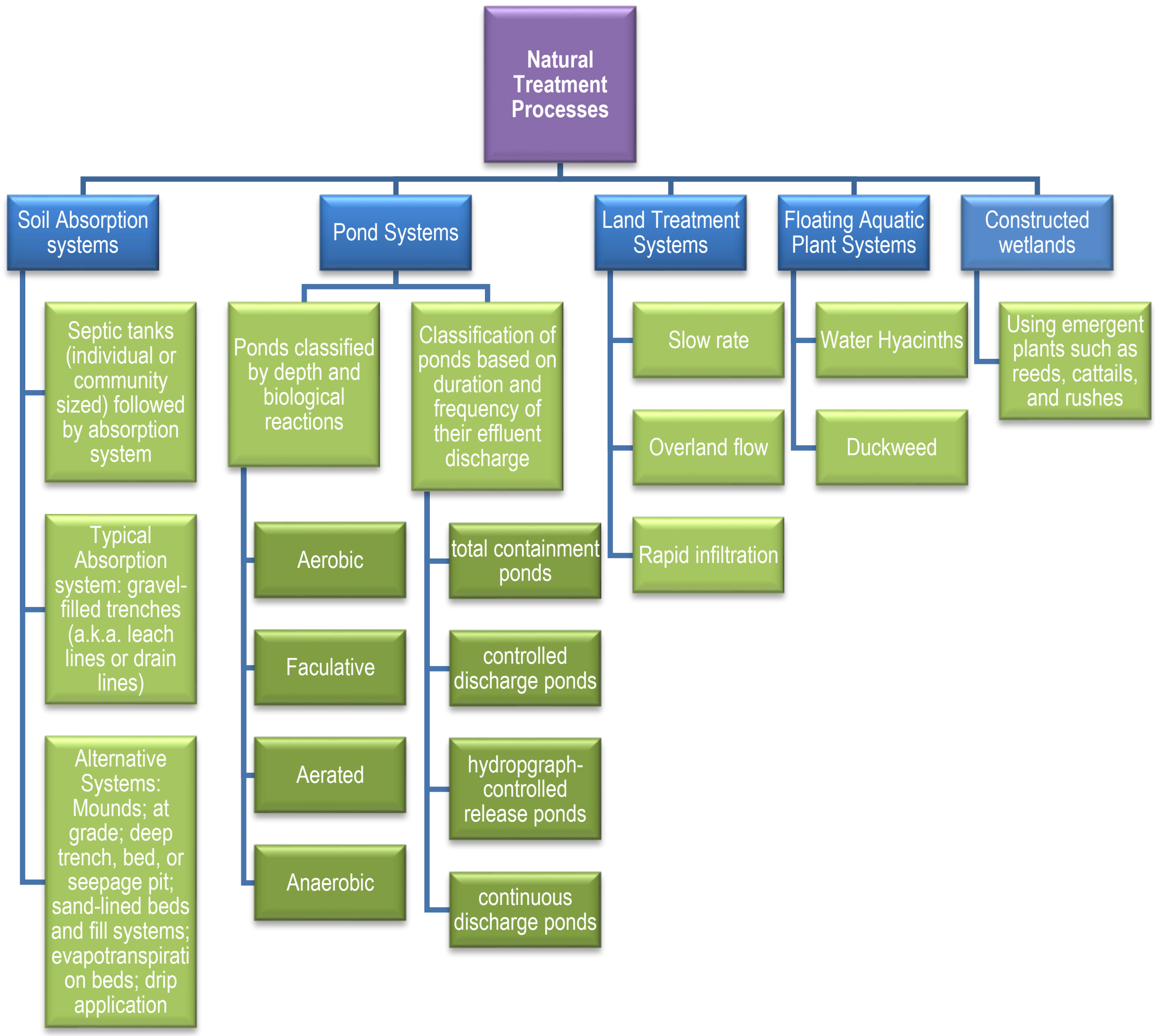


Figure 3.14: Natural treatment processes. Adapted from material in WEF, 2018.

Table 3.4: Energy Requirement of four wastewater treatment processes in the USA for a domestic wastewater flow of 1 million US gallons/day. Adapted from Mara, 2003.

Wastewater Treatment Process	Energy Consumption
Activated Sludge	1,000,000 kWh/year
Aerated Lagoons	800,000 kWh/year
Biodiscs	120,000 kWh/year
WSP	nil

Table 3.5: Comparing Sewage Treatment Systems. The natural processes are highlighted in yellow. FC = Faecal coliforms; SS = Suspended solids; G = Good; F = Fair; P = Poor. Source: FAO, 1992

	Criteria	Package plant	Activated sludge plant	Extended aeration activated sludge	Biological filter	Oxidation ditch	Aerated lagoon	Waste stabilization pond system
Plant performance	BOD removal	F	F	F	F	G	G	G
	FC removal	P	P	F	P	F	G	G
	SS removal	F	G	G	G	G	F	F
	Helminth removal	P	F	P	P	F	F	G
	Virus removal	P	F	P	P	F	G	G
Economic factors	Simple and cheap construction	P	P	P	P	F	F	G
	Simple operation	P	P	P	F	F	P	G
	Land requirement	G	G	G	G	G	F	P
	Maintenance costs	P	P	P	F	P	P	G
	Energy demand	P	P	P	F	P	P	G
	Sludge removal costs	P	F	F	F	P	F	G

3.4 Alternative Wastewater Treatment Technologies

In the context of this thesis, alternative wastewater treatment technologies refer to the technologies that either (1) improve the conventional treatment process by adding additional treatment steps, (2) provide equivalent or more efficient treatment than those technologies that are specified as conventional, and/or (3) expand wastewater treatment management beyond only point source pollution treatment objectives. These methods have been deemed safe and effective methods of treating wastewater. Examples of these types of wastewater management strategies are depicted in Figure 3.15.

Additional steps may be added to the conventional treatment process in order to obtain a higher quality effluent before releasing it back into the natural environment. Tertiary treatment, for example, targets finer suspended materials and dissolved solids. Different types of tertiary treatment methods include biological treatment, membrane filtration, membrane desalination, ozone, and advanced oxidation (American Water Works Association [AWWA], 2016). Figure 3.16 demonstrates how adding and/or rearranging treatment processes allows for different effluent qualities. Of the scenarios compared by Foley *et al*. (2010), the most complex treatment processes which included biological nutrient removal (BNR) systems performed the best. The tradeoff of obtaining a higher quality effluent by adding additional steps, however, usually infers there will be a greater energy demand. Figure 3.17 depicts electricity requirements for a trickling filter, advanced treatment without nitrification, advanced treatment without nitrification, and an activated sludge system. It also adds technical complexity to running the wastewater treatment facility.

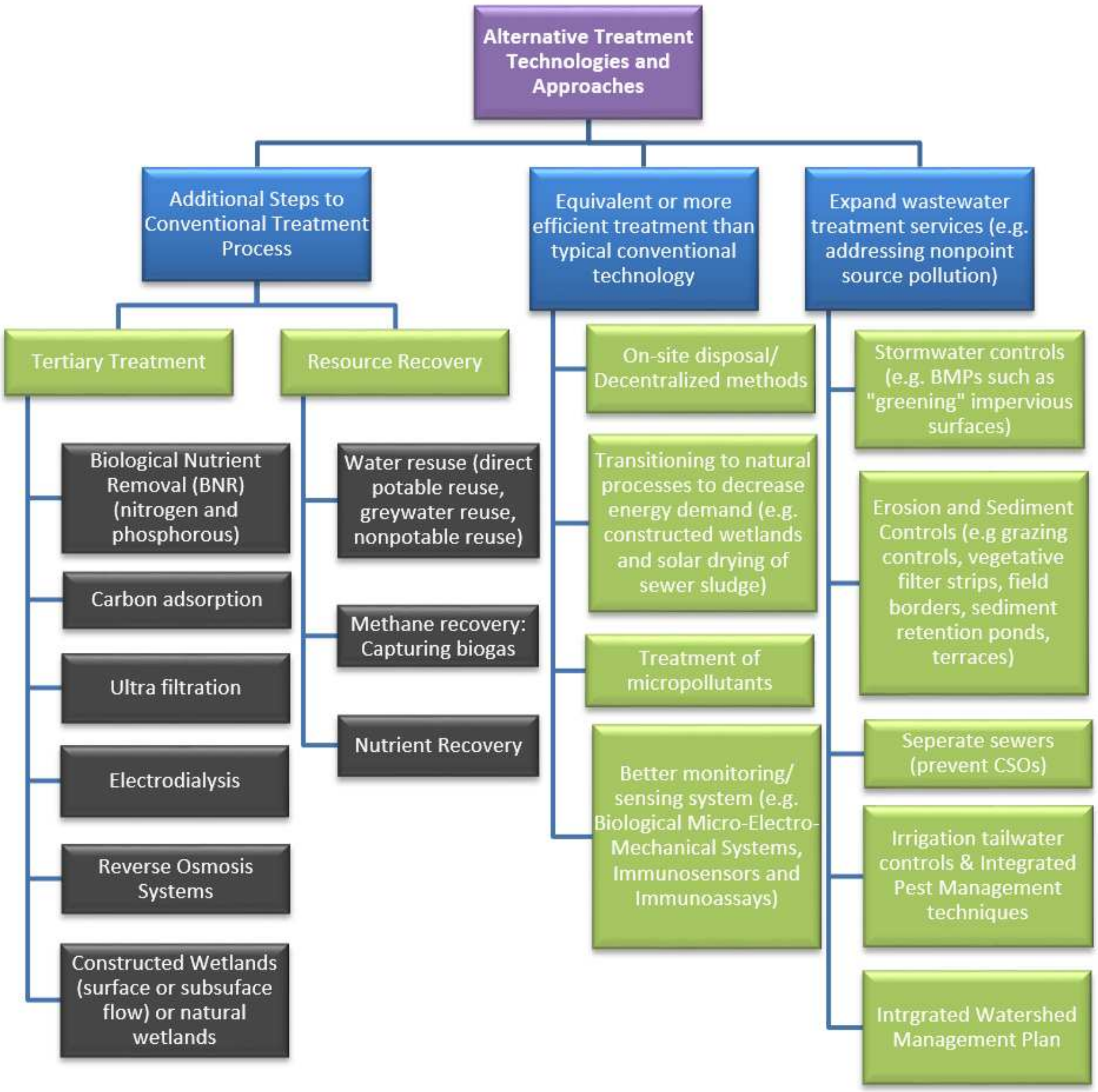


Figure 3.15: Examples of wastewater management strategies that encompass alternative technologies.

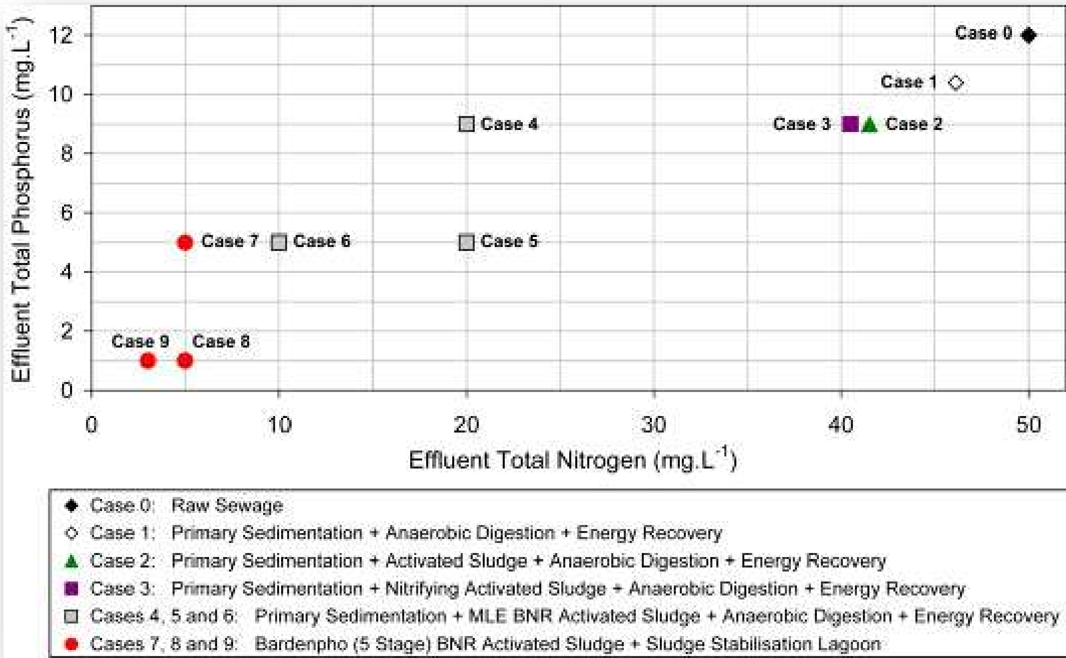


Figure 3.16: Wastewater treatment system scenarios defined by type of process configuration (refer to Legend) and effluent quality (refer to x and y axes). Source: Foley et al, 2010.

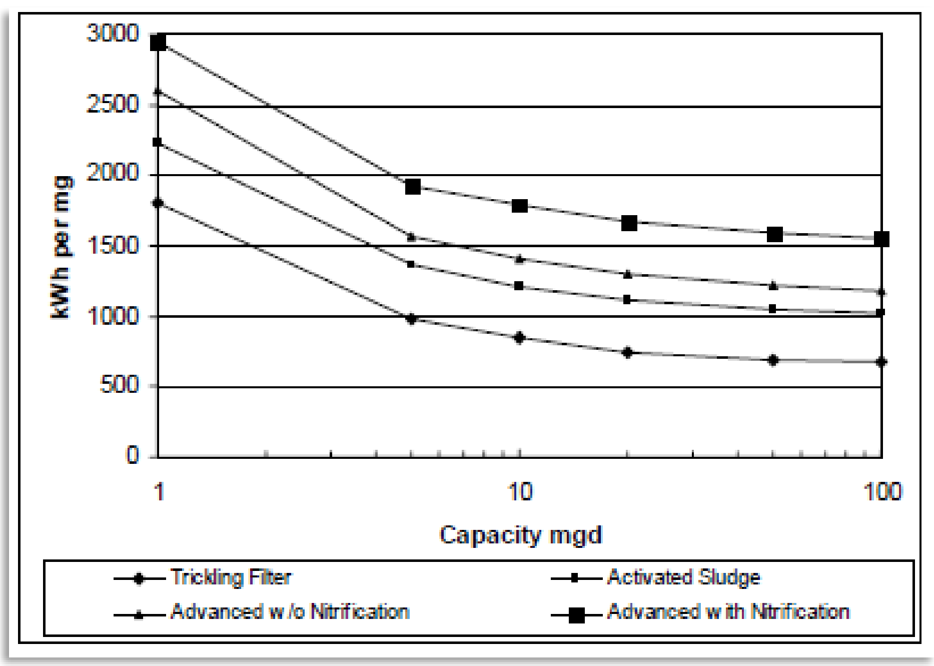


Figure 3.17: Variations in unit electricity consumption with size for representative wastewater treatment processes. Source: EPRI, 2002.

The focus of alternative technologies concentrates on treating wastewater as a feedstock of resources such as nutrients, organic matter, metals, energy, and the water that can be recovered. Wastewater treatment plants are being rebranded as resource recovery facilities. The most common recovered material from wastewater is the water itself (Saad, 2017). Figure 3.18 illustrates where direct potable reuse and indirect potable reuse projects are being initiated in the United States. Indirect potable reuse uses an environmental buffer and dilution before reintroducing the water to a water treatment plant. Direct potable water is a closed looped system although it is typically also combined with raw water. Lazarora *et al.* (2013) reports that in Namibia, 35% of all drinking water is treated wastewater. Water reuse strategies, especially those that treat the wastewater to a level tailored for its next intended use, can reduce pollution and conserve energy when planned properly. This is effective when considering strategies that promote water recycling for non-potable uses, such as greywater reuse applications (e.g. landscape irrigation, agricultural irrigation, industrial processes, toilet flushing).

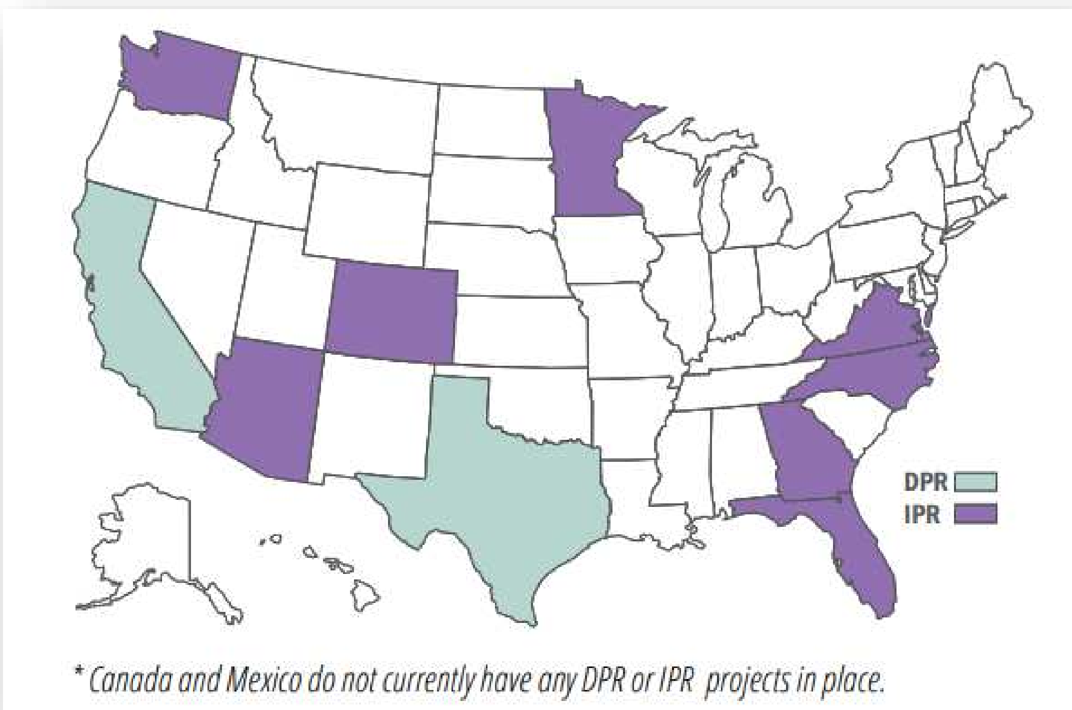


Figure 3.18: Direct Potable Reuse and Indirect Potable Reuse Project in the U.S. as pf April 2016. Source: AWWA, 2016.

Implementing energy efficiency improvements at WWTP provides both environmental and economic benefits. In the operating budget for a WWTP, energy typically accounts for 25–40% of the operating budgets (EPA, 2013a). Onsite renewable power options such as solar panels and low head hydro can be utilized. Decreased demand with water reuse and other water conservation practices like efficient indoor fixtures reduces the amount of water being sent to a WWTP. A WWTP can also employ better energy efficient technologies such as energy-efficient blowers and pumps. Table 3.6 provides different energy conservation measures that can produce potential savings for a WWTP. Energy recovery can be facilitated in many ways from the wastewater treatment operations itself as well (e.g. anaerobic digestion, thermal conversion, heat recovery, microbial fuel cells, algae bioreactors, hydro turbines) (WERF, 2011). The most common method utilized is capturing biogas from anaerobic digesters and burning it within a combined heat and power system (CHP). This biogas can be utilized onsite to offset energy requirements for the WWTP (WERF, 2011). EPA (2013b) reports that "each million gallons per day of wastewater that flow can generate enough biogas in an anaerobic digester to produce 26 kilowatts of electric capacity and 2.4 million Btu per day of thermal energy in a CHP system."

Table 3.6 Summary of potential savings through use of best practices. Source: WERF, 2011.

Energy Conservation Measure	Treatment Stage	Energy Savings Range (%)
Wastewater pumping optimization	Throughout system	<0.7%
Aeration system optimization	Secondary treatment	~15 to 38%
Addition of pre-anoxic zone for BNR	Secondary treatment	~4 to 15%
Flexible sequencing of aeration basins	Secondary treatment	~8 to 22%
High-efficiency UV	Disinfection	~4%
Lighting system improvements	Support facilities (buildings)	~2 to 6%
	AVERAGE RANGE	5.6 to 14.3%

Most developed countries are operating with outdated and undersized wastewater infrastructure, such as their sewer systems. Combined sewers were introduced in 1855, replacing urban cesspool ditches in cities (Tibbetts, 2005). Combined sewers collect runoff from precipitation, sewage, and industrial wastewater together. Now, these systems are notorious for overflowing (i.e. CSOs), dumping untreated sewage and debris into waterbodies. To meet the demand of increasing amounts of runoff from changing climate patterns and alterations to land use, development of decentralized best management practices are becoming more prevalent. Stormwater controls, also known as best management practices (BMPs), such as filtration basins, wetlands, swales, filter strips, and buffer zones, are being implemented as decentralized methods for inducing infiltration and treatment of runoff for catchment areas. Similar methods are also being used to treat runoff from agricultural fields. These treatments not only use natural processes to treat the water effectively increasing energy savings, but it keeps the water in local catchments versus taking the water offsite to be treated.

3.5 Emerging Wastewater Treatment Technologies

A gray line separates alternative and emerging technologies. Both classifications of technologies promote linking sectors (e.g. energy, food. health) in order to achieve a more sustainable utilization of resources. In this thesis, the main distinction between the two groups is based on a technology's novelty. Alternative technologies are relatively more well-known and documented for their treatment abilities. The emerging technologies are mostly current areas of research in wastewater treatment that may still only be either a conceptual idea, a compilation of microcosm lab experiments or a full-scale pilot project to demonstrate proof of concept, and/or a process that is still just not well understood. The direction of research in the wastewater treatment and resource recovery field is heading toward: (1) treating emerging contaminants, (2) mining wastewater for resources beyond water, energy, and nutrients, and (3) increasing understanding of the functions of microbial communities in wastewater treatment processes to promote biomimicry in wastewater treatment processes.

Due to the vast amount of technologies that fit within the category of emerging technologies, this segment of the thesis will focus solely on the algal-based emerging technologies. Section 3.5.4 will provide an example of an algal-based emerging technology, the Omega System, that provides a reference for where the field of wastewater treatment is heading.

3.5.1 Treating Emerging Contaminants

Microalgae-based wastewater treatment alternatives have been one of the primary focuses within evolving the field of wastewater management due to algae's applications in CO_2 sequestration, biofuels, food, feed, and bio-molecules production (Bux & Chisti, 2016). Examples of microalgae application in wastewater treatment systems include open systems such as natural ponds and raceway ponds and closed systems typically referred to as photobioreactors (PBRs) (Faizal & Chisti, 2016; Demirbas, 2011). Microalgae such as the green algae Chlorella sp., has been evaluated for its removal efficiency of nitrogen, phosphorus, chemical oxygen demand (COD), and metal ions (e.g. Al, Ca, Fe, Mg, and Mn) from wastewater (Wang *et al*, 2010). Now, researchers are considering algae's ability to remove micropollutants. In a study by Matamorous *et al.* (2015), they observed that high rate algal ponds (HRAPs) had removal efficiencies ranging from negligible to 90% removal of 26 different organic microcontaminants considered in the study (e.g. pharmaceuticals and personal care products, fire retardants, surfactants, anticorrosive agents, pesticides, plasticizers, etc.). Within the study, it was concluded that biodegradation and photodegradation were the most important removal pathways. Seasonality and hydraulic retention time effected the efficiency of the HRAP systems in removing the selected compounds from real urban wastewater. Figure 3.19 demonstrates the results of the 4 day retention time for the HRAP system in terms of hazard quotients (HQ). HQ is defined as the measured environmental concentration (MEC) at the influent or effluent of each HRAP reactor divided by the predicted non-effect concentration (PNEC):

$$HQ = \frac{MEC}{PNEC}$$

The ecotoxiological risk assessment showed that there was a 90% removal of the HQ for the influent wastewater which translated to the effluent having no acute toxicity risk associated with the studied EOCs. Although microalgae biotechnologies are receiving attention for its ability to remove EOCs (Gentili & Fick *et al.*, 2017; de Wilt *et al*, 2016; Matamorous *et al.*, 2015), the higher retention time of the systems, the land requirements dependent of the form of algal system used, and the technical complications of running a "live" biological system keep the algal treatment alternatives in the emerging technologies category.

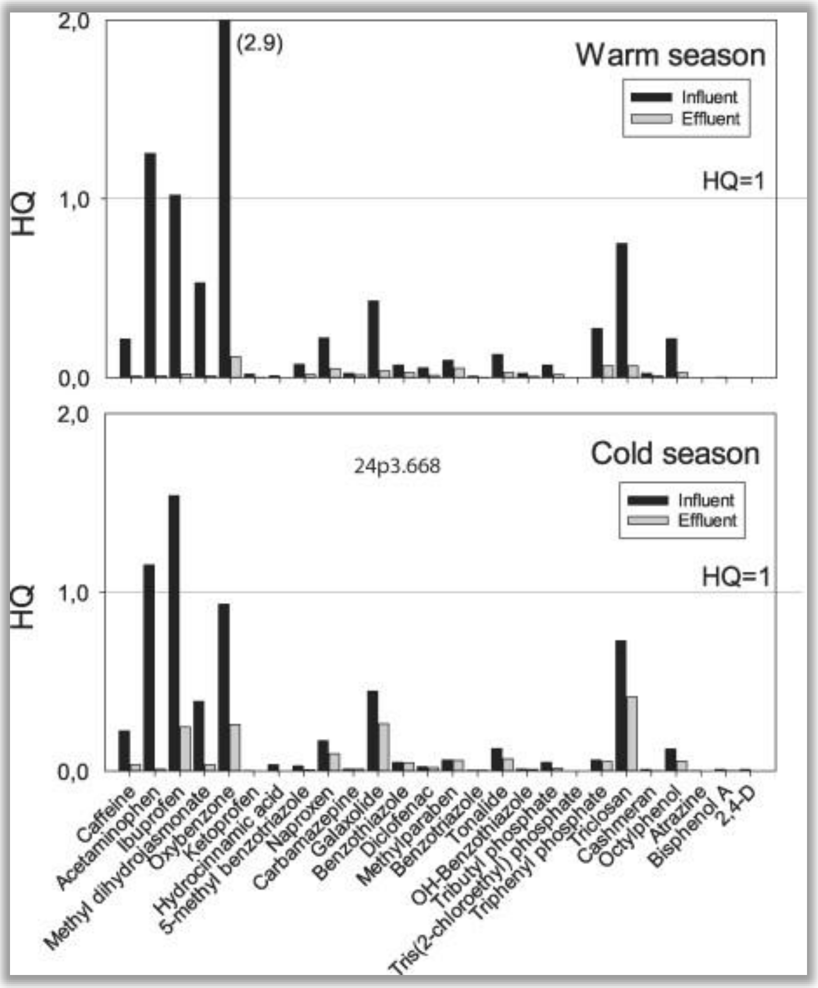


Figure 3.19: Seasonal hazard quotients (HQs) for the influent and effluent water samples collected from the HRAP set at a hydraulic retention time (HRT) of 4 days. Source: Matamorous et al, 2015

3.5.2 Mining Wastewater

The transition to sustainable approaches means moving away from the linear “take-make-waste” approach representative of a business as usual model. A circular economy, supporting the ideals of sustainable development, aims to (1) “maintain products in use for a longer time by reusing and repairing them, reducing waste generation, and (2) use more secondary raw materials in production cycles, creating new growth and job opportunities.” Mining sewage is just one example of resource recovery and materials recycling that plays into reaching the circular economy approach. (Cossu & Williams, 2015). In other emerging technologies besides those that are algal based, there has been growth in the field of sewage mining for products such as biodegradable plastics, adhesives, proteins, enzymes used in biomedical applications, and biopolymers. Although applications have shown an ability to recover these products, there is still the matter of whether it is practical for municipal plants to be able to do so.

In algal based emerging technologies, algae consume large amounts of carbon dioxide and converts it into biomass. The algae biomass can be converted into various kinds of biofuel using liquefaction, pyrolysis, gasification, extraction and transesterification, fermentation, and anaerobic digestion (Demirbas, 2011). Power plant emissions can be utilized as the carbon dioxide feedstock for the algae. When microalgae production is coupled with wastewater treatment, the overall economics of the system is improved (Beal *et al.*, 2012). Replacing fossil hydrocarbons with a renewable biofuel alternative is a growing trend due to the depletion of finite resources and an increasing need for energy. For the various applications of algae, the algal biomass must be harvested, dewatered, or recovered. These essential steps each comes with their own set of technology options with different energy requirements, technical complexity, and associated costs for processing. For algal wastewater biofuel production to become more widespread, there is a need for more efficient harvesting and processing techniques (Pittman *et al.*, 2010).

3.5.3 Understanding Microbial Processes in Wastewater Treatment Applications

The complexity of biotechnology comes from the lack of understanding of how mixed microbial communities interact with each other and how to engineer systems that support stable microbial communities that can process wastewater. This encompasses the current lack of understanding of how to best engineer the nitrogen and carbon cycles to achieve the most efficient processing of wastewater such as in biological nutrient removal processes (Park *et al*, 2017; Bux & Chisti, 2016; Yu *et al*., 2010). In microalgal systems, the control of biomass composition is important for these systems, yet with mixed microbial communities, extremely difficult due to competing organisms. For microalgae biofuel to be an economically viable alternative to fossil fuels, "further optimization of mass culture conditions are needed," according to Pittmanm *et al.* (2010). Increasing the knowledge available on microbial ecology and metabolic and genetic engineering will be crucial to advancing current emerging technologies (Bux & Chisti, 2016).

3.5.4 The OMEGA System

Many of the characteristics described above for what constitutes an emerging technology are encapsulated by The Offshore Membrane Enclosures for Growing Algae (OMEGA) System. The purpose of this section is to provide a specific example of an emerging technology. The OMEGA System specifically tries to link resource recovery from wastewater and marine energy together. The OMEGA system could be utilized to provide cleaner effluent to those marine environments directly affected at the discharge zones. OMEGA stands for offshore membrane enclosures for growing algae. The proposed system by National Aeronautics and Space Administration (NASA) is designed to promote the growth of freshwater microalgae in flexible photo-bioreator tubes anchored offshore, harnessing the energy from waves as a means to induce mixing in the photo-bioreactors and using wastewater as the feedstock for the algae (Wiley, P., *et al*., 2013). According to the World Energy Council (2016), "to date only a handful of commercial ocean energy projects have been delivered, reflecting the current immaturity and high costs of these technologies." The OMEGA system is an accurate reflection of this statement. Inhibitory parameters including environmental (light and temperature); operational (pH, CO2, DO and nutrients), and biological (zooplankton grazing, and pathogens such as fungal and viral infection) limits the ability to scale up algae production (Park *et al*., 2010).

The algae growing in the photobioreactor tubes has the potential to both treat the wastewater by removing nutrients while also creating a renewable energy input for the production of biofuels. The OMEGA system has thus been tested for processing secondary effluent. Therefore, the technology is being utilized as a tertiary/advanced treatment step. By removing nutrients from the wastewater, the threat of dead zones caused by blooms of planktonic and benthic algae will be reduced. Growth of algae to produce biofuels and the use of wastewater as a feedstock for algae has been studied and are even currently used in industry today. A major benefit of the OMEGA system is the concept of eliminating competition with agriculture for water, fertilizer, and land when considering the energy, food, water nexus (Wiley *et al*., 2013 and Carney *et al.*, 2013).

As depicted in Figure 3.20, the OMEGA system structure may induce the growth of marine habitat. Creation of artificial reefs and fish aggregating devices could increase the aquaculture activity. The physical impacts of the OMEGA system include the change in local circulation/wave patterns, sediment composition and accumulation rates, and the light penetration into the water column (Hughes *et al.*, 2014). Some of the biological impacts include the changes in local biodiversity and biomass, the influencing of community structure mainly as a result of the increase in substrate availability, and the removing of contaminants affecting the influence of eutrophication (Hughes *et al.*, 2014). The structure of the OMEGA system may be utilized by wildlife for resting, feeding, and breeding sites. Aquatic structures have been shown to pose risk to wildlife such as collisions, entanglements, acoustic and electromagnetic "noise", habitat fragmentation, and changes in foraging potential (Hughes *et al.*, 2014). Furthermore, wildlife can impact the OMEGA system by biting, pecking, hauling out, perching, scratching, covering, and fouling surfaces (Hughes *et al.*, 2014).

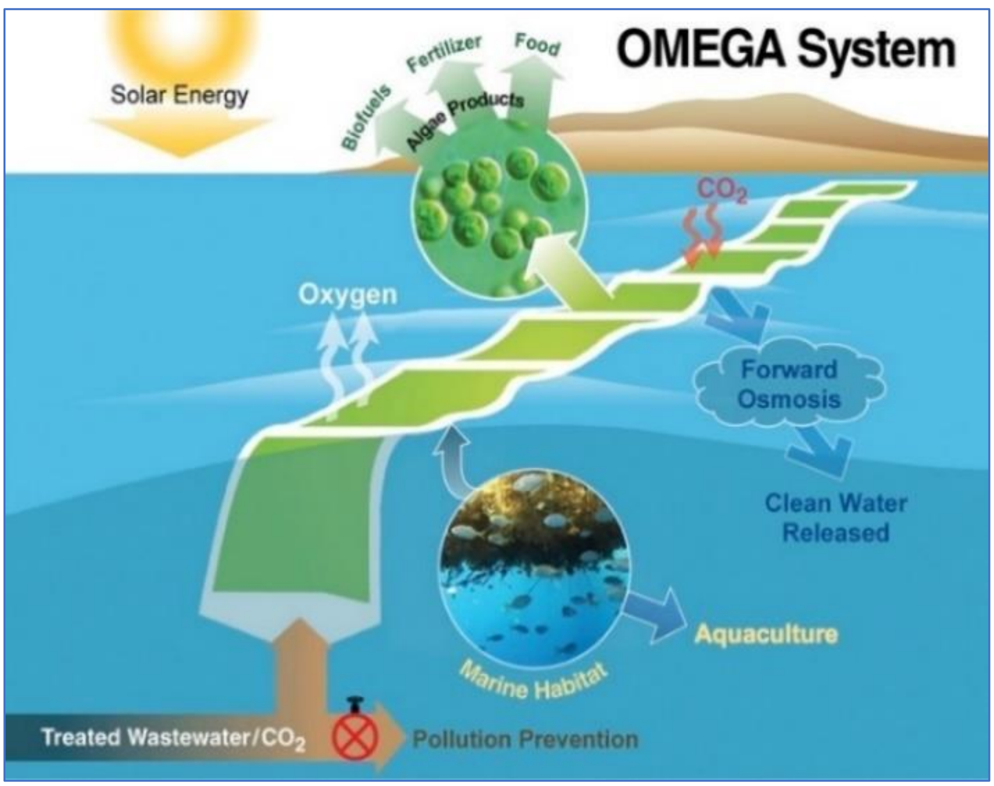


Figure 3.20: NASA (2014) depiction of the benefits of the OMEGA System.

The algae that grows in the marine structure occur naturally due to the nutrient availability of the waste feedstock provided. Carney *et al.* (2013) studied the microalgal mass cultures that grew in municipal wastewater of the San Francisco Treatment Facility demonstrating the challenges of controlling a stable large-scale microalgal culture. Within a 14 day experiment, three notable stages represented the proliferation of algae (days 1-5), a stable state with minor decreases of biomass (days 5-10), and finally the decline of microalgae (days 11-14) (Carney *et al.*, 2013). Carney *et al.* (2013) concluded that the development of specific probes, primers or biomarkers to produce real time monitoring of the OMEGA algal production would establish improved management of large scale algal production. Results of experiments with the pilot projects demonstrated the algae's ability to extract nutrients (nitrogen, phosphate, and potassium) and even treat for pharmaceutical compounds, caffeine, and heavy metals.

The liquid within the semipermeable membrane of flexible photobioreactor tubes and the surrounding salt content of the ocean creates an osmotic pressure gradient to facilitate an energy saving, economical algae dewatering process (Buckwalter *et al.*, 2012). If the algae escape into the ocean, it dies immediately due to its inability to survive in saltwater (Harris *et al.*, 2013). Buckwalter *et al.* (2012) studied the use of flat-sheet cellulose triacetate forward osmosis membranes to dewater *Chlorella vulgaris*, freshwater algae. Although the experiments observed the capability of forward osmosis as a viable initial dewatering step for harvesting the algae in the OMEGA system with volume reductions of 65-85%, the biofouling by the ocean over a 52-day period resulted in leaks within the membrane. In order to create a large-scale OMEGA system, a more durable membrane capable of facilitating the forward osmosis while also mitigating the effects of biofouling would be necessary. Harris *et al.* (2013) considered biofouling a step further by looking at how biofouling affected light transmittance, directly affiliated with the productivity occurring in the photobioreactors. Through these OMEGA system, technical reports we can see that the general small-scale representations of the concept have been both successful in proving feasibility in many aspects of the technology while also opening up many questions still be tested and to be understood at a large-scale version of the system.

With 10.8 million USD of support from both NASA and the California Energy Commission, four years of OMEGA system technical experiments were conducted (OGI, 2015). With a lack of additional financial resources, Jonathan Trent founded the Omega Global Initiative (OGI). OGI is a nonprofit corporation comprised of a consolidated group of “Omega Activists” whose mission is to:

> *“introduce and help local OMEGA developers and entrepreneurs implement this floating “ecosystem” of technologies that will usher in an era of offshore, integrated, sustainable industries that capture solar energy, recycle wastewater as potable water, and produce food from aquaculture.”*

Their vision is to deploy an OMEGA system by 2025 in a coastal community. Dr. Trent expressed that the largest technical problem of the OMEGA system is scaling and securing the capital to install a system. Thus far, the small-scale pilot projects have taken place in Santa Cruz and San Francisco with the previous funding. To complete a full scale modular OMEGA system for San Francisco, Dr. Trent estimates that 1280 acres of an omega farm would be necessary to treat the 65 MGD of wastewater produced. This has the potential to create 2-6 million gallons a year of biodiesel which would meet 20% of San Francisco’s energy demands. Dr. Trent believes that the US will most likely not be an early adopter due to legal reasons (e.g. extensive permits, litigation process). OGI is in the search for a protected bay community interested in green technology. He believes that the capital costs of constructing the system are reasonable but the biggest hurdle will be the actual building of the offshore infrastructure so that it is stable and robust. There are still many hurdles to get over before a viable solution to large-scale algal biomass/biofuel production is a feasible means of meeting energy demand economically and technically making it competitive in the global market.

3.6 Discussion: Implementation of Appropriate Technology

Based on the technologies and processes expanded on in this chapter, it becomes evident that there is an abundance of research and innovation and a change in paradigm within the field of wastewater management. Whereas implementation of conventional technologies can be mainly credited to public health initiatives, the implementation of alternative and emerging technologies is motivated by greater sustainable development ambitions. According to the U.N. (2017), about 70% of the municipal and industrial wastewater generated in high income countries is treated. In upper middle-income countries and lower middle-income countries, the percentage drops down to 38% and 28% respectively. Dismally, wastewater treatment coverage drops down to 8% for low-income countries. (U.N., 2017). Acceptance of the status quo is a major hindrance to improvement in sanitation sector globally. While politicians should have a major impact on improving conditions within their borders, many remain unchanging, not taking the environmental crisis and water security problem at hand seriously (Mara, 2003).

Mara (2003) states that although lack of capital is primarily the reason cited for locations with insufficient or lack of wastewater treatment, there is also "an ignorance of low-cost wastewater treatment processes and of the economic benefits of treated wastewater reuse." Saad *et al.* (2017) points out that technology decisions are usually made by finance institutions outside of the country and typically encourage the installation of "Northern" technology options. This type of interaction is most notable in the case of low-income countries. A major distinction between wastewater treatment options are those that are centralized versus decentralized systems. A conventional central treatment option is usually represented by a single, highly mechanized wastewater treatment plant. A decentralized treatment system entails treating smaller effective areas. Although a centralized plant can be cost effective when treating large quantities of wastewater within in a small, highly populated area, it is not an adequate approach for other areas.

The persistent theme of the chapter is choosing a technology that is appropriate for a given situation. Typically, the scenarios were discussed in terms of developing regions versus developed regions or urban areas versus rural areas. The needs of a society, the capacity and resources of the community, the typical components of their wastewater, and the level of regulation and the intensity at which enforcement occurs makes each scenario of choosing particular wastewater treatment approaches a unique experience. A systems analysis is necessary in order to understand what constitutes an "appropriate" technology for a community. Figure 3.21 provides a basic framework of capacity of developed and developing regions and urban and rural regions.

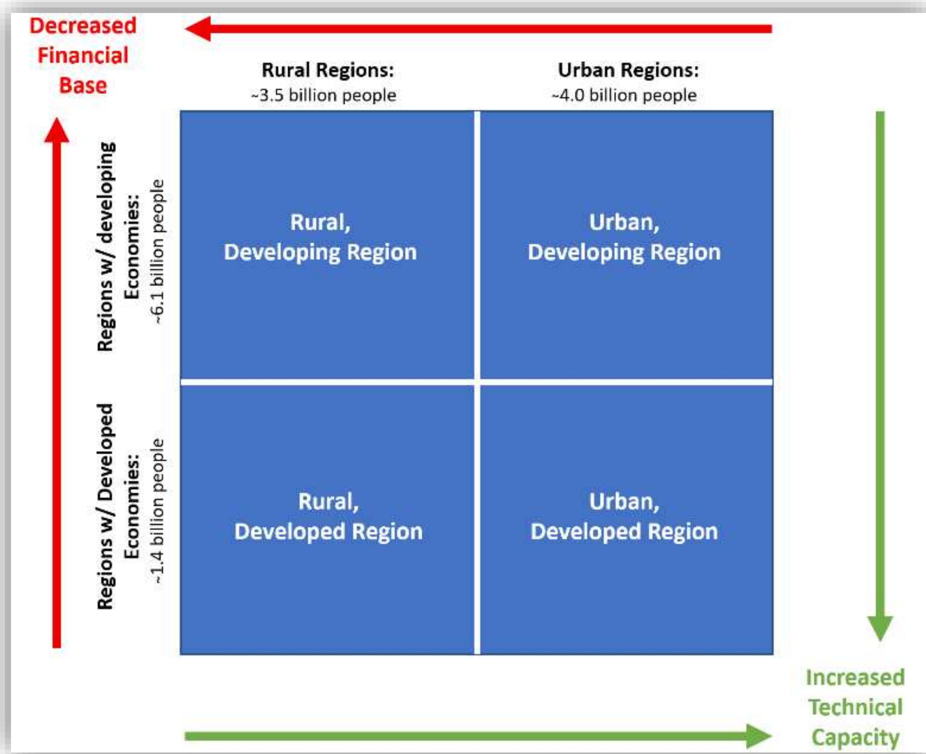


Figure 3.21: basic framework of capacity of developed and developing regions and urban and rural regions.

As expressed in this chapter, the various technologies have their benefits, drawbacks, limits, and constraints. Some of these are expressed in Table 3.7 comparing costs and land area requirements for various treatment processes. These characteristics inherently affect the practicality of implementing various technologies. Figure 3.22 portrays a visual representation of the practicality of implementation for dilution, conventional, alternative, and emerging wastewater treatment systems. Ideally, a community would choose the most efficient technology that matches their capacity for financial and technical capacity and resource availability.

Table 3.7: Costs and Land Area Requirements for waste stabilization pond (WSP) and other Treatment Processes. Source: Mara, 2003.

	Waste stabilization pond system	*Aerated lagoon system*	*Oxidation ditch system*	*Conventional treatment (biofilters)*
Costs (million US$)				
Capital	5.68	6.98	4.80	7.77
Operational	0.21	1.28	1.49	0.86
Benefits (million US$)				
Irrigation income	0.43	0.43	0.43	0.43
Pisciculture income	0.30	0.30	–	–
Net present cost (million US$)	5.16	7.53	5.86	8.20
Land area (ha)	46	50	20	25

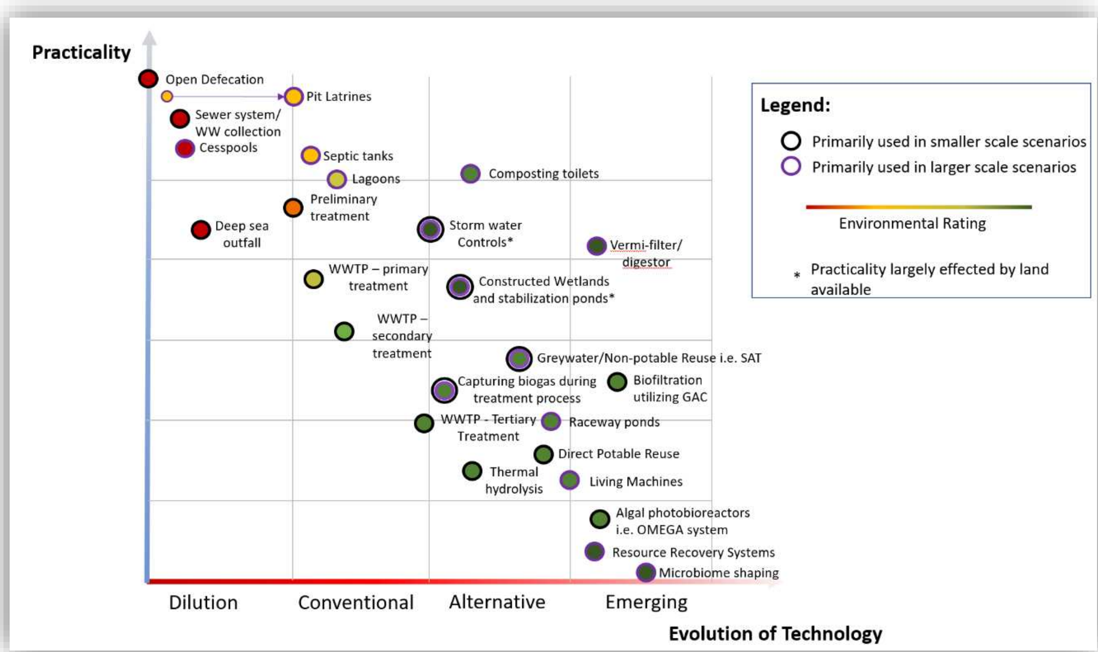


Figure 3.22: Representation of the practicality of implementing different wastewater treatment alternatives.

Exploration of new and emerging water treatment technologies and techniques versus relying on the conventional energy intensive wastewater treatment methods seen in many industrial countries will be vital in appealing to adopt wastewater sanitation more universally. Data collection is important for defining of the problem, deciding upon an intervention, and creating cases for policy changes. The first major step is to expand and increase the monitoring of the environment and implications of current wastewater practices. Then, gaps in water and sanitation services must be identified. The World Bank Group (2016) emphasized the importance of linking stakeholders and identifying strong advocates who can push for change. Better investment advice in wastewater treatment technology with benefit cost analysis will help a community explore their options. This must also be coupled with a revitalization of investment in public infrastructure.

Chapter 4 will now consider the wide variety of technologies utilized in the KwaZulu Natal Province of South Africa that fit within the classification characterized in this Chapter.

CHAPTER 4. CASE STUDY: ETHEKWINI MUNICIPALITY, SOUTH AFRICA

4.1 Introduction

The case study of the eThekwini Municipality in South Africa describes some of the current wastewater practices utilized in a municipality, encompassing wastewater treatment interventions for both urban and rural areas of the municipality. The information in this chapter is primarily based on a literature review of South African water management, technical reports from the government or South African affiliated organizations, and influenced by 4 different interviews that took place during July of 2017. The interviewees either currently work or previously worked for either the eThekwini Municipality or Umgeni Water. The specific interviewees will remain anonymous.

4.2 Literature Review: A History of South African Water Management

Between 1908 and 1996, South Africa has been under the rule of 4 different Constitutions as depicted in Figure 4.1. The purpose of documenting this is to demonstrate the inconsistency of water governance in the country due to the constantly changing political atmosphere.

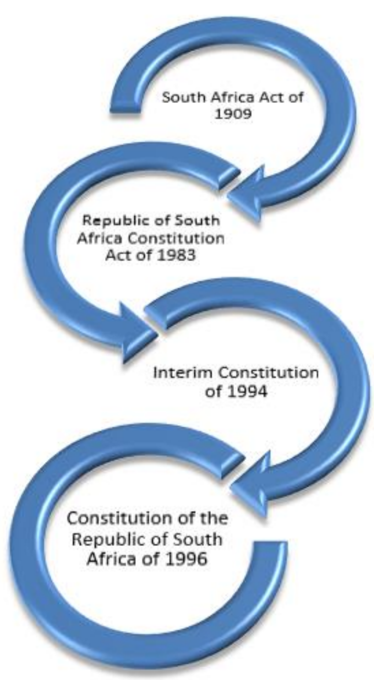


Figure 4.1: The Constitutions enacted in South Africa between 1906 to present day.

The Union of South Africa was formed in 1910 by the South Africa Act of 1909 (an Act of the Parliament of the United Kingdom) which gave South Africa nominal independence from Great Britain and unifying the four former British, Cape Good Hope, Natal, Transvaal and the Free State, into one state (Tempelhoff, 2017). According to Osborn (1988), the pit privy and bucket and dumping of household waste into open street channels that eventually drained into the Umzinduzi River was the conventional wastewater system utilized in Pietermaritzburg (located inland in the Natal Province, see Figure 4.2) before 1905. In Durban, the main drainage and sewerage schemes were constructed in the 1880s and 1890s. The system was not operational until 1896 (Maki, 2010). Then in 1894, a sea outfall was installed in Durban, an option available to them due to their proximity to the ocean (Osborn, 1988). First introduced into South Africa by the British military authorities, the earliest sewage purification observed in South Africa resembled septic tanks with the effluent treated in contact beds and irrigated. The first treatment plants were essentially capable of only preliminary treatment, utilizing detritus chambers, sedimentation tanks, screening, and grit removal. Applying crude sewage over irrigated land was commonly practice, even considered an effective strategy to mitigate stream pollution.

Figure 4.2: Map of the Natal Province. Source: Wikimedia Commons, 2009.

The following examples from Osborn (1998) outline the introduction of new wastewater treatment technologies into South Africa. In 1904, the first sewage treatment plant was operational in Bloemfontein (located in the Free State). The double filtration plant consisted of a single open septic tank with effluent treated by two sets of filters. The following year, 1905, brought upon the first municipal scheme in South Africa, located in Wynberg (in the Western Cape), in operation. The design included fixed screens, a rotary screen operated by a waterwheel, and filter beds with rotating trough sprinklers which could be utilized as either contact beds or percolating filters. In 1908, separate sludge digestion facilities for raw sludge was utilized by a plant for the first time and in the late 1920s, biological filtration was introduced into plant designs (Osborn, 1988). Also in 1920 was the first installation of a conventional activated sludge plant at Boksburg Hospital (located in the vicinity of Johannesburg). In the early 1930s, the earliest form of tertiary treatment was observed with the installation of slow sand filters in Johannesburg (Osborn, 1990).

In 1931, South Africa achieved “full” self-governance through the Statute of Westminster; however, the black majority were still under oppression by the authority of a white minority that imposed discriminative policies. The racial segregation had already been institutionalized previously during South Africa’s colonization era such as with the Native Location Act of 1879, effectively controlling land rights of native, black Africans. The South Africa Act of 1909 was still the acting constitution for the Union which offered very little protection to Africans (South African History Online, n.d). In 1948, the National Party, primarily composed of Afrikaners, rose to power and imposed the Apartheid entailing institutionalized segregation or in other words, “separate development of the different racial groups” (South African History Online, n.d.). Unequal access to sanitation services was just one example of unjust treatment experienced by people of color during this time.

Figure 4.3: Sign from the Apartheid era in South Africa. Source: History Cooperative, 2016.

In 1951, standards for the discharge of effluent to streams was published by the South African Bureau for Standards; however, there was little to no enforcement of the standards established (Osborn, 1988). Whereas the Public Health Act of 1919 prohibited discharging effluents into a river, the Water Act of 1956 mandated the discharge of purified effluents to the watercourse (Osborn, 1988). Permits were mandated for all agricultural users and for any discharged effluent that did not meet quality standards (Osborn, 1990). The Government Notice No. R583 of 1962, revised by the Government Notice No. R991 of 1984, establish the requirements for the purification of wastewater or effluent. The quality standards were prescribed by the Minister of Environment and Fisheries. Methods of testing are given by the Standards Act, No. 30 of 1982, prescribed by the South African Bureau of Standards. Within the Water Act of 1956, the legal doctrine of water use deviated from solely riparian water rights to also recognizing the principle of *dominus fluminus*, i.e. complete ownership of the water by the Government (Tempelhoff, 2017). The Water Act also outlined the responsibilities of water boards and irrigation boards and enumerated on formal subsidies available to urban areas to develop water and wastewater treatment plants. Rural areas and urban slums remained underserved; therefore, insufficient access to water supplies led to the illegal tapping of water.

Wastewater treatment plants were upgrading their processes in order to operate within the new conditions explained above. Depending on the area (e.g. coastal or inland, racial make-up of community which could serve as a predictor of level and quality of service, urban or rural), different technologies were utilized, therefore creating no true conventional technology trends in the country. Commonly, wastewater treatment plants and biofiltration teamed with maturation ponds were being established in growing urban areas whereas aerobic oxidation ponds were being established in smaller communities. The examples given below, based on a study by Osborn (1988), provide an idea of some of the early technologies installed in the Natal Province.

At the Darvill WWTP in Pietermaritzburg serving the Msunduzi Municipality, the process of wastewater treatment included a special stone trap as the grit removal device, a rotary hearth incinerator for the incineration of the solid waste, a primary clarifier, digesters, and a sludge pre-thickener. In 1978, the

Darvill Plant added two 4,5000 m^3 eggshaped sludge mesophilic anaerobic digesters made from prestressed concrete (see Figure 4.4). Even though the height of the digesters are about nine stories, access to sludge is made available at the ground level for the purpose of removal. Gas recirculation in the digester is credited with supplying the mixing mechanism in the digesters (Osborn, 1988). In contrast to these types of digesters, auto-thermal aerobic digestion utilizing the Porteous process (in this case digesting at 2100 kPa and 180 degrees Celsius for about 45 minutes) were utilized in the Durban Southern treatment works and the Durban Northern treatment works (see Figure 4.5). This process allowed the sludge to be dewatered through filter presses. Operational difficulties of the Northern Works Porteus plant led to its eventual replacement. For sedimentation processes, the Durban Central Works Plant utilized a horizontal flow tank. During this time, other types of sedimentation tanks included two-storey tanks (upper sedimentation chamber with sludge dropped through slots into a lower liquifying compartment), vertical flow tank,

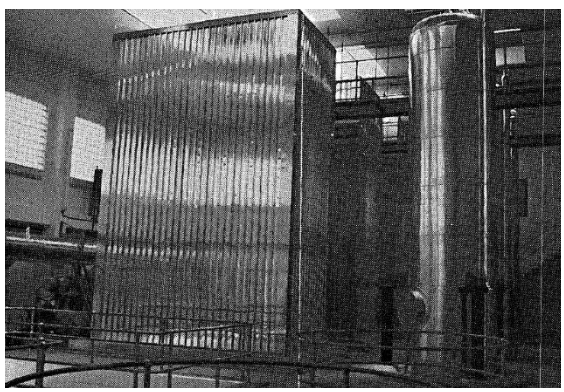


Figure 4.4: Egg-shaped anaerobic digesters at Darvil Treatment Works in 1978. Source: Osborn, 1988.

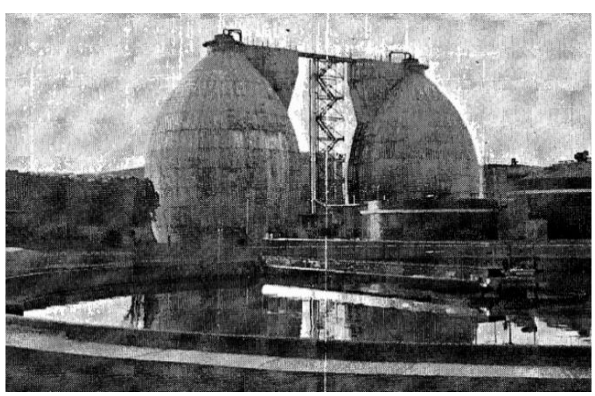


Figure 4.5: Porteous heat treatment plant. Source: Osborn, 1988.

horizontal flow tank, and hummus tank designs. In the 1970s, the Durban Central Works Plant installed fluidized bed incinerators however these would be decommissioned due to high costs of auxiliary fuels. This led to the raw sludge of the Central Treatment works being discharged into sea via a deep-sea outfall. Activated sludge clarifiers at the Durban Northern Treatment Works utilized shallow, radial flow tanks. It was estimated by Brodish in 1985 that almost half of the plants in South Africa were using biological filters and only a tenth were using the combination of biological filters with activated sludge systems.

Unequitable access to sanitation services, among an abundant list of other injustices faced by the majority of South Africans, sparked greater mobilization of activists and protestors. In 1955, the Freedom Charter, demanding that "The People Shall Govern" in a nonracial South Africa, was adopted by the anti-apartheid coalition Congress of the People, affiliated with the African National Congress (ANC) and other groups fighting for equality and the end of apartheid. The government at the time did not appease to the demands of the protestors. The government of South Africa continued to evolve. In 1983, a new constitution for the Republic of South Africa replaced the constitution adopted in 1961. Although it established a Tricameral Parliament, allowing for representation from Colored and Indian groups in one of three separate Chambers, this false notion was meant to disunify the African nationalists and anti-apartheid forces (South African History Online, n.d).

Decolonization efforts and human rights initiatives began to gain major global traction. In December of 1991, the Convention for a Democratic South Africa (CODESA) adopted a Declaration of Intent which demanded the current government to step down and for an interim government to takes its place in order to facilitate the transition to a post-apartheid South Africa. In 1992, the demand was accepted by the National Party providing for the transition to an interim government. This interim government would be known as the South African Government of National Unity which would govern South Africa from April of 1994 to February of 1997.

When the apartheid finally came to an end in 1994, the Department of Water Affairs and Forestry reported that approximately 14 million South Africans did not have access to a formal water supply and 23 million South Africans (accounting for nearly half of the country's population at the time), had no formal sanitation (IRIN, 2008). The White Paper on Water Supply and Sanitation Policy of 1994 began as a means to consolidate water legislation under the basis that all South Africans equally deserve access to essential basic water supply and sanitation services. In line with tackling inequality and poverty and developing an integrated development strategy, the Government of National Unity developed The Reconstruction and Development Programme (RDP) and initiated it in 1996. Water was recognized by the White Paper on Water Supply and Sanitation Policy and the RDP as a social good, central to transition and development and moving toward a more unified country (Sutherland *et al.*, 2014). In 1996, the finalized constitution is signed by President Nelson Mandela and would come into effect February of 1997.

The reformed water policies enacted hereon in water resources management supported the adoption of the integrated water resources management (IWRM) approach (Nomquphu *et al.*, 2007). The Bill of Rights in the Constitution of the Republic of South Africa of 1996 identified that every person in South had the right to equality, human dignity, life, the environment, and sufficient water. The Constitution and the Water Services Act of 1997 formulated the regulatory framework for the provision of water. Major contributions of the Water Services Act included the establishment of compulsory national standards and measures to conserve water, the effectuation of water services development plans, and formulated norms and standards for tariffs and monitoring (Centre for Environmental Rights, 2008). The Water Services Act also established Water Boards (WBs) in South Africa. Considering both quantity *and quality*, the National Water Policy of 1997 specifies regulations for water supplies. The policy sought to more holistically address water management within the context of the hydrological cycle (Nomquphu *et al.*, 2007). The Water Services Providers (WSPs) of South Africa have acquired their power from the Local Government Municipal Structures Act.

South Africa is a peninsula surrounded by ocean. The marine ecosystem is an extremely important resource to the country. The Marine Living Resources Act of 1998 was enacted in order to protect and preserve the marine ecosystem by the conservation of marine living resources and biodiversity, restructuring of the management of fisheries, and the reduction of marine pollution. The National

Environmental Management Act (NEMA) of 1998, following the largely inadequate implementation of the ECA, became the main legislation that provided the framework for environmental management. The policy's objective is to promote co-operative governance which included acknowledging the importance of economic development for South Africa when implementing integrated management of the environment.

The National Water Act (NWA) of 1998 represented a shift in paradigm from primarily supply driven water management to additionally supporting equity, sustainability, and economic efficiency in water management (Nomquphu *et al.*, 2007). Prior to the Act, water quality monitoring was completed with the objective of development and operation of the national water infrastructure. Water quality monitoring was utilized under the NWA to assess additional objectives such as "compliance with resource quality objectives, management targets and water use license conditions at national, regional (catchment) and local levels" (Nomquphu *et al.*, 2007). The Minister of Water and Sanitation is tasked with establishing a national monitoring system and formulating national information systems on water resources. Whereas water policy leading up to this point was driving toward increased centralization of management duties into the national government, the National Water Act of 1998 focused on passing down responsibilities to regional and local institutions, such as envisioning the implementation of Catchment Management Agency (CMA) in each of the water management areas (WMAs). It was not until 2001 that the Free Basic Water (FBW) Policy was included into national level policy, to be executed at the local/municipality level. The FBW Policy entails that poor households are given access to a basic supply of water, to be a minimum of 6,000 liters per household per month, at no cost.

Incentive based regulation was introduced into South African water management in 2008 with the formulation of the Blue Drop Certification Program in regard to drinking water quality management regulation and the Green Drop Certification Program in regard to wastewater quality management regulation by the Minister of the Department of Water and Sanitation (Burges, n.d.; Department of Water and Sanitation, 2014). A Green Drop score, based on the performance of individual wastewater system, allows for the identification of those working well versus those not meeting minimum standards or requirements. The Certification takes place every other year with the gap year utilized to track and report progress. Performance is measured in the following areas (Burges, n.d.):

1. process control, maintenance and management skills,
2. wastewater quality monitoring
3. credibility of wastewater sampling and analysis.
4. submission of wastewater quality results
5. wastewater quality compliance
6. management of wastewater quality failures
7. storm-water and water demand management,
8. by-laws,
9. capacity and facility to reticulate and treat wastewater,
10. publication of wastewater quality performance, and
11. wastewater asset management.

The Green Drop Program also entails (1) a Cumulative Risk Rating for each WWTP which focuses on the critical risk areas within the treatment process, (2) a Municipal Green Drop score which is based on the design capacities of plants, and (3) a Site inspection score which is based on the infrastructure's physical condition (Burges, n.d.). Figure 4.6 depicts a municipal Green Drop scorecard.

The 2014 Green Drop Report is the most recent report made available online by the Department of Water and Sanitation establishing the current status of the wastewater services. Data was collected from 824 public wastewater treatment plants from 152 different municipalities. See Table 4.1 for size description of public WWTP participating in the program. These WWTP account for a total of 5,000 million liters of wastewater per day (over 1.32 billion gpd). As illustrated in Figure 4.7, the green drop performance scores are extremely low for municipal WWTP, scoring as either in critical state or very poor performance. In KwaZulu Natal, the number of plants at critical risk positions and high-risk positions were 13 and 55 respectively (DWS, 2014). IRIN (2008) reported that "outdated infrastructure and problems in retaining skilled staff have contributed to what DWAF admits are unacceptably high levels of pollution in some rivers and dams." IRIN (2008) backed-up this claim by stating that in 2004 South Africa had just 15,000 civil engineers, and out of those, only 11 percent of those engineers were working for local government.

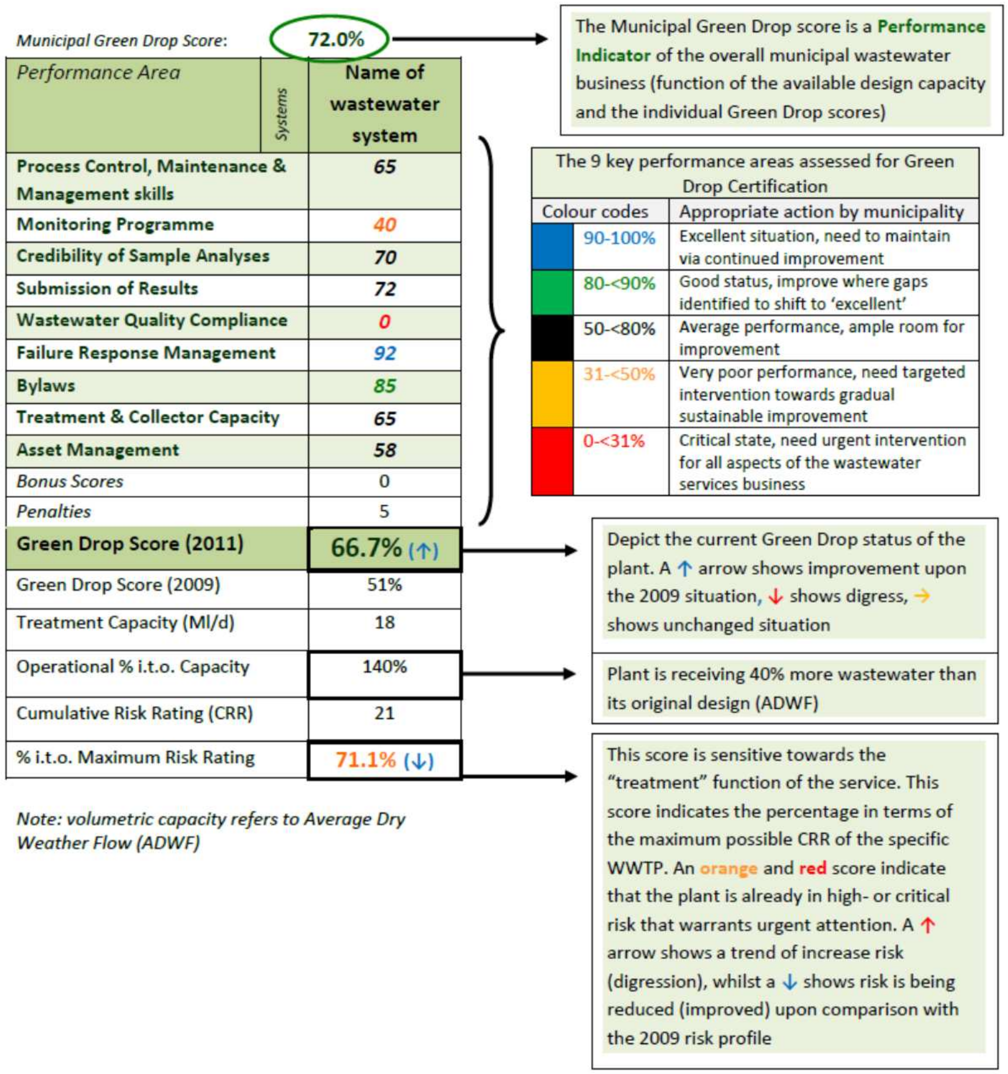


Figure 4.6: Example of a Green Drop Scorecard. Source: Burges, n.d.

Table 4.1: Public WWTP participating in the Green Drop Certification Program. Source: Department of Water and Sanitation, 2014.

	MICRO SIZE <0.5 Mℓ/day	SMALL SIZE 0.5-2 Mℓ/day	MEDIUM SIZE 2-10 Mℓ/day	LARGE SIZE 10-25 Mℓ/day	MACRO SIZE >25 Mℓ/day	Undeter mined	Total Mℓ/day
No of municipal WWTPs	168	269	232	65	62	28 (43)	824
Total Design Capacity (Ml/day)	37.55	256.88	1019.73	939.90	4178.30	28 (43)	6432.36
Total Daily Inflows (Ml/day)	9.39	85.43	485.65	496.05	3923.06	450 (243)	4999.58

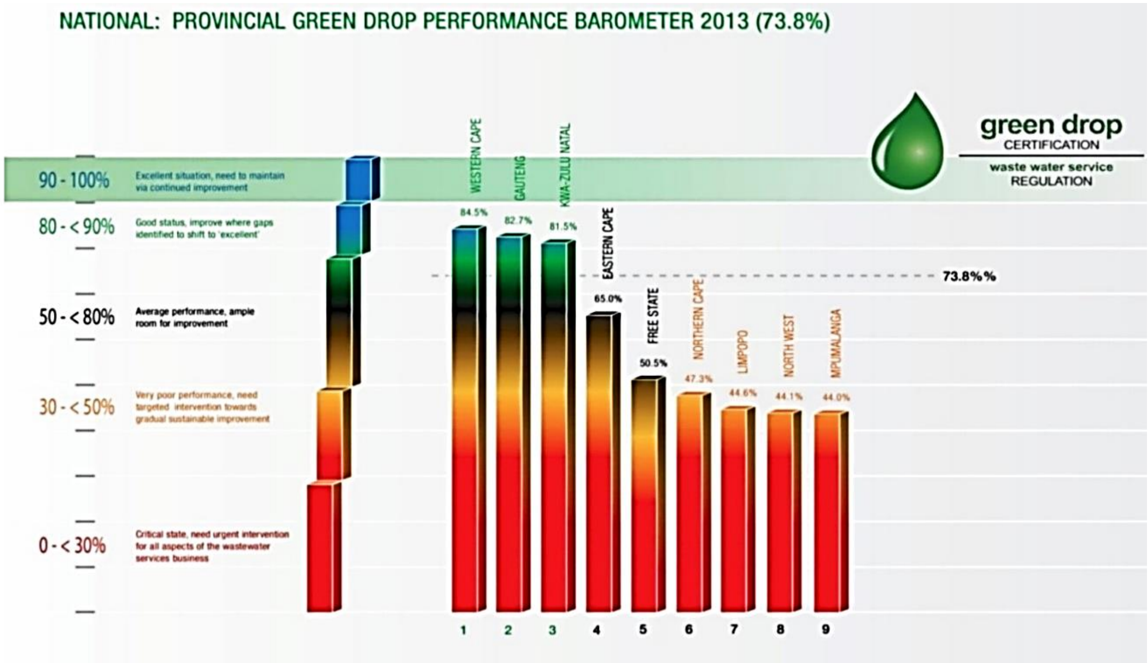


Figure 4.7: Green Drop Performance Barometer 2013. Source: Department of Water and Sanitation, 2014.

The current water resources management situation in South Africa is battling with: (1) attaining water security, (2) mitigating environmental degradation and resource pollution, and (3) inefficiently using water (DWA, 2013). The National New Development Plan of 2011 is pursuing the elimination of poverty and reduction of inequality in South Africa by 2030. The priorities set by the National Water Act and the National Development Plan are integrated within the National Water Resource Strategy (NWRS*).* According to the NWRS for South Africa, the water supply and demand gap of 17% is expected by 2030 as the demand for water is rising approximately 1.2% per year. Water consumption from the domestic sector alone increased by 5% over a period of ten years. The irrigation sector uses up to 60% of South Africa's water resources. Water losses from agricultural schemes is approximated at 35% to 45% (DWA, 2013). Over the past six years for urban supply systems, the NWRS reports that an average of 36.8% is non-revenue water. This equates to 1,580 million meters cubed per year (m^3/yr), or approximately 1,142,781,000 gallons per day (gpd), of the total urban consumption is not creating revenue (DWA, 2013). Many municipal water suppliers determined that an upward of 90% of their water was supplied on a nonrevenue basis.

With water infrastructure in South Africa steadily increasing, the country is rapidly approaching full utilization of their surface water yields. In 2013, there were around 4,400 registered dams (DWA, 2013). The majority of the wastewater treatment plants discharge their final effluent into the river systems. A common alternative to this is for coastal cities to utilize deep sea outfalls. The NWRS states the importance of reducing water demand and increasing water supply in ways that “move beyond 'traditional engineering solutions' of infrastructure development” (South African Department of Water Affairs, 2013). The DWA (2013) is concentrating on implementing strategies such as:

1. water conservation and water demand management (WCWDM),
2. increased use of groundwater,
3. desalination (Large scale and small scale. Also includes treated mine water desalination),
4. water reuse (i.e. re-use of wastewater at the coast),
5. constructing dams (though limited in areas where this is still applicable)
6. transfer schemes
7. rain water harvesting,
8. treated acid mine drainage,
9. catchment rehabilitation,
10. and the import of water intensive goods.

The Government Notice No. 943 of 2013, i.e. the National Norms and Standards Relating to Environmental Health in Terms of National Health Act of 2003, established expectations for health-related water quality monitoring, waste management (general, hazardous and health care risk waste), and hazardous substances and chemicals management among other matters. The norms and standards are affiliated with many pieces of legislation such as the Hazardous Substances Act, 1973 and the National Environmental Management Waste Act of 2008.

4.2.1 Current South African Federal Governmental Agencies and Management Structures

This section will provide a fuller explanation of current governance structure of South Africa which is depicted in Figure 4.8. Within the South African Constitution, a list of subjects is provided that both national and provincial governments share concurrent responsibility. Subjects include agriculture, education, disaster management, environment, health services, pollution control, public works, and regional planning and management. The Constitution also states matters to be governed primarily at the provincial level, i.e. provincial planning, provincial recreation; and at the local level, i.e. municipal planning,

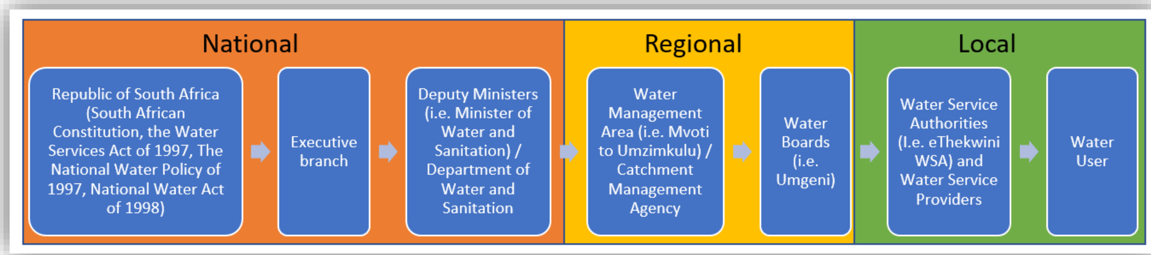


Figure 4.8: South Africa's flow of authority within governmental structure pertaining to the governance of water management.

municipal health services, municipal public works, stormwater management, and water and sanitation services. As realized with the United States, the local government is generally tasked with the implementation side of regulation such as constructing and operating infrastructure.

At the national level, the Department of Water and Sanitation, Department of Agriculture, Forestry and Fisheries, the Department of Health (DoH), and the Department of Environmental Affairs (DEA) are the main bodies of the South African National Government concerned with managing and regulating South Africa's water resources. The Department of Water and Sanitation is analogous to the U.S. EPA in the role the organization plays in supporting efforts to monitor, regulate, and prevent water pollution and in conducting and disseminating research to protecting human and environmental health. The Department responsibilities entail (Nomquphu *et al.*, 2007):

> *"the design and coordination of water monitoring programs, development of technology and methods to support monitoring, assessment and auditing; standardization of approved methods and techniques for monitoring, analysis and assessment; regular review of regulations, standards, methods and accreditation requirements; design, establishment and maintenance of national monitoring networks; and the development and maintenance of information management systems."*

At the regional (i.e. provincial) level, nineteen watershed management areas (WMAs) were established by the South African Government in 1999t. The thirteen Water Boards (WB) of South Africa, established by the Water Services Act of 1997, report to the DWA. The WBs are the primary entities involved with regional infrastructure of water resources within these management areas. WBs are generally responsible for the operations of dams and bulk water supply infrastructure (Tissington, 2011). Water Service Authorities (WSAs) are involved with implementing provisions of national policy and regional water management planning by providing services at the municipality (i.e. district, local or metropolitan) level. Tissington (2011) reports that there are 169 WSAs in South Africa including water boards, district municipalities, local municipalities, and municipal companies. Their power is contrived from the Municipal Structures Act (Tissington, 2011). As previously mentioned, the National Water Act of 1998 also envisioned a Catchment Management Agency (CMA) in each of the WMAs; however only 2 CMAs have been thus implemented in other WMAs (Meissner *et al*, 2017).

The Municipal Systems Act requires all municipalities to create Integrated Development Plans (IDP). A major component of the IDP, obligatory by the Water Services Act, is the Water Services Development Plan (WSDP) to be produced by WSAs. Delivering water services or conducting waste water treatment services can also be contracted out to Water Service Providers (WSPs) by WSAs. WSAs are required to formulate Water Services Development Plans (Tissington, 2011). See Figure 4.9 for the depiction of the Umgeni WB Operational Area and the WSAs within.

Figure 4.9: The Umgeni Water Operational Areas. Source: Umgeni, n.d.

4.3 eThekwini Municipality

The eThekwini Municipality is within the greater Mvoti to Umzimkulu WMA and under the jurisdiction of the Umgeni Water Board. The eThekwini WSA, commonly referred to as the eThekwini Water and Sanitation Unit (EWS), is responsible for providing the water and sanitation services. The theoretical responsibilities of the CMA in the Mvoti to Umzimkulu WMA fall to the DWAF's Regional Offices until the CMA is established (eThekwini Municipality, 2011c).

As of the 2011 census, eThekwini is a city of over 3,442,398 people (eThekwini Municipality, 2011). The Mooi-Mgeni System (pictured in Figure 4.10 and Figure 4.11), the main water source in the Durban and Pietermaritzburg areas, supplies water to almost 5 million people and industries. It is known that the yield of the Mgeni System will not be able to meet future water demands (DWS, n.d. a). The current and expected increase in water demand is also putting pressure on the wastewater treatment facilities.

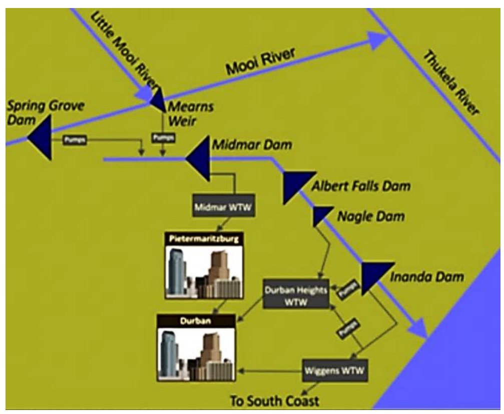


Figure 4.10: Mgeni System. Source: DWS, n.d. a.

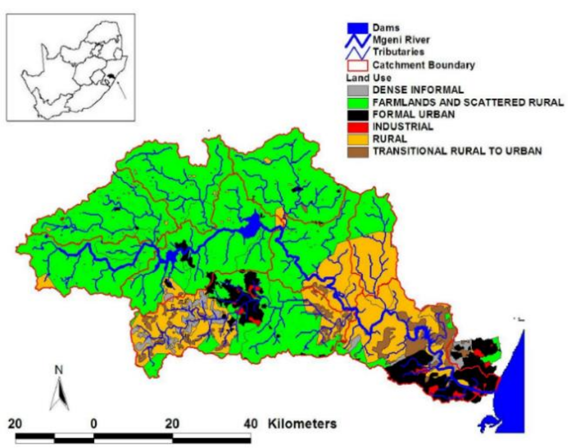


Figure 4.11: Land use within the Mgeni System. Source: Kiker et al, 2006.

In the Greater Durban Metropolitan Area, there are thirty-five operational wastewater treatment plants (City of Durban, n.d.). Durban's Metro's Wastewater Management Department handles 435 million liters of domestic and industrial sewage per day (City of Durban, n.d.). Around 30-40 Ml/day is industrial wastewater (Interviewee 1, 2017). Industries are supposed to monitor their wastewater, but with the inadequacy of current enforcement from the municipality, this is not always the case (Interviewee 1, 2017). Figure 4.12 depicts that during 1966 to 1997, industrial discharges were responsible for 56% of the contamination present in water sources in KwaZulu Natal. The bio-system of the Mgeni System is being overloaded with contamination which in turn disrupts its capacity to complete natural recycling processes (e.g. photosynthesis, respiration, nitrogen fixation, evaporation and precipitation) (Rawat *et al*, 2010).

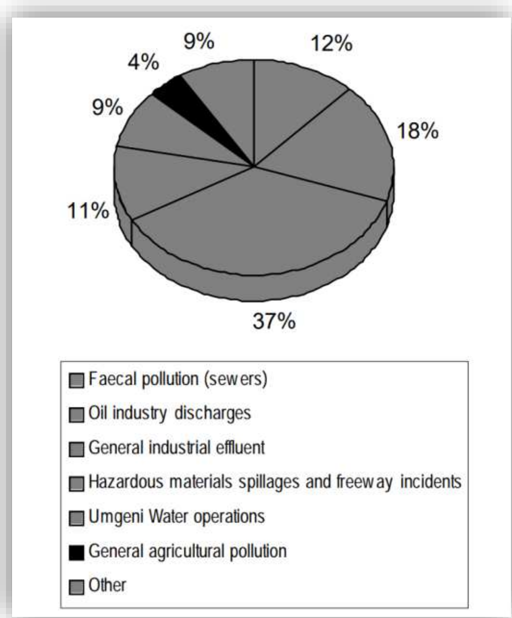


Figure 4.12: Contributing incidents causing contamination of water sources during 1996-1997 in the KwaZulu-Natal region Source: Atkinson et al, 1998. Data from Umgeni Water, 1997.

In a previous study of water governance in the eThekwini Municipality, Sutherland (2014) defined four different discourses that have shaped water governance in the municipality. These discourses are human rights discourse, economic good discourse, spatial discourse, and experimental governance and incremental learning distance. The premise of each discourse is presented in Table 4.2. These themes surrounding water management will be evident throughout this chapter.

Table 4.2: Discourses of water governance. Source: Surtherland et al., 2014.

Discourses of water governance in eThekwini Municipality

Discourse	Main premises
Human rights discourse	Water is a social good Social justice Water is a basic human right Sanitation is a basic human right and is strongly associated with dignity Water should not be commodified but, rather, be valued as a fundamental component in just socio-ecological systems that support transformation
Economic good discourse	Water is an economic good Neo-liberal ideology Water and sanitation service provision must be financially sustainable Cost-efficiency to ensure sustainable provision of services
Spatial discourse	Inequality has clear spatial patterns Topography of the city: periphery has steep, incised valleys Legacy of apartheid Urban–rural continuum Outer edge of bulk infrastructure provision and waterborne sewerage Costs of servicing the periphery Sustainable service delivery approaches for the future: new environmentally sensitive technology
Experimental governance and incremental learning discourse	Diversity of actors Diversity of approaches Flexibility in decision-making Space for adaptation Increasing levels of trust Incremental learning A certain level of participatory knowledge production Capacity building at all levels

4.4 Current Treatment Practices Utilized in KwaZulu, Natal, South Africa

The following section will walk through examples of technologies implemented or piloted in the eThekwini Municipality that fall within the categories dilution, conventional, alternative, and emerging.

4.4.1 Dilution

Sewer Conveyance System. According to Interviewee 1 (2017), there are 280 sewage pump stations and 7,500 km of main sewer lines in eThekwini. Due to population growth in the area, the sewer system in many areas is undersized and/or falling into disrepair. Due to poor maintenance of the sewer system, pipes are bursting on a regular basis (Interviewee 1, 2017). There are also major issues with infiltration into sewer lines (Interviewee 1 & 3).

Table 4.3: Dimensions of the two sea outfalls in the eThekwini Municipality. Source: CSIR (2011)

Feature	Central Works	Southern Works
Length of outfall from shoreline (m)	3 200	4 200
Main diameter (m)	1.32	1.37
Length of diffuser section (m)	450	290
Number of diffusers	18	34
Depth of diffuser section (m)	43 - 53	54 - 64
Capacity (megalitres per day)	135	230

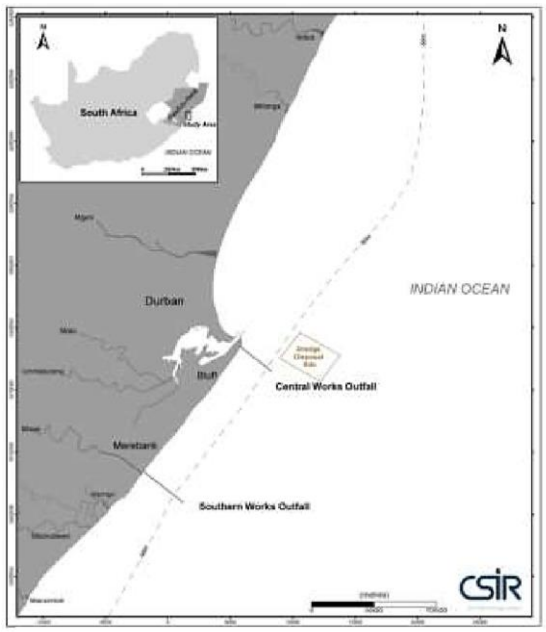


Figure 4.13: The location of the two sea outfalls in the eThekwini municipality. Source: CSIR (2011).

Ocean Outfalls (Southern and Central Treatment Works). Since 1970, effluent has been discharged from the two deep sea outfalls of the Central and Southern Works plants (eThekwini Municipality, 2011). See Figure 4.13 for the location of the outfalls and Table 4.3 for information regarding the design parameter of the ocean outfalls. The outfall pipes release the sewage at a depth of sixty meters through 400 meters of diffusers. The water quality of the ocean is tested on a weekly basis by the government for recreational activities. Currently the municipality does a "suite of microbiological chemical and ecological measurements that focus on assessing the state of the environment in the vicinities of the two outfall and along adjacent beaches" (eThekwini Municipality, 2011). Water samples collected are measured for metals, toxicity, bacteria, nutrients and conventional variables such as salinity, pH, dissolved oxygen, and turbidity (CSIR, 2012). The South African Water Quality Guidelines for Coastal Marine Waters is the governing policy over the effluent quality entering into the sea. According to the CSIR study (2012), the outfalls generally are in compliance with the standards except for pH, dissolved oxygen concentrations, and cooper. The sediment had high counts of faecal indicator bacteria cfus and the discharge area was particularly "enriched with particulate organic material" with an increase in capitellid polychaetes (CSIR, 2012).

The municipality had been considering adding another sea outfall up the coast from Durban in Umdloti. The suggestion of adding another outfall has received a lot of pushback from the Department of the Environment (Interviewee 4, 2017). The Department of Environment is extremely concerned about the potential negative environmental impact of releasing wastewater into the ocean whereas some municipality officials of eThekwini consider the wastewater as a feed of nutrients for the ocean near Durban which is considered to be nutrient deficient (Interviewee 4, 2017).

Conventional Sanitation Services to the Poor. Like many other major cities, Durban is experiencing the rapid increase in migration to urban areas, as well as the increase in informal settlements (Schneider, 2016). Sewage connections are generally not available to the informal settlements; therefore, dry toilets and pit latrines (e.g. VIPs, double pit toilets) are most common in these areas (City of Durban, n.d.; Interviewee 2, 2017). Durban has also been proactive with providing sanitation services to the over one million people living in the informal settlements with "community ablution block" public washrooms (Schneider, 2016). Many issues persist of people tapping into the current sewer and storm water system. Interviewee 4 (2017) shared a story concerning a person who built a structure over a storm water manhole to replicate functions of a conventional flush toilet.

4.4.2 Conventional

Permitting Point Sources. The eThekwini Municipality is currently creating new permits or renewing permits with only an allotted five-year concordance until a reassessment of the permit must occur for a renewal. Theoretically, the permit is monitored on an ongoing basis. If a permit holder is proven to not be compliant, the municipality will come, up to 8 times a month, to test the permit holder's effluent to make sure it reaches compliance. Each time the municipality tests the permit holder's effluent for compliance in this scenario, the permit holder is responsible for paying for that testing. This can become extremely punitive. If the permit holder continues to fail, municipality has power to say they can no longer discharge effluent which will overarchingly shut down the operations occurring. When the municipality tries to tighten up permits, they get a lot of rebuke from industry. In many instances, the municipality officials have received threats and abuse (Interviewee 4, 2017).

Northern Treatment Works*:* The flow into the Northern Treatment Works is around 70-100 Ml/day. The plant operates with two biological nutrient removal active sludge modules with four primary settling tanks, two activated sludge reactors, and seven clarifiers. Three heated and mixed anaerobic digesters treat the activated sludge. Sludge is dewatered and then used for land application on agricultural fields (WEC Projects [Pty] Ltd., 2016). The plant is being revamped. According to Interviewee 1 (2017), the maturation ponds have been silted up with sludge and been needing rehabilitation for past 10 years. See Figure 4.14 for an aerial view of the Northern Treatment Works.

Figure 4.14: Aerial view of Northern Treatment Works. Source: Google Earth, 2015.

Central Works: The flow entering the Central WWTP is around 180 Ml/day. The water does pass through primary settling tanks but unclear if any other processes are occurring before effluent is discharge into the sea by the sea outfall described in Section 5.2.1 on dilution technologies. (WEC Projects [Pty] Ltd., 2016).

***Southern Treatment Works*:** According to Interviewee 1 (2017), the Southern Treatment Works has an inflow of around 120-140 Ml/day. Most of that flow is directed to the sea via a deep-sea outfall. About 20 Ml/day is treated at a reclaimed water plant (Interviewee 1, 2017). The reclaimed water plant is part of a PPP and will be discussed in the following section on alternative technologies. Due to the storm water infiltration problem into the sewers, the flow will peak to around 140 Ml/day but the load will remain the same. Before disposal into the ocean, preliminary treatment occurs in the form of screening and gritting processes. For the past 13 years, the municipality has been trying to get facilities that have fallen into disrepair (primary clarifiers and digesters) back into commission. There have been proposals to rehabilitate the treatment mechanisms, but they are still not operational leading to untreated sewage effluent entering the ocean. (Interviewee 1, 2017).

Transporting, or ”tankering,” of effluents “is a nightmare” according to Interviewee 3 (2017). Industry creates an effluent and depending on what it is comprised of (e.g. if it is likely to be corrosive), it may or may nor be allowed to be entered into the sewers to prevent damage to the infrastructure. In this scenario, industry has to pay for the cost of a tanker to transport the waste to the Southern Treatment Works. The testing (e.g. toxicity testing, pH, etc.) required of the wastewater in the tanker in order to receive approval for discharged via the deep-sea outfall can become extremely cost prohibitive; therefore, wastewater is improperly dumped in many cases to avoid fees. (Interviewee 4, 2017).

Sludge Disposal. eThekwini Municipality is treating about 100 tons of sludge per day and has about 300,000 tones it needs to get rid of (Interviewee 2, 2017). There is a great opportunity to repurpose the sludge such as with compost, brickmaking, chicken pellets; but, the municipality is having trouble finding organization to invest in it. One of the sectors the municipality tried to appeal to be the forestry sector. A big obstacle they found with sludge management was the transporting of the sludge to its next beneficial use (Interviewee 2, 2017).

Interviewee 1 (2017) believed sludge management was the main problem concerning wastewater management in the eThekwini Municipality. The interviewee observed that most WWTP in the city were choked with sludge; therefore, a lot of sludge was going through to their final effluents. Most estuary mouths are open so a WWTPs can get away with it; however, for the ones that aren't open (e.g. dammed up rivers) anaerobic conditions form and the loss of storage results. The municipality has also had countless experiences with sludge haulers who do not properly dispose of the sludge in the way they agreed to under contract. The interviewee recognized the issues in sludge management not as a technological problem, but rather as social and political ones.

Data collection. Plants and agencies are producing a lot of data but not utilizing or analyzing it to make intelligent operation decisions (Interviewee 3, 2018). To address this, the eThekwini Water and Sanitation Department is implementing the I2MTS (Integrated Innovating Maintenance Technologies & Solution) system. The system is designed "to maximise available data to optimize management/engineering decision making, improving operational efficiency, reducing non-revenue losses, and meeting regulatory compliances." (Centre for Expertise, 2018).

Season variability. KwaZulu Natal is South Africa's second largest economy, contributing an average of 16.4% (1995-2008) to the country's GDP. The Port of Durban is also the largest shipping terminal on the African continent and the 4th largest container terminal in the South Hemisphere (South African Tourism, n.d.). Domestic tourism also accounts for an estimated 8% annum of the region's GDP (eThekwini Municipality, 2011). The dynamics of Durban's economy lends itself to seasonal loading effects for wastewater treatment facilities. This can stem from popular times that tourists visit or industries shutting down for holidays. These variations can be difficult for wastewater treatment plants to handle. Interviewee 1 (2017) observed that during offseason, many plants in the municipality worked much better because they were not being overloaded.

4.4.3 Alternative

Water Gap. Aforementioned, there is a growing water gap in the Mgeni System, especially with the elongated droughts the municipality has been facing for the past few years and the increased demand on water supplies from urbanization and industrialization. One means of augmenting the supply is the eminent construction of the Smithfield Dam on the uMkhomazi River near Richmond (DWS, n.d). The dam will not be completed for a while longer; however, Interviewee 2 (2017) stated that it needs to be running by 2025 to avoid running out of water. Drought has somewhat been helpful in the way that water has become an issue; therefore, the field is receiving a lot of attention and helping push past the status quo. (Interviewee 4, 2017). Reuse becomes extremely important topic when considering augmenting supplies to meet long term demands in the system.

Interviewee 3 (2017) eloquently stated that "waterborne sewage has to die if we want water to drink." Whether South Africans should be striving for a traditional westernized model of flush toilets is out of the question according to Interviewee 4 (2017) due to the lack of available water supplies. Even with this constraint, more and more people want and even expect the installation of conventional flush toilets. This calls for "out of the box solutions" according to Interviewee 2 (2017) who recognized that many people, mostly in rural areas, need access to sanitation services. For instance, currently, urine from latrines typically are treated with the help of soak away pits. Interviewee 2 (2017) recommends that the urine should be collected as it is a feedstock of resources and that the process should be integrated with a program to create jobs in the rural communities. In fact, the municipality has tried programs that have done very similar initiatives focusing on hiring community contractors to maintain treatment interventions used. A consideration with implementing reduced flow type models of wastewater management means wastewater treatment plants must prepare to start seeing greater loads and decreased influent flows (Interviewee 4, 2017).

Smaller, more practical schemes suitable for rural areas are still needed. The technologies should be low tech; however, that characteristic of the technology may come across as insulting to people's intelligence. Researchers looking at appropriate technology options for developing communities need to think about the soft, social issues as well as the technical ones. Interviewee 3 (2017) referred to this as "cross[ing] the divide from research to application." Interviewee 3 observed that in developing world settings, culture is more important; therefore, governments handing down decisions based in "foreign" concepts is not going to work in these contexts. Genuinely, there are people who want to stay in their rural communities so solutions are needed to best provide sanitation services in a way that is effective in meeting both cultural and technical objectives.

Amanzimtoti Wastewater Treatment Works. The plant is piloting UV disinfection of wastewater effluent to be compared to conventional chlorination of wastewater effluent. This particular pilot study is applying a closed vessel, medium pressure UV technology. This alternative is benefical in that it does not have the associated health and safety concerns (e.g. disinfection by products, harm to aquatic life, safety aspects for operators) as using traditional chlorination. The UV disinfection systems have also been known to kill Cryptosporidium and Giardia, two notoriously chlorine resistant pathogens. (Centre of Expertise, 2018).

Phoenix Wastewater Treatment Works. At the Phoenix plant operated by eThekwini, the plant is testing the yields of digestion of sludge linked with reclaiming energy with a thermophile sludge digestion process. Although this technology is commonly practiced in other developed countries, this project is showing proof of concept so it can be more widely adopted in KZN and South Africa. When considering an implementation strategy, current mesophilic digesters conventionally utilized could be converted to thermophilic digesters. (Centre for Expertise, 2018).

Southern Treatment Works. In the eThekwini Municipality, PPPs exist within operations at both the Central Water Treatment Works (discussed in Section 5.2.4) and the Southern Treatment Works. At the Southern Treatment Works, the Durban Water Recycling (Pty) Ltd. (51% OTV France [Veolia] and 18.5% Umgeni) entered into a contract in 1999 with eThewkini Municipality to produce high quality reclaimed water for the clients MONDI (paper industry) and SAPREF (refinery). Loan agreements were facilitated through the Development Bank of Southern Africa and the Rand Merchant Bank. The Veolia reclaimed water plant with 7 stages for recycling industrialized water was originally treating 40 Ml/day but now treats closer to 20 mL/day. When the economy went down, Mondi paper began shutting down some paper manufacturing machines, decreasing the demand for the reclaimed water. The eThekwini Water and

Sanitation Unit has a business development manager looking to find new ways to sell the reclaimed water. (Interviewee 1, 2017).

4.4.4 Emerging

According to Interviewee 3 (2017), South Africans are exceptionally good at networking and forging collaborations. In some scenarios, this stems from the mentality that South Africa does not have the answers and has to look out to see what else is out there. Interviewee 3 believes South Africa has the talent and skills in house; however, being a middle-developed country, the country lacks the confidence at times to forge its own path. Nevertheless, collaborations with the private sector and other countries has led to the following examples of pilot projects occurring in the eThekwini Municipality.

Northern Works WWTP. At the northern treatment works, the plant is piloting Struvite precipitation technology with anaerobic effluent that has passed through a belt press. This resource recovery method is targeting phosphate removal. The phosphate can then be recovered in the form of struvite crystals which can be repurposed for fertilizer. (Centre Of Expertise, 2018).

Central Works. At the Central Treatment Works Plant, Hitachi Ltd. (headquartered in Japan), and the Japan International Cooperation Agency (JICA) entered into agreement in 2016 to build a demonstration project called "RemixWater" that integrates wastewater treatment recycling and desalination processes (JICA & Hitachi Ltd., 2016). The Seawater Desalination and Water Reuse Integrated System is a brand-new technology using wastewater mixed with sea water to reduce the osmotic pressure and the energy requirements for water recycling. See Figure 4.15 for a depiction of the technology. The "RemixWater" project duration will span 4 years: November 2016 to November 2020. The demonstration project is expected to treat approximately 6.25 Ml/day. (Hitachi, 2016).

Algae Technology. Professor Faizal Bux (anonymous 1, 2017) director of the Institute for Water and Wastewater Technology at the Durban University of Technology specializes in water quality issues. Recently he completed some experiments with treatment of wastewater with algae (Interviewee 1, 2017).

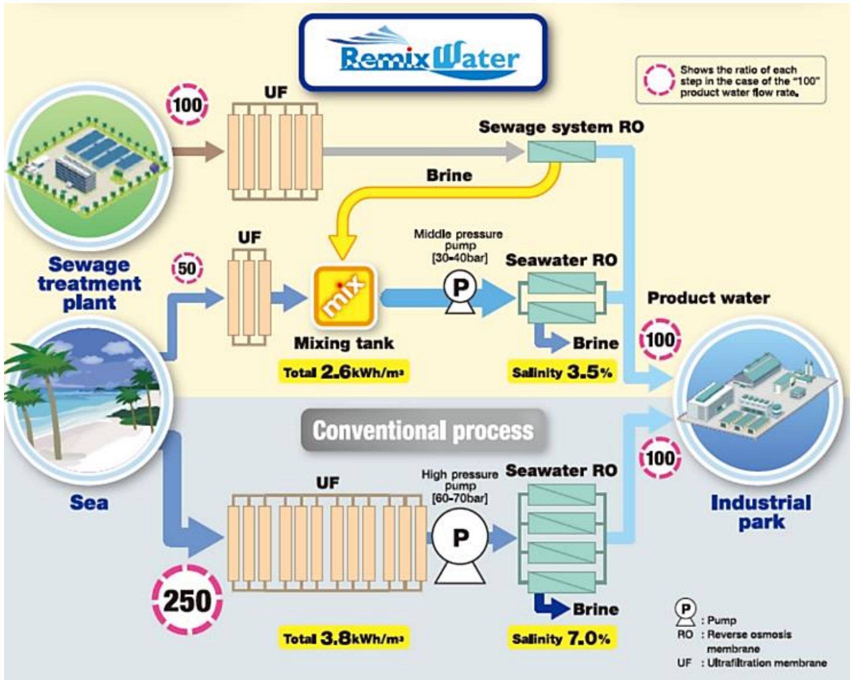


Figure 4.15: Depiction of the "RemixWater" Seawater Desalination and Water Reuse Integrated System. Source: Hitachi, n.d.

Professor Bux's primary research areas include wastewater biotechnology, bioremediation, algal biofuels research and biotechnology, constructed wetlands/rhizofiltration and rainwater harvesting (DUT, 2015).

Professor Derek Stretch, an environmental fluid dynamics expert at the University of KwaZulu Natal, is also heavily involved in algal based wastewater treatment research. He currently holds the eThekwini-sponsored Chair in Civil Engineering. Similar to the functioning of the OMEGA System, Dr. Stretch is investigating a marine structure wastewater treatment system that utilizes ocean waves as a source of energy for pumping of wastewater through photobioreactor tubes.

4.5 Social Constraints of Water Management at the Local Level

Corruption at the national level, death threats, assaults, and crime have been inhibitors of progress in the eThekwini Municipality (Interviewee 1 and Interviewee 3, 2017) According to Interviewee 1 (2017), sewers in the Durban basin are not getting repaired due to social constraints. The Municipality is trying to promote educational opportunities that inform the public and industry on not polluting and such. These interventions are designed with the objective of changing cultural behavior and build public buy-in

(Interviewee 2, 2017). This is a reaction to Municipality employees being assaulted and one employee who was even murdered (Interviewee 4, 2017).

4.6 Implementation: Water as a Human Right

Due to South Africa's core governing document recognizing water as a human right, policies, strategies and institutions to manage and deliver water services has resulted but not without some major barriers and limitations. Due to the apartheid, historical disparities can still be found in both spatial separation and allocation of people and resources. South Africa's Water Services Act of 1997, also known as the Free Basic Water Policy aims at reducing the inequalities in service provision by providing everyone with the right of access to basic water supply and sanitation. The policy calls for the amount of at least 6,000 liters water per household of 8 people which was drawn from the WHO standard (stipulates a standard of 25 liters/person/day). The amount of free water provided can differ among the municipalities but not be below the above stipulated amount. The main responsibility of implementing water and sanitation as a human right, especially when it comes to installing infrastructure, has been placed on the local governments. In developing regions, many local governments lack financial resources, technical skills, and structure.

In 1998, Durban was the first city in South Africa to implement the policy of Free Basic Water. The eThekwini Municipality has made both strides and been met with setbacks trying to enforce the free basic level of water and sanitation services. The municipality's Department of Water Sanitation has instituted guidelines such as the Water Supply and Sanitation Provision to Communities in order to adhere to national policy. The guidelines consider equity in providing acceptable infrastructure and providing services at an affordable rate (which includes free basic water. In Durban, members of the eThekwini Water and Sanitation District and Umgeni Water (a state water entity) are struggling with meeting the demand caused by the influx of people moving to the municipality, particularly those into informal settlements (Schneider, 2016). Most of these people are moving closer to the cities such as Durban and Pietermaritzburg to find economic opportunity, a trend seen throughout Africa and even on a global scale. The city of Durban is dealing with a shrinking population who form the tax base and a growing population of people in need of public infrastructure and social safety nets.

The local government has a legal obligation to make sure all people, including those that form informal settlements, have equal access to basic water and sanitation. Sewage connections are generally not available to the informal settlements; therefore, dry toilets, pit latrines, and or community abolition blocks are most commonly implemented in these areas (City of Durban, n.d.; Schneider, 2016). Even though they have made large strides, the municipality is finding it impossible to keep up with the new people moving to the area (see Figure 4.16 for depiction of growth of an informal settlement).

There is also a strong amount of civil unrest between the people who know they are entitled to basic water and sanitation services. It creates resentment toward the people working for the municipality. Technicians from the municipality are placed in unsafe working conditions fueled by the political unrest which makes their job increasingly more difficult to carry out. The municipality is also trying to remedy extremely polluted rivers, upgrade and resize broken down infrastructure that has not been well maintained, and plan for climate change which has already caused prolonged severe droughts leading to major water supply shortages.

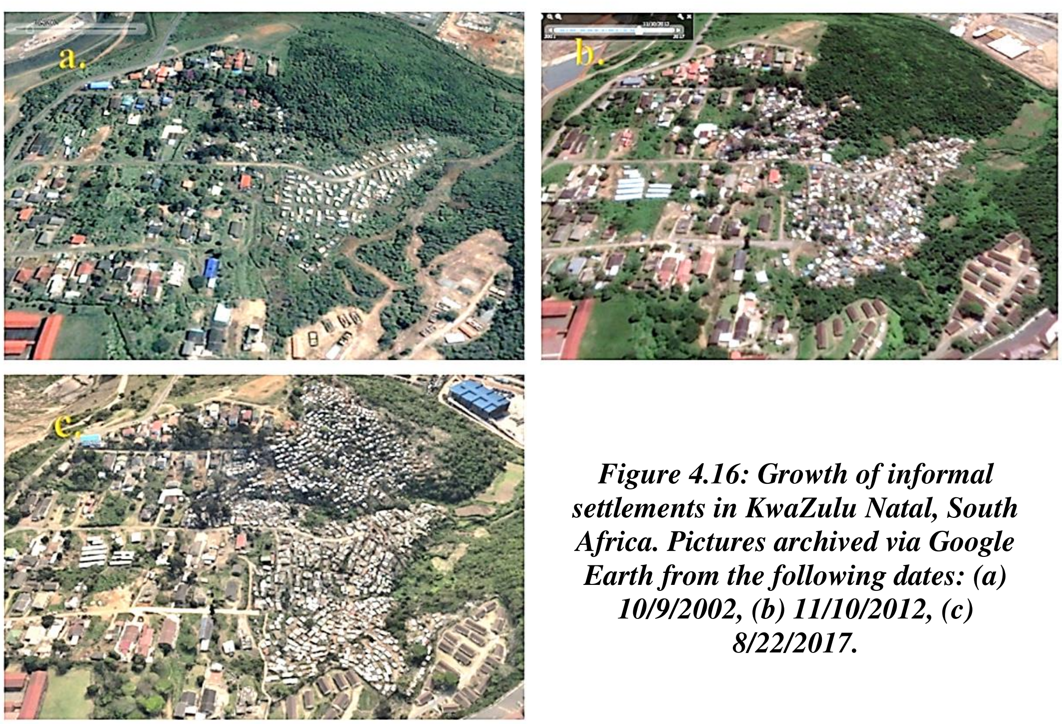


Figure 4.16: Growth of informal settlements in KwaZulu Natal, South Africa. Pictures archived via Google Earth from the following dates: (a) 10/9/2002, (b) 11/10/2012, (c) 8/22/2017.

According to Interviewee 4 (2017), the municipality is at its tipping point. The FBW Policy does not take into account how much growth a municipality be expected to support. There has also been an observance that people who do not pay for the services have less incentive to conserve it or take care of it. The people of the Municipality demand they receive access to water services and electricity; however, the Municipality does not have the budget to bring this to fruition immediately. The Municipality is stuck in a vicious cycle characterized by (1) unhappy customers who create their own connections or rebel by damaging infrastructure which both negatively impact the infrastructure in place, (2) then the Municipality has to fix those infrastructure damages instead of regularly planned maintenance or projects, (3) and then more unhappy customers because they are not getting served. (Interviewee 4, 2017).

4.7 Conclusion

The eThekwini Municipality is working with a wide spectrum of technologies. The municipality is working toward understanding the whole watershed as a system which means better collaboration between eThekwini's stakeholders are necessary for the further progression of wastewater evolution (Interviewee 3, 2018). Many of the issues of the municipality are not even tied to the lack of novel technologies available but rather the issue of implementation, whether they be cultural, political, or financial. The Municipality of eThekwini has promoted that it wants to be the most caring and livable city, but the municipality does not say for how many people (Interviewee 4, 2018). The municipality, although on the frontier for their efforts to provide free, basic services to the poor, are struggling immensely with the task. Distrust in the government by many South Africans, not to say it is not warranted, has made it exceptionally difficult for government authorities to work in certain areas or make changes in wastewater treatment practices. Durban is open to collaboration and networking with entities whether they be private organizations, development organizations, or other countries. eThekwini's openness to innovation and new, progressive ideas means that an optimistic future for water quality is still possible for the region; however, it will mostly take education and poverty alleviation initiatives for the public as well as relationship and trust building between the people of eThekwini and its government.

CHAPTER 5. LINKING PUBLIC PERCEPTION WITH THE FIELD OF WASTEWATER MANAGEMENT

5.1 Introduction

Wastewater is most often spoken of in the context of a problem that needs to be dealt with (Drechsel *et al*, 2015). Traditionally, wastewater management strategies have been motivated primarily by considerations of efficiency, safety, and cost-effectiveness (Saad, 2017). Culture is typically overlooked as a driver of evolution in the field of wastewater. Wastewater is a resource with both social and economic value. Saad *et al* (2017) states that improvement in wastewater management practices can be realized through "adopting holistic methodology that acknowledges sociological factors" in order to "shift the focus from perceiving wastewater as a nuisance that needs disposal, toward a resource not to be wasted, which can contribute to food security, human and environmental health, access to energy as well as water security." Much research has been undertaken to understand the link between social acceptance and the sustainable adoption of alternative water management practices (Saad *et al*, 2017; Wester *et al*, 2015; Ormerod & Scott 2012; Hurlimann & Dolnicar, 2010; Hurlimann *et al*, 2009; Wilson & Pfaff, 2008).

Cultural context is highly variable both spatially and temporally. Applying cultural context in order to achieve public buy-in when problem solving begets solutions that are unique to fitting the needs of a society. Social acceptance can serve as an indicator for predicting the sustainable success or potential failure of implementing a new technology or management approach in a given community (Saad *et al*, 2017, Hurlimann & Dolnicar, 2010; Hurlimann *et al*, 2009; Menegaki *et al*, 2009). When Toowoomba, a city in Australia, was facing a severe drought, a referendum failed to pass in 2006 that would treat and reuse 25% of the city's wastewater. The "yuck" factor created enough public opposition for the city to ultimately decide upon bringing in piped water from the Wivenhoe Dam in Brisbane, costing ratepayers almost $100 million more than the reuse project would have cost (Saad *et al*, 2017). In this classic example, the implementation of cutting-edge water reuse technology, often characterized as being on the frontline of achieving water security, was rejected by the community even when they were in the face of dire water scarcity. This case study demonstrates that the attitude of the public can formulate irrespective of scientific data that addresses both public health and efficiency concerns for advanced technologies (Saad *et al*, 2017).

Cultural values are typically intangible, therefore, difficult to quantify when analyzing a problem. Surveys are a popular tool utilized to collect social perception data (Friedler *et al* 2006). The contents in this chapter reflect the type of results a survey can produce for water managers in order for them to pursue combined socio-technological planning and design strategies. The insights gained from conducting a similar type of survey can help water managers make decisions in their respective communities. Not only do surveys provide water managers with helpful information, but they also simultaneously achieve the goal public involvement and community participation, crucial to the endeavor of achieving sustainable development.

5.2 Objectives of the Study

The objective of this chapter is:

- to illustrate how social perception data can be utilized to affect management decisions in the field of water resources,
- to demonstrate the usefulness of surveys when used in conjunction with examining engineering problems in order to quantify the culture aspect,
- and to shed light upon underlying tradeoffs and limitations when conducting this survey study.

The survey described in this chapter also had the added benefit of raising awareness on the topic of wastewater treatment.

5.3 Methods

The “Wastewater Treatment Survey” consists of 16 questions. The questions are categorized in Table 5.1 (a copy of the survey can be found in Appendix A). The survey was designed to take an estimated five to ten minutes to complete with the consideration that a diverse set of participants with varying knowledge in the topic area would be responding to the survey. To test the suitability of the survey, it was made active from October 31st to January 31st. The survey was completed on two platforms: SurveyMonkey and paper copies. Paper surveys were left in classrooms, student lounges, and computer labs at Colorado State University. The link to the online version of the survey was shared via social media, emails, and paper

Table 5.1: The Wastewater Survey designed by Turner, 2017.

Level	#	Question
Level 1 – Consent (fulfilling IRB requirement)	1	Do you agree to the above terms? By clicking Yes, you consent that you are willing to answer the questions in this survey.
Level 2 - Demographics of participants	2	What is your age?
	3	Indicate your gender identity: (e.g. female, male, transgender female, transgender male, etc.)
	4	In what city/county, state, country do you live? If you do not wish to disclose this information, leave the comment box blank. (City/County, State, Country)
	5	What is the highest level of school you have completed or the highest degree you have received?
	6	Which of the following best describes the field in which you received your highest educational qualification?
Level 3 - Participants prior knowledge/ biases	7	How confident are you in your ability to explain what happens to the wastewater once you flush your toilet? (e.g. does it go to a septic tank or wastewater treatment plant, are all contaminants removed at the wastewater treatment plant, what water body does the treated effluent/water discharge into, are there downstream users of the water, etc.)
	8	How concerned are you about water pollution?
	9	Why is wastewater treatment important to you? Rank the following choices on a scale from 1 (most important) to 5 (least important).
Level 4 - Perception toward alternatives.	10	Around the world, outfalls (a drain or sewer that empties into a water body) release varying levels of treated and/or untreated sewage into water bodies (e.g. deep-sea outfalls). Many of these outfalls utilize "dilution as the solution to pollution," the idea that nature has the capability to assimilate polluted water to a degree (e.g. natural wetland's ability to treat stormwater). In your opinion, does "dilution as the solution to pollution" seem like an adequate approach to wastewater treatment?
	12	The overarching goal of wastewater treatment is to remove contaminants from water so it may be returned back to the natural environment/water cycle with minimal impairment to any water body. If your utility/provider wanted to update the wastewater treatment infrastructure for increased TREATMENT efficiency, but it would result in an increase to your wastewater bill per month to invest in the project, would you be willing to pay more for the services? Background Information: In Fort Collins, the average 2016 single family home paid about $36.12 for an estimated 4,800 gallons per month to be treated.
	13	If your utility wanted to update the wastewater treatment infrastructure for increased ENERGY efficiency, but it would result in an increase to your wastewater bill per month to invest in the project, would you be willing to pay more for the services?
	14	The EPA defines greywater as "reusable wastewater from residential, commercial and industrial bathroom sinks, bath tub shower drains, and clothes washing equipment drains." Note that wastewater from toilets is not included in this definition. The purpose of storing greywater onsite is to reuse it for a non-potable (not drinking water) application. In most cases, it is typically used for landscape irrigation. How safe do you feel using greywater for non-potable uses? (e.g. using greywater in toilets, gardening, etc.)
	15	The National Water Research institute defines direct potable reuse as the planned introduction of recycled water (reusing treated wastewater) either directly into a public water system or into a raw water supply upstream of a water treatment plant. Note that potable means safe to drink. Would you be willing to drink direct potable reuse water?
Level 5 - Considering opinion versus action	11	Have you ever considered a political candidate's position on water resources management as a reason to vote for or against a candidate? (e.g. voting for or against a water transfer plan or more stringent water quality standards for a body of water)
	16	How likely are you to get involved with the watershed management/planning? Getting involved can range from attending community meetings that discuss planning, to considering watershed management when voting for a candidate, to working on local watershed projects (e.g. restoration projects), etc.

surveys. The survey was made available to people interested in distributing them in their own circles. Due to the non-random, convenience type recruitment for this survey with an added snowballing effect, the results test the suitability of the survey, it was made active from October 31st to January 31st. The exploratory survey has very limited generalizability. Time and resource constraints did not allow for a more rigorous sampling technique to be utilized. Simple statistics were used in analyzing the survey results in the following section in order to illustrate the types of insights that can be gained through similar survey formats. Statistics include calculating the mean, median, mode, quartiles, and utilizing two tailed distribution t-tests. Two different t-tests were utilized to understand correlations in the data: heteroscedastic and paired.

5.4 Results

A total of 742 people responded to the survey. Immediately, 7 surveys were excluded due to withholding consent. The remaining 735 surveys are composed of 655 participants from the United States, 40 participants from 16 other countries, and 40 participants who did not disclose their location (see Figure 5.1). Out of the 40 participants from other countries, 10 participants were U.S. military members stationed abroad. The U.S. participants lived in forty-four different states plus the District of Columbia. Of the 655 participants, 204 lived in Colorado and 133 lived in Virginia. From the 204 Colorado participants, 162 lived in Larimer County. See Appendix A for further breakdown by U.S. states and countries. The analysis in the following sections will be broken down by where participants are from.

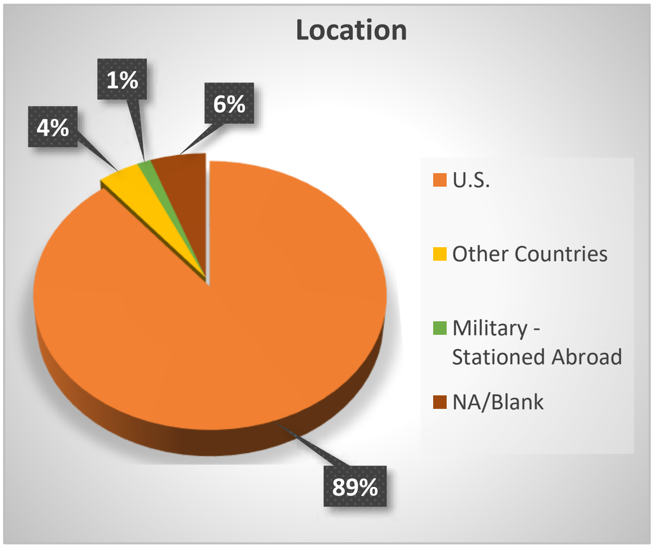


Figure 5.1: Location of participants.

5.4.1 U.S. Participants

Females are disproportionately represented in this survey, making up 68.7% of the responses from the U.S. participants as illustrated in Figure 5.2. Men only made up 30.08% of responses. The 2010 U.S. Census reports that males represent 49.1% of the U.S. population and females represent 50.9% (Howden & Meyer, 2011). In the survey, seven of the U.S. participants (~1%) identified with other gender identities while only one participant did not disclose their gender identity. Data was also collected from a large distribution of age groups (see Figure 5.3) and a variety of backgrounds (see Figure 5.4 and Figure 5.5) in

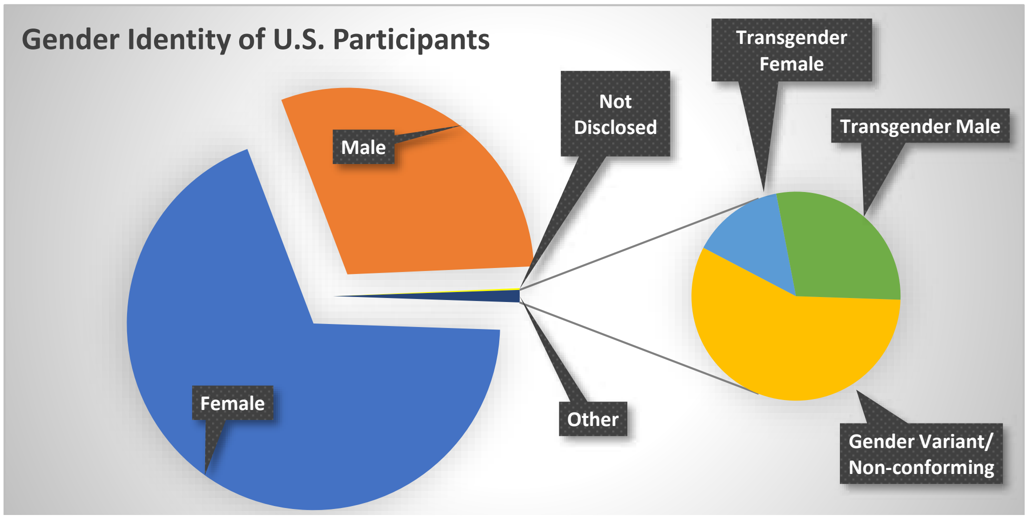


Figure 5.2: U.S. Participants gender identity.

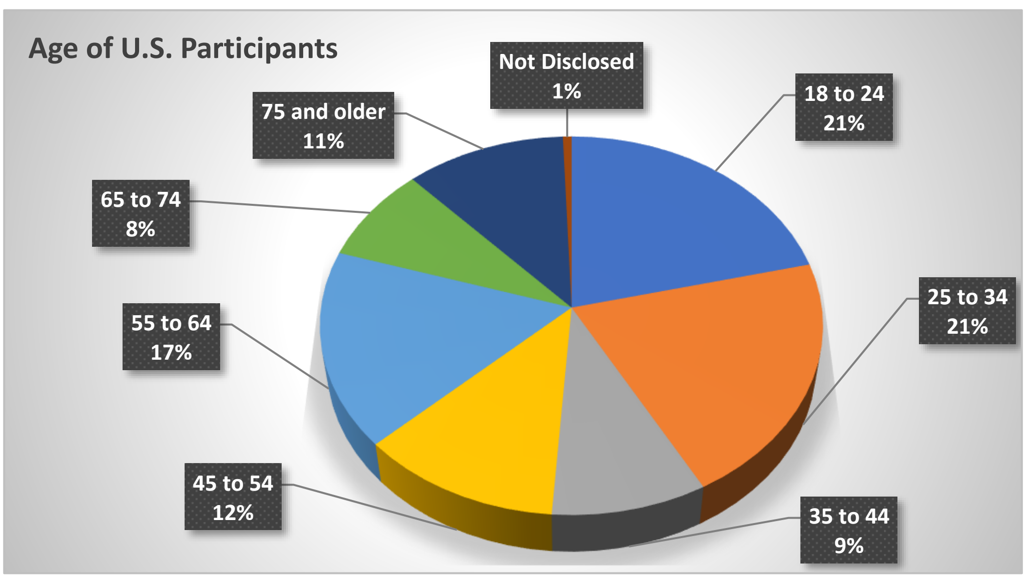


Figure 5.3: Age group breakdown of U.S. participants.

the survey as well. As depicted in Table 5.2, the distribution of age groups is not proportionate to the representation observed from the 2010 U.S. Census (Howden & Meyer, 2011). About 79% of the survey participants claimed to have achieved a higher educational degree or certification degree after high school, around 17% reported that they are in the process of pursing a higher educational degree. For a full breakdown of participants demographics, refer to Appendix A.

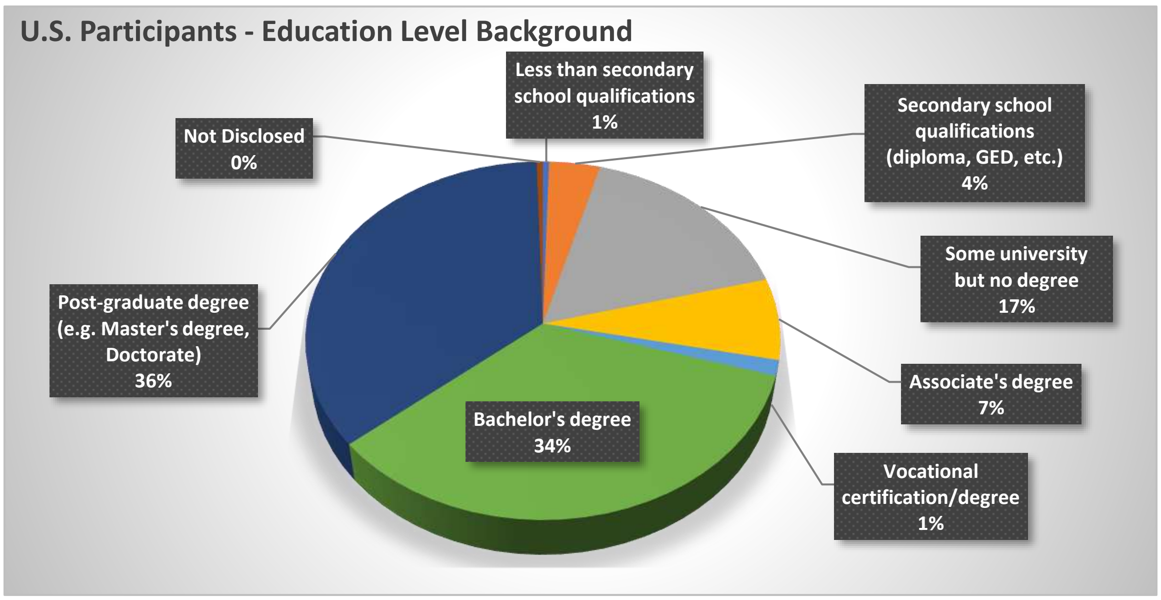


Figure 5.4: U.S. participants educational background.

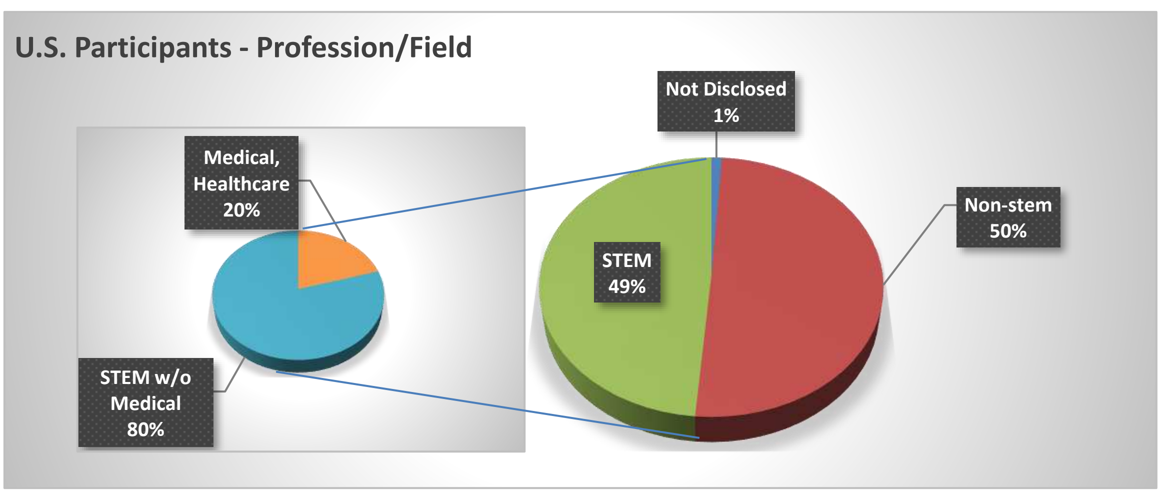


Figure 5.5: U.S. participants profession or field of education.

Table 5.2: Comparing 2010 Census age data with survey participants age group distribution. Census data adapted from Howden & Meyer (2011).

Age Group	US 2010 CENSUS (%)	Survey (%)
18 to 24	13.1%	21.2%
25 to 34	35.0%	29.9%
35 to 44		
45 to 54	34.7%	28.7%
55 to 64		
65 to 74	17.2%	19.5%
75 or older		
Not Disclosed		0.6%

The third level of questions seeks to uncover opinions and knowledge on the topic of wastewater on the topic of wastewater. When asked how confident the participant felt in their ability to explain what happens to the wastewater once a toilet was flushed, the participant could choose from the following choices (with given numerical scale): not at all likely (1), not so likely (2), somewhat likely (3), very likely (4), and extremely likely (5). Based on the responses of the U.S. participants, the average was 3.03. When the responses were divided by participants with STEM versus non-STEM backgrounds, the participants with STEM backgrounds appear more confident in their ability to explain what happens with wastewater. When STEM is further divided into the healthcare profession versus all other STEM fields, the pariticpants in the medical/healthcare field felt far less confident in their ability to explain the fate of the wastewater once it is flushed down a toilet. Figure 5.6 depicts these results.

Figure 5.6: Results for Survey Question 7 considering the participants ability to explain what happens to captured domestic wastewater.

Question 8 asked the participant to consider how concerned they are about water pollution. The participant could pick a response ranging from extremely concerned (5) to not at all concerned (1). Figure 5.7 depicts the results between participants with STEM and non-STEM backgrounds and Figure 5.8 represents the concern level at different age levels. Overall, the participants are generally moderately to very concerned about water pollution. The mean steadily increased from 3.71 to 4.35 with an increase in age until the last age group (75+) dropped back down to 3.92. The most concerned group of participants were between the ages 65-74 for both STEM and non-STEM participants. Non-STEM participants from age 25-34 had the lowest reported concern for water pollution. No correlation was determined between confidence in topic area and concern for water pollution.

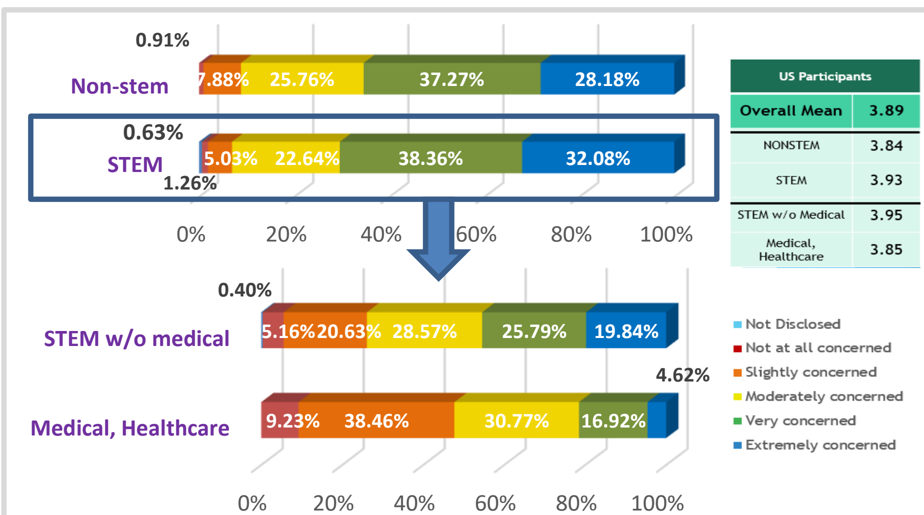


Figure 5.7: Results for Survey Question 8 considering the participants concern for water pollution.

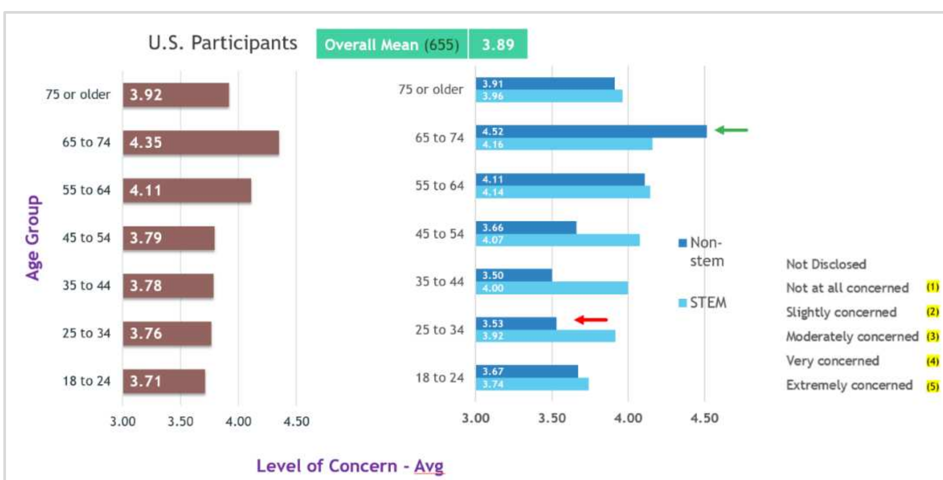


Figure 5.8: Results for Survey Question 8 considering the participants concern for water pollution in different age groups.

The survey did not directly ask for a participant to disclose their political party affiliation; however, the following result divides responses based on whether the state in which the participant lived was designated as blue or red in the 2016 U.S. Presidential Election (see Figure 5.9 for percentage of participants located in either a blue or red designated state). Figure 5.10 illustrates that the STEM majors show similar results whether participants hail from a blue or red state. On the other hand, participants with a non-STEM background from a red state showed less concern for water pollution than participants with a non-STEM background from a blue state.

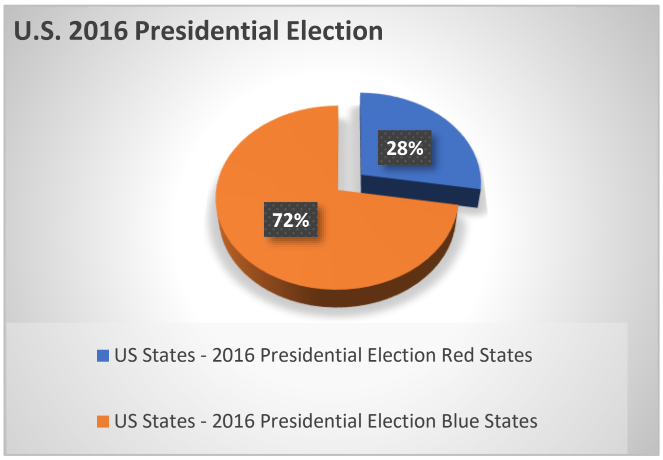


Figure 5.9: Percentage of participants located in either a blue or red designated state from the 2016 U.S. Presidential Election.

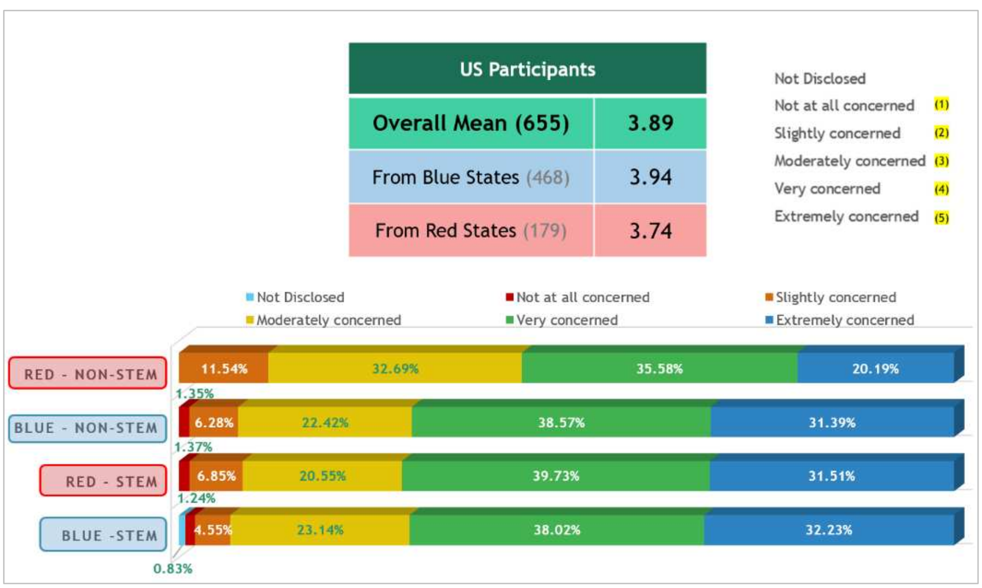


Figure 5.10: Results for Question 8 on concern for water pollution considering party affiliations of states from the 2016 U.S. Presidential Election.

Question 9 asked the participant why wastewater treatment was important to them. The participant was then given the option to rank the following choices 1 (most important) to 5 (least important): environment, recreation, smell, health, and ambience. As depicted in Figure 5.11, the U.S. participants ranked health (mean rank: 1.78) and the environment (mean rank: 2.06) the highest and ranked recreation (mean rank: 3.35), smell (mean rank: 3.70), and ambience (mean rank: 3.85) the lowest.

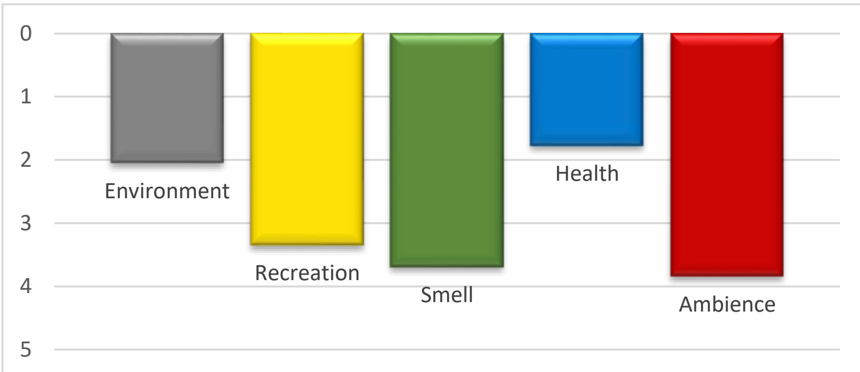


Figure 5.11: Results for Question 10 on why wastewater treatment is important (1-most important, 5 least important) to the participant of the survey.

The interpretation of the results for the Level 4 Questions convey the participants' perceptions on wastewater treatment technologies. Question 10 investigated how the participant felt about "dilution as the solution to pollution" as an adequate approach to wastewater treatment. The question eluded to the use of outfalls to discharge wastewater into waterbodies such as the ocean or wetlands. From the response, we can see most U.S. participants (over 75%) feel that using dilution as wastewater treatment approach is not so sufficient to not at all sufficient with a mean rating of 1.89 among the U.S. respondents. This feeling is mutually shared between people with both STEM and non-STEM backgrounds; however, there was a difference between participants with a STEM background excluding the medical/healthcare profession versus the participants with a medical/healthcare profession background. Figure 5.12 depicts these results.

Questions 12 and 13 considered perception of wastewater treatment approaches by asking the participant how much they are willing to pay for upgrades in either treatment or energy efficiency. U.S. participants showed interest in supporting both increased treatment efficiency and energy efficiency in their respective areas of residence. When the two questions are compared, illustrated in Figure 5.13, participants would rather pay for an increase in treatment efficiency versus an increase in energy efficiency.

Questions 14 and 15 asks the participants to comment on two specific water management approaches: greywater reuse and direct potable reuse. Question 14 pertains to how safe the participant feels using greywater for non-potable uses with answer choices ranging from not safe at all (1) to extremely safe

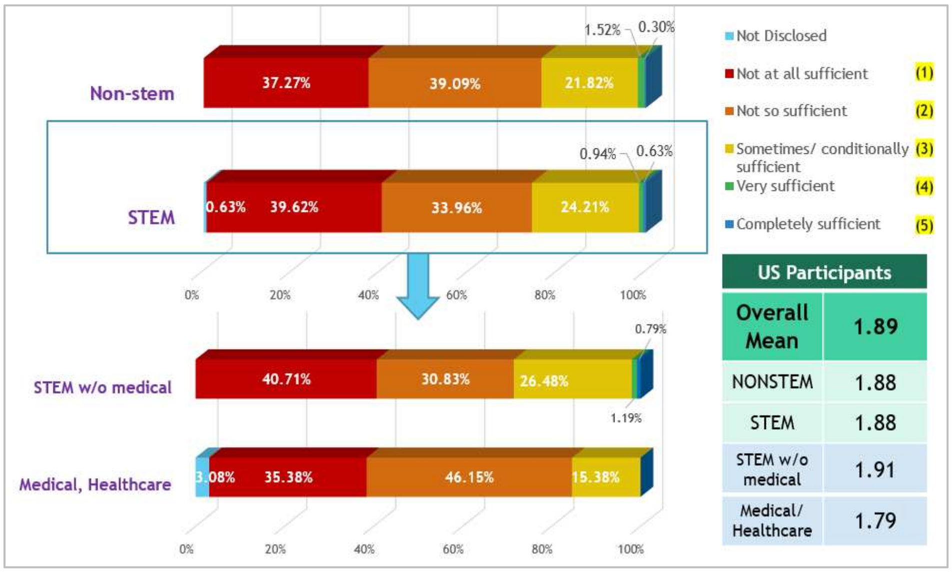


Figure 5.12: Results for Question 10 on perception of "dilution as the solution for pollution."

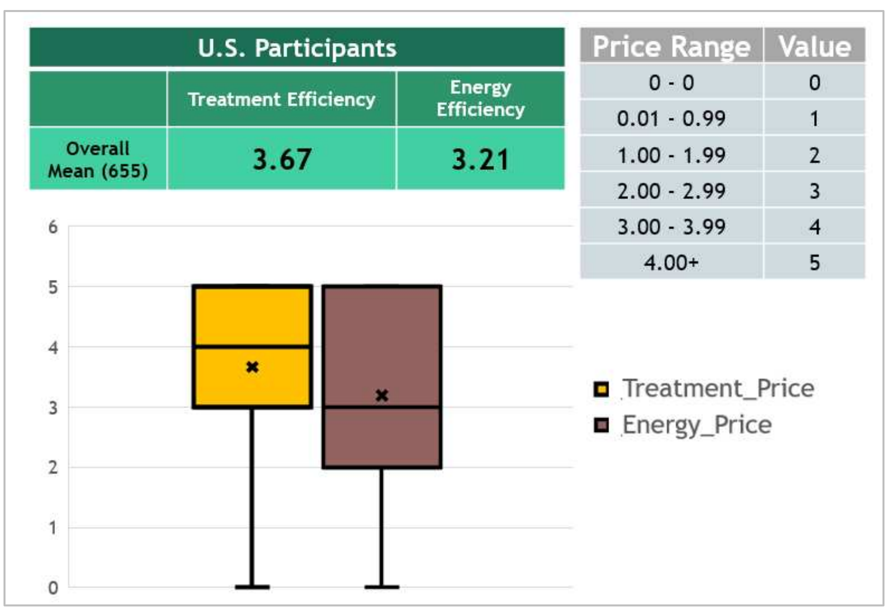


Figure 5.13: Results for Questions 12 and 13 considering the willingness of the participant to pay for treatment or efficiency upgrades to the wastewater treatment approach in their area.

(5). The mean score of 3.42 demonstrated that the participants in this survey felt somewhat to very safe utilizing greywater reuse practices. The mean remained constant among the different age groups as seen in Figure 5.14. Question 15 asks the participant how willing they would be to drink direct potable reuse water with answer choices ranging from not at all willing (1) to extremely willing (5). The mean score of 2.96 demonstrates that most of the participants felt not so safe to somewhat safe drinking direct potable reuse water. Unlike the previous question, the mean score did vary among age groups demonstrating that the participants from the younger generations were more willing to drink direct potable reuse water than the participants from older generations (see Figure 5.15). When comparing participants from arid Colorado and humid Virginia, Colorado participants were more willing (3.21) than Virginia participants (2.83) to drink direct potable reuse water.

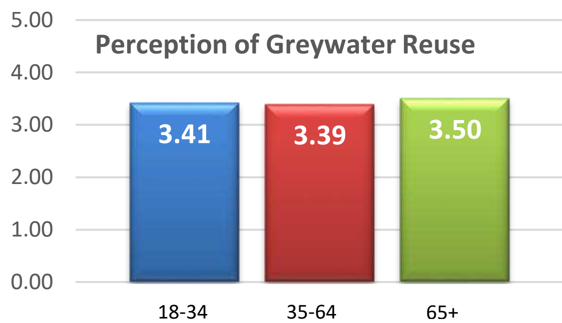


Figure 5.14: Breaking down the results by age group for Question 14.

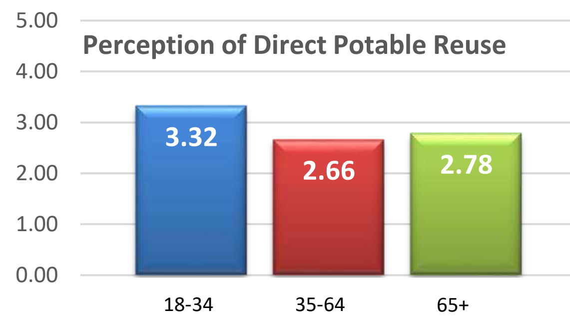


Figure 5.15: Breaking down the results by age group for Question 15.

When Question 14 on greywater reuse and Question 15 on direct potable reuse water are compared against each other, illustrated in Figure 5.16, participants felt safer utilizing greywater reuse than drinking direct potable reuse water. Furthermore, Question 8, referring to the participants' confidence in understanding basics principles of the wastewater treatment process, can be taken into consideration with how it relates to the participants responses to Questions 14 and 15. Those that responded with higher confidence levels felt both safer utilizing greywater use practices and more willing to drink direct potable reuse water (see Figure 5.17).

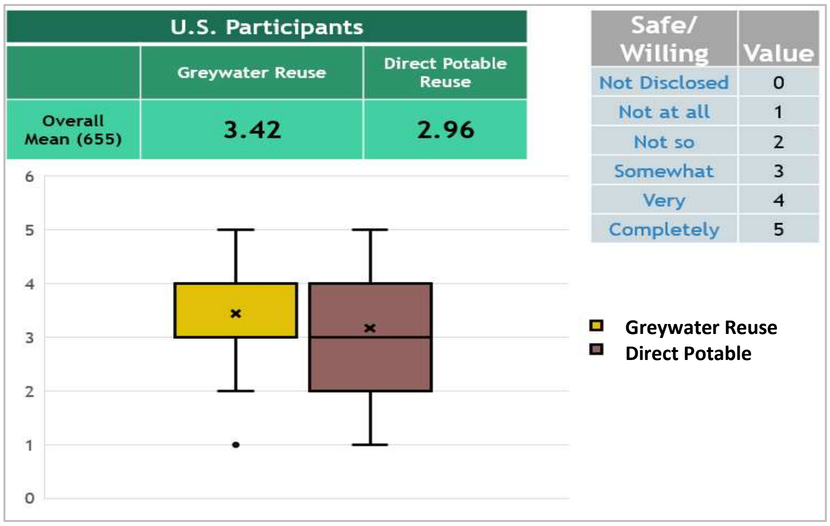


Figure 5.16: Results for Questions 14 and 15 considering how safe the participant feels utilizing greywater reuse versus how willing they are to drink direct potable reuse water.

Safe/Willingness		Confidence Level	
Response	Score	Response	Score
Not at all	1	Not at all confident	1
Not so	2	Not so confident	1
Somewhat	3	Somewhat confident	2
Very	4	Very confident	2
Extemely	5	Extremely confident	2

Response to "Confidence" Question	Mean for Response to Greywater Reuse "Safe"	Mean for Response to Direct Potable Reuse "Willing to Drink"
Confidence Level 1 (Not at all, Slightly)	3.15	2.77
Confidence Level 2 (Somewhat, Very, Extremely)	3.56	3.06

Figure 5.17: Comparing perceptions of alternatives (Questions 14 and 15) with different levels of confidence participants disclosed about understanding the wastewater treatment process (Question 8).

Question 11 and Question 16 make-up the fifth layer of questions meant to see if the participants are going to act on behalf of their opinions that have thus been presented. Question 11 asked the participant if they have ever considered a political candidate's position on water resources management as a reason to vote for or against a candidate (see Figure 5.18 for results). Around 42% of respondents claimed they do consider a politician's stance on water resources management. The majority of respondents (53%) said they do not vote on candidates based on a politician's stance on water resources management. Of the respondents that said no, only 2.3% of respondents responded that they do not consider a politician's stance on water management based on their own indifference to water management as an issue. Approximately 21% of respondents said no based on the fact that other issues exist of higher priority to the respondent. The last category of respondents who answered no did so because they felt as if they were not aware of water management platforms.

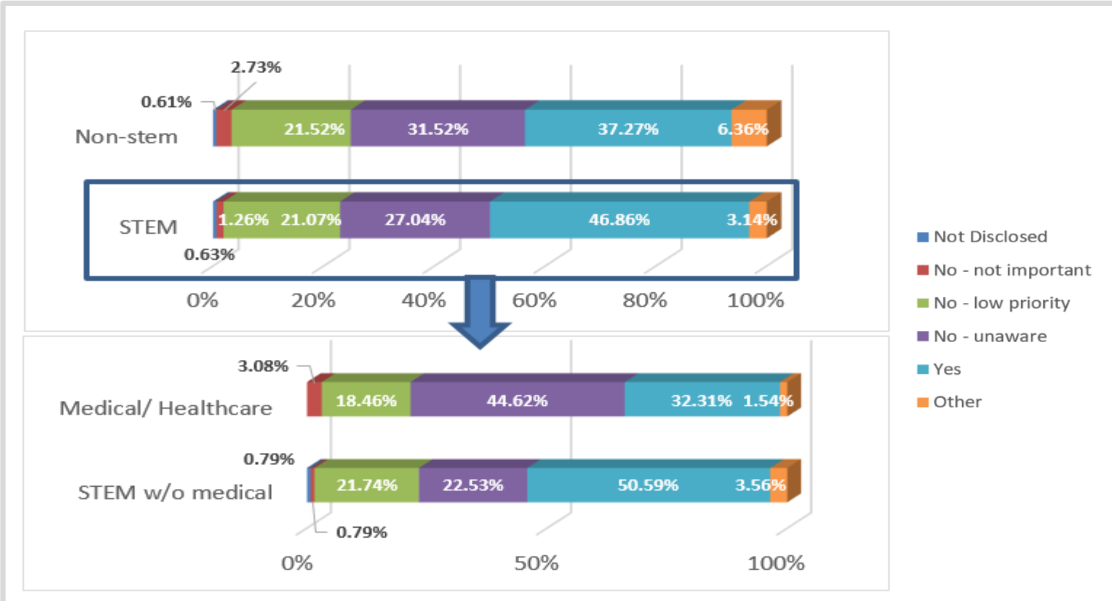


Figure 5.18: Results to Question 11 on whether a participant has ever considered a political candidate's position on water resources management as a reason to vote for or against a candidate

Question 16 asked the participant if they are likely to get involved with the watershed management/planning (see Figure 5.19 for results). In the question statement, getting involved was defined as a wide range of activities such as attending community meetings that discuss planning, considering watershed management when voting for a candidate, or working on local watershed projects (e.g. restoration projects).The participants' responses were as follows: 10% of participants claimed they are not at all likely to get involved, 30% of respondents claimed they were not so likely to get involved, 35% claimed they were somewhat likely to get involved, 15% claimed they were very likely to get involved, and 9% claimed they were already involved. Figure 6.19 depicts the distribution of responses based on age groups. The age group 18-24 is most likely to get involved whereas the oldest age group is least likely to get involved in water management. When concern level for pollution (Question 8) and willingness to get involved with water resources management (Question 16) is compared, it can be observed that people who showed concern for water pollution stated they would be more likely to get involved in water management (see Figure 5.20).

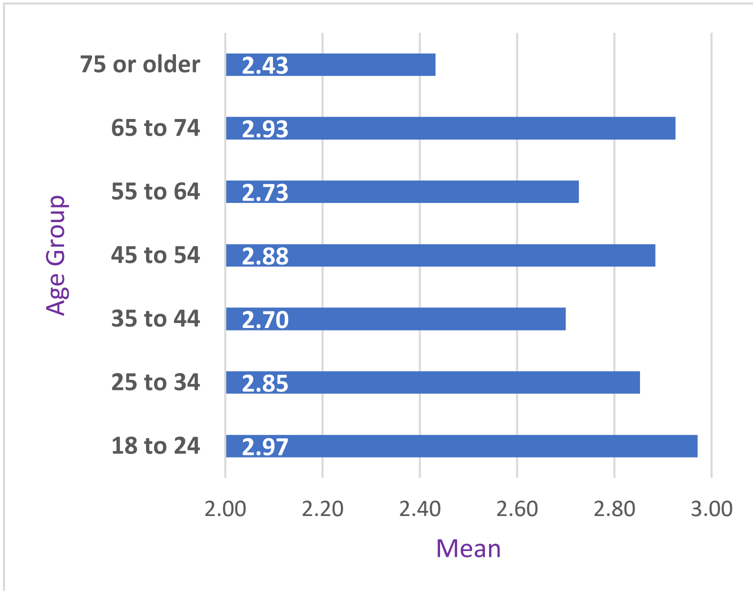


Figure 5.19: Comparing age groups and their willingness to get involved with water management.

Involvement		Concern	
Response	Score	Response	Score
Not at all likely	1	Not at all concerned	1
Not so likely	2	Slightly	1
Somewhat likely	3	Moderately	2
Very likely	4	Very concerned	2
Extemely likely	5	Extremely Concerned	2

Response to “Concern for Water Pollution” Question	Mean for Response to “Likeliness of Involvement”
Concern Level 1 (Not at all, Slightly)	1.86
Concern Level 2 (Moderately, Very, Extremely)	2.91

Figure 5.20: Comparing getting involved (Question 16) with different levels of concern for water pollution (Question 7).

5.5 Lessons Learned

Within creating thus survey, lessons were learned concerning (1) choosing the content of the survey, (2) conducting the survey in a meaningful and practical way, and (3) analyzing the data.

5.5.1 Survey Content

The objective of the survey should be clear and embedded within each question of the survey. The survey should be simple as possible. Although less information is collected with a shorter survey, more people are inclined to take the survey if it is brief. Demographic information helps to gather information on the respondents which can be helpful with the analysis of the survey. If the purpose of the survey is to guide water managers in water resources management, a survey should be conducted at a local level with questions tailored to a community. Specific questions specially made for a community that can provide useful information to the water managers may pertain to possible contaminations sources of concern (e.g. agriculture, industry) and treatment processes and management strategies being considered in the area. The survey in this particular thesis was broad, or in other terms, not designed for a specific area; therefore, the results of this survey may not be very applicable for water managers trying to operate in their specific regions. However, a broad survey can show if there are any spatial societal trends. For example, pertaining to the results for U.S. participants presented in this thesis, participants from dry, arid regions of the country could be compared to participants from wet, humid regions of the country or states with certain political inclinations could be compared with states with different political inclinations.

Choosing certain wording for questions was just as important as picking the topic of each question. Due to the technical nature of the topic of wastewater treatment technologies, it is important that the survey is accessible and comprehensible to a lay audience. Different regions will have varying levels of educational background or knowledge on water resources management. Once again, the best way to implement a survey is to make it specific to the audience it is being presented to. There may be instance where certain names of technologies or phrases have been given bad connation or publicity, such as the concept of reuse with drinking toilet water. An objective of the survey should be to be informative by illuminating upon what is inside the black box of wastewater treatment technologies. Unbiased information should be presented in the questions and answer choices in order to expect results that are representative of the opinions of the respondents. In summation, the questions should avoid ambiguity and should not lead to the respondent to answer in a particular way.

5.5.2 Conducting a Survey as a Research Strategy

First and foremost, the research must be done in an ethical matter. Due to surveys utilizing human subjects for research, the project needs to undergo Institutional Review Board (IRB) Committee Review for initial review and the investigator on the project must complete training through the CITI Program before interacting with participants. Due to the content in the survey presented in this thesis, the IRB Committee deemed that the project was exempt (category 2). If the project had not been exempt, then the full review process would have taken more time. Researchers conducting surveys should make sure to keep in mind the time and effort that is required to initiate survey research.

Before creating the survey, the investigator should first see if previous surveys have been completed in the same field. Once the survey has been created, focusing on strategies considered in the previous section, the survey should be piloted before the distribution to a larger audience. This step is crucial for fine tuning the survey such as if participants will understand the instructions and meaning of questions. In the instance of piloting the survey in this thesis, feedback was obtained about the appropriateness of questions and answer choices given within the survey.

In the words of Kelley *et al* (2003), "it is easy to conduct a survey of poor quality rather than one of high quality and real value." Good practices and conduct are necessary for a survey to present credible and useful results. The largest pitfall of conducting the full-scale survey in this thesis is that a specific, proven sampling methodology was not utilized; therefore, the results presented cannot be generalized for a specific subset of the population and a response/return rate could not be determined. The validity of survey results is generally judged by the rigorous sampling techniques utilized. Random sampling is most appropriate for surveys because then results can be generalized for a chosen population and statistical analysis will be relevant (Kelley *et al*, 2003). The exploratory Wastewater Treatment Survey followed more of a non-random selection of participants by means of convenience and snowballing. The survey was accessible to anyone with either the link to the web-based version of the survey or a paper copy of the survey. Distribution of the survey did lead to a large number of respondents in a short amount of time; however, the results are not reliable due to the sampling error being unknown because a sample was not predetermined. For the purposes of this thesis, the survey was used to demonstrate how surveys could be utilized within the field of wastewater management. Traditional surveys used to gather information have used mail methods which make quantifying response rate straightforward; however, response rate is usually very low. This survey was primarily web-based. In the way this survey was conducted, there was no quantification of how many potential respondents came in contact with the survey. Web based surveys, even when proper sampling methodologies are utilized, can potentially can present biases within sampling. In future surveys, when considering sample size, it should be based on the size of the population you are attempting to gather information about and the desired level of confidence for results. It will also be based on available resources such as time.

5.5.3 Analyzing Survey Data

Results from survey research that produces data based on real-world observations should be analyzed against the initial objectives of the survey. The researcher should prepare to spend a substantial amount of time on data analysis (Kelley *et al*, 2003). Proving statistical significance is an important aspect of analyzing survey data results.

Using a numerical/rating scale for qualitive answer choices when applicable makes analyzing the data easier. Presenting the information in graphs and tables helps visualize the results from the survey, making the information more engaging. For the questions with a rating scale, the stacked bar chart was the simplest option for producing a visual of the responses. Opened ended comments, such as the answer choice “Other, please specify” are difficult to categorize or present. Fully open-ended questions should be avoided if collecting large amounts of data.

From the results of the survey presented in this thesis, it became apparent that a survey tool can be extremely useful for water managers. The type of information that can be gathered will be pertinent to their ongoing operations, especially if they plan to evolve the services they provide.

5.6 Conclusion

Through the experience of conducting the survey, the impression was maintained that "the general public has less specific knowledge than experts and sometimes an inaccurate understanding of technical aspects of water quality and water management" (Gartin *et al*., 2010; Boyer *et al*, 2012). After completing the survey, some participants disclosed that the topic was something they knew very little about. A survey not only collected data of societal opinion, but it conversely altered what people knew about wastewater treatment. The key findings from analysis of the survey included:

1. that significant differences existed between participants of
    a. different generations (age groups),
    b. STEM versus non-STEM backgrounds,
    c. medical and healthcare field versus the other STEM technical fields, and
    d. different locations such as dry regions versus wet regions;
2. that respondents in this survey are more willing to pay for treatment efficiency over energy efficiency;
3. that respondents in this survey were more comfortable with the idea of greywater reuse versus willingness to drink direct potable reuse water;
4. that no correlation as found between the participants' confidence level in topic area of wastewater treatment and the respondents' concern for water pollution;
5. that the respondents that indicated concern about water pollution also indicated they were more likely to get involved in water resources management activities;
6. and if the respondents show greater confidence in the topic area of wastewater treatment, they also indicated they were more comfortable with the wastewater treatment alternatives greywater reuse and direct potable reuse.

Although some of these findings seem inherently correct, they have not been proven by quantification in the context of wastewater treatment. This exploratory survey indicates how a survey can be designed in order to bring quantitative results for qualitative cultural values incapsulated by societal opinion. The results of a similar survey performed with more rigorous sampling techniques could provide very useful data for a water manager.

As described in the previous section, many lessons were learned on the proper methodology of conducting a survey. The tradeoff for creating and conducting a high-quality survey is the amount of time, planning, and possibly financial resources necessary to support it. For water managers moving forward, they may want to consider consulting with groups who have experience with surveys and knowledge of the community in which the survey will be utilized.

CHAPTER 6. CONCLUSIONS

6.1 Summary of Research

The thesis began with a literature review in Chapter 2 that characterized wastewater and brought to light vital components to the water quality nexus. Then, in Chapter 3, the evolution of wastewater treatment technologies was represented in 4 main categories: dilution, conventional, alternative, and emerging. A discussion followed based on what made certain technologies "appropriate" in implementation. Chapter 4 considered the important role of institutional arrangements in enforcing water quality management objectives in South Africa. The structure of multilevel governance was described in terms of roles and performance. Different regulation strategies were also portrayed. Chapter 4 presented KwaZulu Natal, South Africa as a case study, considering their current treatment technologies and management strategies for wastewater treatment. Finally, Chapter 5 took a closer look at the role of societal opinion plays in the management of wastewater treatment.

6.2 Major Conclusions

The following represent major themes presented in this thesis: (1) a systems approach must be taken in order to intervene in the water quality nexus, (2) the field of wastewater treatment is evolving, however differently depending on the region, (3) strong institutional arrangements are important to reinforce water quality management, (4) implementing water as a human right is not straightforward, and (5) holistic, sustainable methodologies used in the field of wastewater treatment acknowledge sociological factors.

6.2.1 A Systems Approach must be taken to Intervene in the Water Quality Nexus

Degradation of water quality has been progressing with the proliferation of societal development. Unbounded growth, especially in terms of industrial growth, has in the past been encouraged, allowing for ignorance toward the deterioration of water quality of most waterbodies around the world and of the environment as a whole. Now, with regional shortages that are becoming more prevalent in some areas due to increased demand on water resources and the effects of climate change, public health crises caused by exposure to contaminated water, and the decrease of biodiversity in the environment, wastewater management is seen as a major component toward achieving water security. Water management decisions, including those regarding energy and food production, at local levels are now also being considered for their impact in regional catchment areas. These local level decisions are highly variable, incapsulating how the society values water and the environment within their culture. The future goal of wastewater treatment is to harmonize development of society with preservation of the environment. Sustainable development goals will only be achieved when all components of the water quality nexus are considered in an integrated manner.

6.2.2 The Field of Wastewater Treatment is Evolving

The field of wastewater treatment grew from the impacts of societal development. Basic societal planning usually provides for the initiation of wastewater treatment methods such as collecting the waste and conveying it away from where people would interact with it. Dilution processes are heavily utilized in this elementary stage of implementation of wastewater management. Adding treatment to wastewater is the next step when a need is perceived either because there is an abundance of health issues in a community or the environment's ability to assimilate waste was been exceeded. Conventional wastewater treatment technologies then become the next stage in the evolution of wastewater treatment technologies. "Conventional" is dependent of cultural behaviors perpetuated by the framework created by institutional arrangements. Policy is generally the largest proponent defining what constitutes the standard level of treatment necessary; therefore, construes what type of technologies are necessary to meet those standards. Water scarcity caused by increased water demand, decreased quality of available water, and, in some areas, changed weather patterns by virtue of climate change, has pushed communities to adopt alternative and emerging technologies to enhance wastewater treatment and to recover resources from wastewater. This transition is generally characterized by considering wastewater treatment plants as resource recovery facilities. The technologies in these latter two categories also seek to link wastewater management with the entirety of the water quality nexus in order to meet the objective of sustainable development.

From the analysis of technologies in all categories of wastewater treatment technologies and processes (i.e. dilution, conventional, alternative, and emerging), it became clear that a large range of wastewater treatment technologies exist. Due to the uniqueness of waste in both quantity and quality in each application of a wastewater treatment technologies and the available resources (natural, financial, technical, infrastructure) that the community possesses, it is extremely difficult to compare technologies in both efficiency and costs, but also in what constitutes an appropriate technology for a community. The comparisons of live wastewater treatment systems found in scholarly publications are hardly based on similar scenarios. Therefore, it is extremely crucial for environmental engineers to understand the processes undertaken by treatment technologies to know what to recommend for a certain mix of wastes and to recognize the capacity of the community in which the technology will be implemented.

The field of wastewater treatment is becoming more interdisciplinary than ever before, yet the field is generally only examined by civil or environmental engineers. The following elements that were presented in the thesis represent examples of how the advancement of the wastewater treatment would benefit from a greater diversity of fields working together:

1. designing, constructing, operating, and analyzing wastewater treatment technologies (environmental engineers, civil engineers),
2. determining and promoting the economic value of environmental preservation and improved water quality (economists),
3. understanding microbial communities which is extremely pertinent to grasp how treatment of wastewater can become more efficient (biologists, microbiologists, chemists, environmental engineers),
4. examining the institutional arrangements such as laws that have impacted the enforcement of water quality prevention measures (lawyers, political scientists, environmental scientists), and
5. studying how people value water and the environment (anthropologist, sociologist).

6.2.3 Strong, Reinforcing Institutional Arrangements are Important

Integrative water resources management requires strong institutional arrangements that enforce water quality management. Different levels of management typically fulfill different roles in wastewater management. International organizations are concerned with sustainable development and human rights initiatives as well as conflict resolution. International law seeks to create collective action among countries to mitigate the impacts of climate change, keep peace between countries, especially those with transboundary waters, to improve public health and to promote the global economy. To achieve these objectives, international organizations provide resources and technical support for federal governments.

Federal institutions provide the framework of water quality objectives and standards that regional and local governments will have to meet or exceed. Regional government focus on catchment level management decisions and project implementation. Stakeholder involvement is extremely pertinent at a regional level in order to successfully manage the quality of a specific catchment. Lastly, the local level is where implementation of infrastructure and services occurs. The available technical and financial resources are lessened with each step down of governance from international to local governance. Therefore, in order for all objectives for water quality to be met, a steady flow of resources is necessary to bolster local implementation of projects.

Various regulation strategies are utilized to enforce water quality management. Without the enforcement or flow of resources to the local levels of government, policy on its own does not effectuate change. When in tandem with adequate resources and enforcement, policy can make a large impact on how water is managed and treated. As discussed previously, “conventional” technologies are inherently selected based on the strictness of water quality standards. The conventional means of regulating water pollution has been restricting and banning specific pollutants or regulating discharges of point sources. Integrative watershed planning transitions regulation from an individual permit basis to fitting within the context of what the assimilative capacity of a specific watershed is, and not exceeding it. To push the evolution of treatment technologies, economic incentives can be utilized to channel the flow of resources to regional and local entities. As depicted in the United States’ and South Africa’s narratives of water quality management, intersectoral policy (i.e. education, environmental, public health) has also played a large role in bringing forward progression in water quality management activities.

6.2.4 Implementing Water as a Human Right is Not Easy

Water as a human right has been promoted most effectively at the international realm. Strong organizational structures at the international level has led to robust monitoring on important social issues globally. The international organizations, such as the U.N., do not have strong enforcement mechanisms. They can apply international pressure if there is a large humanitarian crisis where rights are being violated, but it takes a large event or set of events for this to occur. This means that many people do not have full access to practices the human rights that have been described as undeniable, inalienable rights. Nationally, more countries are beginning to adopt policy that explicitly or implicitly eludes to water as a human right. At the local scale, lack of funds makes it extremely difficult to implement infrastructure that would address giving people access to a cleans supply of water and adequate sanitation services. Offering the water and wastewater treatment at an equitable rate is another significant hurdle when addressing expanding services to people who may not be able to afford services at the normal retail rate. Planning and implementation are very disconnected in the scenario of water as a human right. Although presenting water as a human right seems inherently noble, there is no perfect model for how to logistically implement it.

6.2.5 Holistic Methodologies Acknowledge Sociological Factors

The creation of new, innovative wastewater treatment technologies does not directly correlate to advancement of the wastewater treatment field. Sociological factors have to be considered that affects the implementation of the technologies. Obtaining societal acceptance is important when implementing water management strategies because communities can easily intervene, resulting in the delaying of the project or halting it all together. Water managers can benefit from understanding what a society values and how to leverage that to motivate water quality improvement objectives. Surveys can be used as an effective means of relaying intangible societal perception into quantifiable data that can impact management decisions made by water managers.

From the survey, it was observed that over 35% of U.S. participants were not at all likely or not so likely able to explain what happens to their wastewater. Even within the STEM field respondents, 30% were unsure what happens to their wastewater. This exemplifies a wide gap in the link between humans and their waste disposal. Of the 655 U.S. respondents, over 90% were moderately to extremely concerned about water pollution. A higher level of concern for wastewater pollution was also correlated with people who believed they had a better understanding of wastewater treatment. Those who were more concerned about water pollution were also more likely to get involved in water resources management activities. The respondents chose protecting public health and the integrity of the environment as the two main reasons why wastewater treatment is necessary. Of the U.S. respondents, around three-quarters of the participants believe that no longer can dilution be treated as the solution to pollution with the majority of the other participants believing that it may only be conditionally sufficient.

Almost 60% of the U.S. participants were willing to increase a utility bill by atleast 3 additional USD to pay for improvements in their wastewater treatment plant's treatment capabilities whereas only 46% were willing to pay atleast 3 additional USD for improvements in their wastewater treatment plant's energy efficiency. In the real world, these improvements for a treatment plant may not be mutually exclusive; however, this type of information may help a water manager build public buy-in for the project. Only 14.35% of U.S. respondents were completely willing to drink direct potable reuse water, with an additional 22.29% very willing to drink it. Respondents from arid Colorado were more likely to try direct potable reuse water than those respondents from a more humid Virginia.

6.3 Recommendations for Further Work

The advancement of the wastewater treatment field is dependent of many factors such as (1) the continued research of treatment processes and microbial communities, (2) the innovation of technologies that either utilize new process or improve the treatment efficiency of old processes, (3) the exploration of new or common regulation strategies that will further push the evolution of wastewater treatment technologies conventionally implemented, and (4) the study of how to educate the public on the importance of water quality and change preconceptions of status quo wastewater treatment in communities.

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APPENDIX THE SURVEY: SUPPLEMENTAL DATA

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1.) **Paper Version**

Wastewater Treatment Survey

The survey is being conducted by personnel at CSU to be included in a master's thesis and/or published in a journal article and/or presented at a conference/meeting. The purpose of this research is to link people's perception of wastewater to the ongoing evolution of wastewater management approaches.

The survey will take approximately **7-10 minutes** and is **completely voluntary**. Participants are asked to fill out the survey to the best of their ability. Questions can be skipped if the participant wishes to not answer specific questions. No names will be collected and data will be reported in aggregate. There are no known risks for participating. While there are no direct benefits to you, we hope to gain more knowledge on wastewater treatment perceptions. If you have any questions about your rights as a volunteer in this research, contact the CSU IRB at: RICRO_RB@mail.colostate.edu; 970-491-1553. If you have any other questions or concerns, please contact Sydney Turner at ssturner@colostate.edu.

Thank you for your contribution!

***1. Do you agree to the above terms? By clicking Yes, you consent that you are willing to answer the questions in this survey.**

- ○ Yes
- ○ No

For the following questions, please either check (✓), fill in (•), draw an x (x), or write legibly in the box. Choose only 1 answer for each question (unless otherwise stipulated) or the response will be omitted from the study. You may skip questions if you prefer not to disclose your answers.

2. What is your age?

- ○ 18 to 24
- ○ 25 to 34
- ○ 35 to 44
- ○ 45 to 54
- ○ 55 to 64
- ○ 65 to 74
- ○ 75 or older
- ○ I prefer not to disclose

3. Indicate your gender identity: (e.g. female, male, transgender female, transgender male, etc.)

[ ]

4. In what city/county, state, country do you live? If you do not wish to disclose this information, leave the comment box blank. **(City/County, State, Country)**

[ ]

5. What is the highest level of school you have completed or the highest degree you have received?

- ○ Less than secondary school qualifications
- ○ Secondary school qualifications (diploma, GED, etc.)
- ○ Some university but no degree
- ○ Associate's degree
- ○ Vocational certification/degree
- ○ Bachelor's degree
- ○ Post-graduate degree (e.g. Master's degree, Doctorate)
- ○ I prefer not to disclose
- ○ Other (please specify)

[ ]

6. Which of the following best describes the field in which you received your highest educational qualification?

- ○ General Education
- ○ Arts and Humanities
- ○ Science
- ○ Mathematics
- ○ Computing
- ○ Technology
- ○ Engineering
- ○ Business
- ○ Law & Justice
- ○ Healthcare & Medicine
- ○ Public and Social Services
- ○ I prefer not to disclose
- ○ Other (please specify

[ ]

7. How confident are you in your ability to explain what happens to the wastewater once you flush your toilet? (e.g. does it go to a septic tank or wastewater treatment plant, are all contaminants removed at the wastewater treatment plant, what water body does the treated effluent/water discharge into, are there downstream users of the water, etc.**)**

- ○ Extremely confident
- ○ Very confident
- ○ Somewhat confident
- ○ Not so confident
- ○ Not at all confident

8. How concerned are you about water pollution?

- ○ Extremely concerned
- ○ Very concerned
- ○ Moderately concerned
- ○ Slightly concerned
- ○ Not at all concerned

9. Why is wastewater treatment important to you?
Rank the following choices on a scale from 1 (*most important*) to 5 (*least important*).

_______Maintaining the natural environment

_______Recreational purposes (swimming, fishing, boating, etc.)

_______Reducing smell

_______Public health concerns

_______Ambiance (e.g. enjoy parks with water features)

10. Around the world, outfalls (a drain or sewer that empties into a water body) release varying levels of treated and/or untreated sewage into water bodies (e.g. deep-sea outfalls). Many of these outfalls utilize "dilution as the solution to pollution," the idea that nature has the capability to assimilate polluted water to a degree (e.g. natural wetland's ability to treat stormwater). **In your opinion, does "dilution as the solution to pollution" seem like an adequate approach to wastewater treatment?**

- Completely sufficient
- Very sufficient
- Sometimes/conditionally sufficient
- Not so sufficient
- Not at all sufficient

11. Have you ever considered a political candidate's position on water resources management as a reason to vote for or against a candidate? (e.g. voting for or against a water transfer plan or more stringent water quality standards for a body of water)

- Yes, I do consider a political candidate's stance on water resource management.
- No, I do not consider a political candidate's stance on water resource management because it is not important to me.
- No, I do not consider a political candidate's stance on water resource management because other topics are higher priority to me.
- No, I do not consider a political candidate's stance on water resource management because I am unaware of water management future plans in my area.
- Other (please specify)

12. The overarching goal of wastewater treatment is to remove contaminants from water so it may be returned back to the natural environment/water cycle with minimal impairment to any water body. **If your utility/provider wanted to update the wastewater treatment infrastructure for increased TREATMENT efficiency, but it would result in an increase to your wastewater bill *per month* to invest in the project, would you be willing to pay more for the services?** Background Information: In Fort Collins, the average 2016 single family home paid about $36.12 for an estimated 4,800 gallons per month to be treated.

- $0 per month (Not at all willing)
- $0.01 to $0.99 per month
- $1.00 to $1.99 per month
- $2.00 to $2.99 per month
- $3.00 to $3.99 per month
- $4.00 + per month

13. If your utility wanted to update the wastewater treatment infrastructure for increased ENERGY efficiency, but it would result in an increase to your wastewater bill per month to invest in the project, would you be willing to pay more for the services?

- $0 per month (Not at all willing)
- $0.01 to $0.99 per month
- $1.00 to $1.99 per month
- $2.00 to $2.99 per month
- $3.00 to $3.99 per month
- $4.00 + per month

14. The EPA defines greywater as "reusable wastewater from residential, commercial and industrial bathroom sinks, bath tub shower drains, and clothes washing equipment drains." *Note that wastewater from toilets is not included in this definition.* The purpose of storing greywater onsite is to reuse it for a *non-potable* (not drinking water) application. In most cases, it is typically used for landscape irrigation. **How safe do you feel using greywater for non-potable uses?** (e.g. using greywater in toilets, gardening, etc.)

- Completely safe
- Very safe
- Somewhat safe
- Not so safe
- Not at all safe

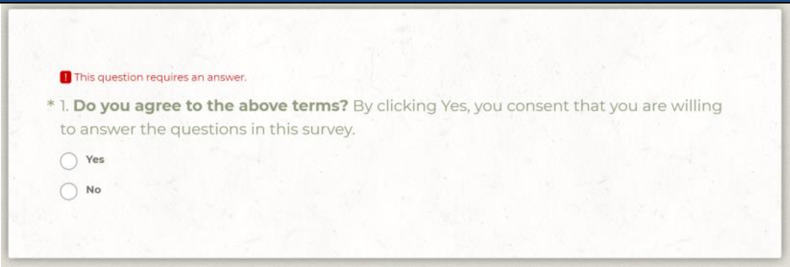
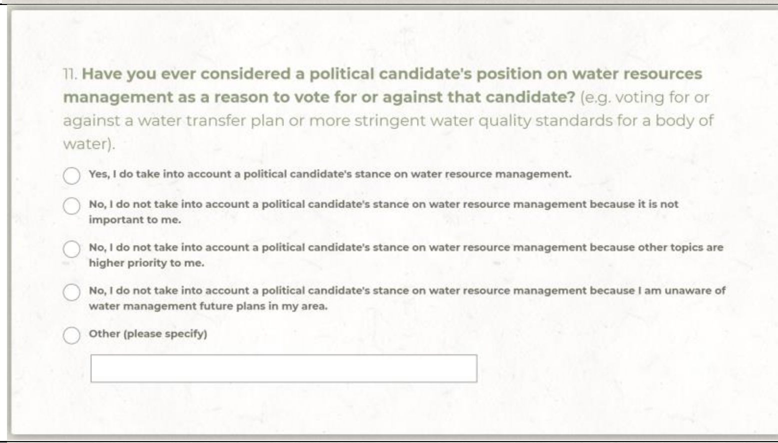
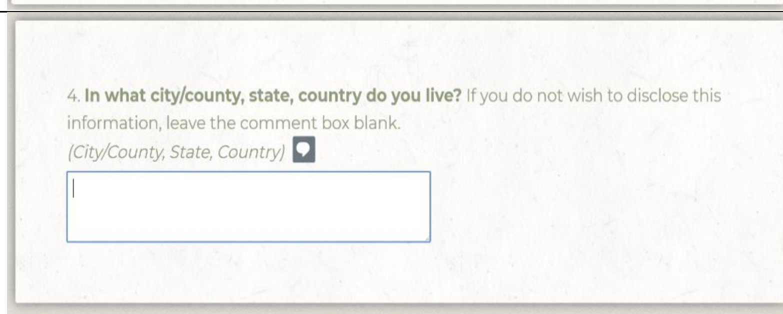
15. The National Water Research institute defines direct potable reuse as the planned introduction of recycled water (reusing treated wastewater) either directly into a public water system or into a raw water supply upstream of a water treatment plant. *Note that potable means safe to drink.* **Would you be willing to drink direct potable reuse water?**

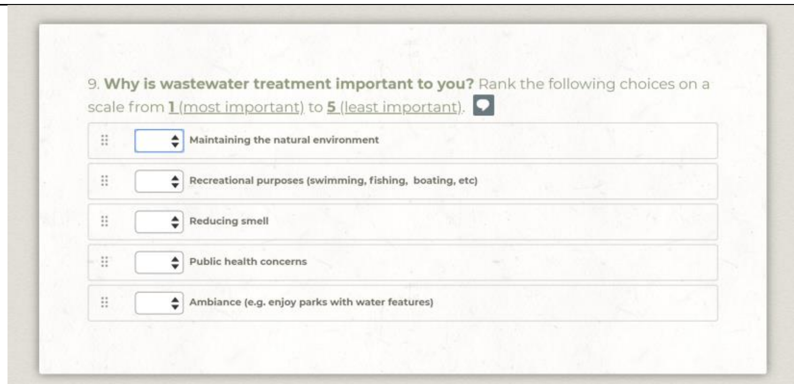
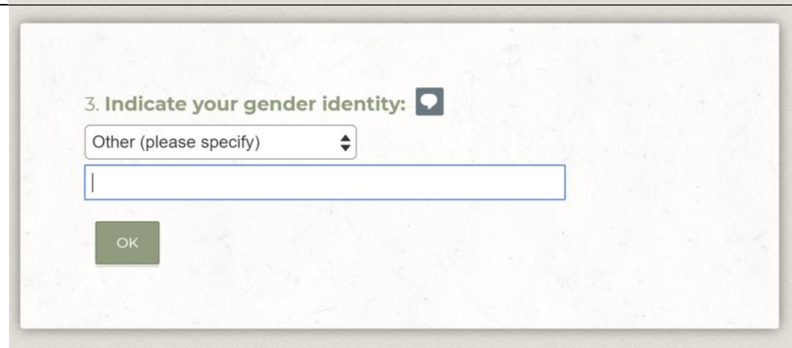
- Completely willing
- Very willing
- Somewhat willing
- Not so willing
- Not at all willing

16. How likely are you to get involved with the watershed management/planning? Getting involved can range from attending community meetings that discuss planning, to considering watershed management when voting for a candidate, to working on local watershed projects (e.g. restoration projects), etc.

- Already involved
- Very likely
- Somewhat likely
- Not so likely
- Not at all likely

2.) Survey Monkey Online Platform

RESPONSE TYPE	QUESTION	EXAMPLE QUESTIONS
MULTIPLE CHOICE WITH REQUIRED RESPONSE	1	 This question requires an answer. * 1. **Do you agree to the above terms?** By clicking Yes, you consent that you are willing to answer the questions in this survey. Yes No
MULTIPLE CHOICE	2, 7, 8, 10, 12, 13, 14, 15, 16	 2. **What is your age?** 18 to 24 25 to 34 35 to 44 45 to 54 55 to 64 65 to 74 75 or older I prefer not to disclose
MULTIPLE CHOICE W/ "OTHER" FILL IN THE BLANK OPTION	5, 6, 11	 11. **Have you ever considered a political candidate's position on water resources management as a reason to vote for or against that candidate?** (e.g. voting for or against a water transfer plan or more stringent water quality standards for a body of water). Yes, I do take into account a political candidate's stance on water resource management. No, I do not take into account a political candidate's stance on water resource management because it is not important to me. No, I do not take into account a political candidate's stance on water resource management because other topics are higher priority to me. No, I do not take into account a political candidate's stance on water resource management because I am unaware of water management future plans in my area. Other (please specify)
FILL IN THE BLANK	4	 4. **In what city/county, state, country do you live?** If you do not wish to disclose this information, leave the comment box blank. *(City/County, State, Country)*

DROP DOWN	9	
DROP DOWN W/ "OTHER" FILL IN THE BLANK OPTION	3	

3.) Results Tables and Figures

Table 1: U.S. Participants - Breakdown by State

U.S. Participants			
State	# of Participants	State	# of Participants
Alabama	6	Missouri	2
Alaska	1	Nevada	1
Arizona	12	New Hampshire	1
California	27	New Jersey	15
Colorado	204	New Mexico	2
Connecticut	4	New York	7
DC	2	North Carolina	14
Delaware	3	Ohio	6
Florida	26	Oklahoma	5
Georgia	17	Oregon	6
Hawaii	1	Pennsylvania	24
Illinois	9	Rhode Island	1
Indiana	4	South Carolina	13
Iowa	1	Tennessee	5
Kansas	2	Texas	23
Kentucky	1	Texas	1
Louisiana	1	Utah	4
Maryland	15	Virginia	133
Massachusetts	14	Washington	19
Michigan	7	West Virginia	1
Minnesota	5	Wisconsin	2
Mississippi	1	Wyoming	1

Table 2: Participants - Breakdown by Country

Participants - Country Breakdown			
Country	# of Participants	Country	# of Participants
Not Disclosed	40	Hong Kong	2
Argentina	1	India	1
Australia	2	Japan	1
Belgium	3	Singapore	1
Brazil	2	Slovakia	5
Canada	3	Spain	1
Denmark	1	United Kingdom	1
England	1	USA	655
Finland	1	Military - Stationed Abroad	10
France	4		

Table 3: U.S. Participants – Gender Identity

U.S. Participants		
Gender Identity	**# of Participants**	**%**
Female	450	68.70%
Male	197	30.08%
NA/Blank	1	0.15%
Gender Variant/ Non-conforming	4	0.61%
Transgender Female	1	0.15%
Transgender Male	2	0.31%

Table 4: U.S. Participants – Age Group Breakdown

U.S. Participants		
Age Group	**# of Participants**	**%**
18 to 24	139	21.2%
25 to 34	136	20.8%
35 to 44	60	9.2%
45 to 54	78	11.9%
55 to 64	110	16.8%
65 to 74	54	8.2%
75 or older	74	11.3%
Not Disclosed	4	0.6%

Table 5: U.S. Participants – Highest Education Level Achieved

U.S. Participants		
Highest Level of Education	**# of Participants**	**%**
Less than secondary school qualifications	3	0.46%
Secondary school qualifications (diploma, GED, etc.)	25	3.82%
Some university but no degree	109	16.64%
Associate's degree	48	7.33%
Vocational certification/degree	9	1.37%
Bachelor's degree	225	34.35%
Post-graduate degree (e.g. Master's degree, Doctorate)	233	35.57%
Not Disclosed	3	0.46%

Table 6: U.S. Participants – STEM vs. Non-STEM Fields

U.S. Participants		
Field	**# of Participants**	**%**
Not Disclosed	7	1/07%
Non-stem	329	50.31%
STEM	318	48.62%
STEM w/o Medical	253	9.94%
Medical/ Healthcare Profession	65	38.69%

Table 7: U.S. Participants – Profession/Field

U.S. Participants		
Profession/Field of Study	# of Participants	%
Arts & Humanities	78	11.91%
Business	69	10.53%
Computing	14	2.14%
Engineering	96	14.66%
General Education	67	10.23%
Healthcare & Medicine	62	9.47%
Law & Justice	20	3.05%
Mathematics	11	1.68%
Public and Social Services	28	4.27%
Science	103	15.73%
Technology	13	1.98%
Other (please specify)	87	13.28%
Did not disclose	7	1.07%

Table 8: U.S. Participants – Question 7 Statistical Analysis

US PARTICIPANTS					
	Stem	Non-stem		Medical	STEM w/o Medical
Mean	3.211	2.824	Mean	2.692	3.345
T-test (2-tailed, heteroscedastic)	1.781E-05		T.test (2-tailed, heteroscedastic)	1.776E-05	
Mode	3	3	Mode	2	3
Median	3	3	Median	3	3
STDEV	1.162	1.113	STDEV	1.0143	1.162

Table 9 : U.S. Participants – Question 7 Responses

	U.S. Participants -Confidence in Topic Area (WWT)								
Education Filed		Not Disclosed	Not at all likely	Not so likely	Somewhat likely	Very likely	Extremely likely	Total	%
	Non-stem	-	39	91	119	51	30	**330**	50.38%
	STEM	1	19	77	92	76	53	**318**	48.55%
	Not Disclosed	-	1	2	4	-	-	**7**	1.07%
	STEM w/o med	1	13	52	72	65	50	**253**	38.63%
	Medical, Healthcare	-	6	25	20	11	3	**65**	9.92%
	Total	**1**	**59**	**170**	**215**	**127**	**83**	**655**	
		0.15%	**9.01%**	**25.95%**	**32.82%**	**19.39%**	**12.67%**		

Table 10: U.S. Participants – Question 8 Responses

Education Filed	U.S. Participants- Water Pollution Concern	Not Disclosed	Not at all concerned	Slightly concerned	Moderately concerned	Very concerned	Extremely concerned	Total	%
	Not Disclosed			1	3	2	1	**7**	1.07%
	Non-stem		3	26	85	123	93	**330**	50.38%
	STEM	2	4	16	72	122	102	**318**	48.55%
	STEM w/o medical	2	4	12	53	97	85	**253**	38.63%
	Medical, Healthcare			4	19	25	17	**65**	9.92%
	Total	**2**	**7**	**43**	**160**	**247**	**196**	**655**	
	%	0.31%	1.07%	6.56%	24.43%	37.71%	29.92%		

Table 11 : U.S. Participants – Question 8 Responses

U.S. PARTICIPANTS – Water Pollution Concern					
	Stem	**Nonstem**		**Medical**	**STEM w/o Medical**
Mean	3.949	3.808	**Mean**	3.833	3.975
T-test (2-tailed)	0.046		**T-test (2-tailed)**	0.249	
Mode	4	4	**Mode**	4	4
Median	4	4	**Median**	4	4
STDEV	0.926	0.957	**STDEV**	0.887	0.934

Table 12 : U.S. Participants - Comparing Responses to Question 7 and 8.

	Response	Given Numerical Value
Level 1 of Confidence/Concern	Not at all	1
	Not so/Slightly	1
Level 2 of Confidence/Concern	Somewhat/Moderately	2
	Very	2
	Extremely	2
U.S. Participants		
	Q7_Confidence	**Q8_Concern**
T.Test (2-tailed, heteroscedastic)	6.73E-35	
T.Test (2-tailed, paired)	7.93E-37	

Table 13 : Percentage of participants located in either a blue or red designated state from the 2016 U.S. Presidential Election.

U.S. Participants		
Participants located in "Red" States	Participants located in "Blue" States	Total Participants who disclosed which state they reside
179	470	649

Table 14: Response to Question 8 considering participants located in either a blue or red designated state from the 2016 U.S. Presidential Election.

Education Filed		Not Disclosed	Not at all concerned	Slightly concerned	Moderately concerned	Very concerned	Extremely concerned	Total	%	Overall Total	Overall %
		U.S. Participants – Water Pollution Concern									
Red	Not Disclosed	-	-	1	1	-	-		1.12%	**2**	0.31%
Red	Non-stem	-	-	12	34	37	21		58.1%	**104**	16.0%
Red	STEM	-	1	5	15	29	23		40.8%	**73**	11.2%
Red	**Total**	**-**	**1**	**18**	**50**	**66**	**44**	**179**			
Red	**%**	0.0%	1.12%	10.1%	27.9%	36.9%	24.6%				
Blue	Not Disclosed	-	-	-	2	2	1		1.06%	**5**	0.77%
Blue	Non-stem	-	3	14	50	86	70		47.4%	**223**	34.4%
Blue	STEM	2	3	11	56	92	78		51.5%	**242**	37.3%
Blue	**Total**	**2**	**6**	**25**	**108**	**180**	**149**	**470**			
Blue	**%**	0.43%	1.28%	5.32%	23.0%	38.3%	31.7%				
	Overall Total	**2**	**7**	**43**	**158**	**246**	**193**			**649**	
	Overall %	0.31%	1.08%	6.63%	24.3%	37.9%	29.7%				

Table 15: Results to Question 9 asking participants to rank why wastewater treatment is important to them .

U.S. Participants – Prioritizing what makes WWT Important					
Environment		**Recreation**		**Smell**	
Rank	**# of Participants**	**Rank**	**# of Participants**	**Rank**	**# of Participants**
1	178	1	23	1	25
2	251	2	72	2	54
3	48	3	219	3	161
4	41	4	157	4	149
5	26	5	77	5	174
Did not disclose	111	Did not disclose	107	Did not disclose	92
Total	**655**	**Total**	**655**	**Total**	**655**
Health		**Ambience**			
Rank	**# of Participants**	**Rank**	**# of Participants**		
1	343	1	44		
2	146	2	53		
3	34	3	101		
4	30	4	180		
5	39	5	243		
Did not disclose	63	Did not disclose	34		
Total	**655**	**Total**	**655**		

Table 16: Results to Question 10 asking participants how they feel about the sufficiency of "dilution as the solution for pollution."

	U.S. Participants -Sufficiency of Dilution								
Education Filed		Not Disclosed	Not at all sufficient	Not so sufficient	Sometimes/ conditionally sufficient	Very sufficient	Completely sufficient	total	%
	Non-stem		123	129	72	5	1	**330**	50.38%
	STEM	2	126	108	77	3	2	**318**	48.55%
	Not disclosed		1	5	1			**7**	1.07%
	STEM w/o medical		103	78	67	3	2	**253**	38.63%
	Medical, Healthcare	2	23	30	10			**65**	9.92%
	total	**2**	**250**	**242**	**150**	**8**	**3**	**655**	
	%	0.3%	38.2%	36.9%	22.9%	1.2%	0.5%		

Table 17: Results to Question 12 asking participants if they are willing to pay more on their utilities' bill toward improvements in the wastewater treatment efficiency.

	U.S. Participants – WTP for Treatment Efficiency									
Education Filed		Not Disclosed	0 - 0	0.01 - 0.99	1.00 - 1.99	2.00 - 2.99	3.00 - 3.99	4.00+	total	%
	Not Disclosed			4		2		1	**7**	1.07%
	Non-stem	1	10	22	51	57	55	134	**330**	50.38%
	STEM	1	8	18	44	48	46	153	**318**	48.55%
	STEM w/o medical	1	4	14	35	40	36	123	**253**	38.63%
	Medical/ Healthcare		4	4	9	8	10	30	**65**	9.92%
	total	**2**	**18**	**44**	**95**	**107**	**101**	**288**	**655**	
	%	0.31%	2.75%	6.72%	14.50%	16.34%	15.42%	43.97%		

Table 18: Results to Question 13 asking participants if they are willing to pay more on their utilities' bill toward improvements in the wastewater energy efficiency.

	U.S. Participants – WTP for Energy Efficiency									
Education Filed		Not Disclosed	0 - 0	0.01 - 0.99	1.00 - 1.99	2.00 - 2.99	3.00 - 3.99	4.00+	total	%
	Not Disclosed		1	1	3	2			**7**	1.07%
	Non-stem	3	16	40	56	63	45	107	**330**	50.38%
	STEM	1	19	42	50	55	40	111	**318**	48.55%
	STEM w/o medical		14	32	41	42	30	94	**253**	38.63%
	Medical/ Healthcare	1	5	10	9	13	1010	17	**65**	9.92%
	total	**4**	**36**	**83**	**109**	**120**	**85**	**218**	**655**	
	%	0.61%	5..50%	12.67%	16.64%	18.32%	12.98%	33.28%		

Table 19: Comparing Questions 12 and 13 Results.

U.S. Participants – Comparing Willing to Pay Scenarios		
	Treatment Efficiency	Energy Efficiency
Mean	3.67	3.21
T-test (2-tailed, heteroscedastic)	7.16E-08	
T-test (2-tailed, paired)	4.80E-26	
Mode	5	5
Median	4	3
STDEV	1.46	1.61

Table 20: Results to Question 14 asking participants how safe they feel using greywater reuse practices.

	U.S. Participants – Safe Using Greywater Reuse Practices								
		Not Disclosed	Not at all safe	Not so safe	Somewhat safe	Very safe	Completely safe	total	%
Education Filed	Not Disclosed			2	4	1		**7**	1.07%
	Non-stem	1	13	61	126	78	51	**330**	50.38%
	STEM	1	3	46	107	91	70	**318**	48.55%
	STEM w/o medical			29	87	75	62	**253**	38.63%
	Medical, Healthcare	1	3	17	20	16	8	**65**	9.92%
	total	**2**	**16**	**109**	**237**	**170**	**121**	**655**	
	%	0.31%	2.44%	16.64%	36.18%	25.95%	18.47%		

Table 21: Results to Question 15 asking participants how safe they feel using greywater reuse practices.

	U.S. Participants – Willing to drink direct potable reuse water								
		Not Disclosed	Not at all willing	Not so willing	Somewhat willing	Very willing	Completely willing	total	%
Education Filed	Not Disclosed		2	3	2			**7**	1.07%
	Non-stem	1	48	93	109	55	24	**330**	50.38%
	STEM	1	3	46	107	91	70	**318**	48.55%
	STEM w/o medical	1	15	47	87	54	49	**253**	38.63%
	Medical, Healthcare		9	15	24	10	7	**65**	9.92%
	total	**2**	**53**	**142**	**218**	**146**	**94**	**655**	
	%	0.31%	8.09%	21.68%	33.28%	22.29%	14.35%		

Table 22: Comparing responses from Colorado and Virginia to Question 14 and Question 15.

Comparing participants' responses from arid Colorado and humid Virginia		
Greywater Reuse		
	Colorado	Virginia
Mean	3.471	3.386
T-test (2-tailed, heteroscedastic)	4.48E-01	
Mode	3	3
Median	3	3
STDEV	1.014	0.978
Direct Potable Reuse		
Mean	3.206	2.833
T-test (2-tailed, heteroscedastic)	3.51E-03	
Mode	3	3
Median	3	3
STDEV	1.099	1.1536

Table 23: Comparing Participants' Perceptions of Water Reuse Alternatives from Responses to Questions 14 and 15.

U.S. Participants – Perceptions of Water Reuse Alternatives		
	Treatment Efficiency	Energy Efficiency
Mean	3.42	2.96
T-test (2-tailed, heteroscedastic)	1.98E-13	
T-test (2-tailed, paired)	3.34E-22	
Mode	3	3
Median	3	3
STDEV	1.05	1.17

Table 24: Comparing results from different age groups when considering Question 14 & 15.

U.S. Participants			
Greywater Reuse			
	18-34	35-64	65+
Mean	3.41	3.39	3.50
T-test (2-tailed, heteroscedastic) 18-34 vs. 35-64	0.786455781		
T-test (2-tailed, heteroscedastic) 18-34 vs. 65+	0.443361398		
T-test (2-tailed, heteroscedastic) 35-64 vs. 65+		0.33478716	
Mode	3	3	3
Median	3	3	3
STDEV	1.0372	1.0686	1.0334
Direct Potable Reuse			
	18-34	35-64	65+
Mean	3.32	2.66	2.78
T-test (2-tailed, heteroscedastic) 18-34 vs. 35-64	5.94082E-11		
T-test (2-tailed, heteroscedastic) 18-34 vs. 65+	1.29467E-05		
T-test (2-tailed, heteroscedastic) 35-64 vs. 65+		0.34640365	
Mode	3	3	2
Median	3	3	3
STDEV	1.0938	1.1516	1.1472

Table 25: Results to Question 11 asking participants whether they have ever considered a politician's stance on water resources management as a reason to vote for or against a candidate.

	U.S. Participants – Voting for water resources platform								
Education Filed		Not Disclosed	No – not important	No – low priority	No - unaware	Yes	Other (specified by participant)	total	%
	Not Disclosed	-	2	1	2	2	-	**7**	1.06%
	Non-stem	2	9	71	104	123	21	**330**	50.4%
	STEM	2	4	67	86	149	10	**318**	48.5%
	STEM w/o medical	2	2	55	57	128	9	**253**	38.6%
	Medical, Healthcare	-	2	12	29	21	1	**65**	9.9%
	total	**4**	**13**	**138**	**190**	**272**	**31**	**655**	
	%	0.61%	2.0%	21.1%	29.0%	41.5%	4.7%		

Table 26: Results to Question 16 asking participants how likely they are to get involved in water resources management activities

	U.S. Participants – Getting Involved in water resources management activities								
Education Filed		Not Disclosed	Not at all likely	Not so likely	Somewhat likely	Very likely	Already involved	total	%
	Not Disclosed	-	1	2	2	1	1	**7**	1.07%
	Non-stem	2	38	110	129	36	15	**330**	50.38%
	STEM							**318**	48.5%
	STEM w/o medical	2	20	56	80	52	43	**253**	38.6%
	Medical, Healthcare	1	8	27	19	9	1	**65**	9.9%
	total	**5**	**67**	**195**	**230**	**98**	**60**	**655**	
	%	0.76%	10.23%	29.77%	35.11%	14.96%	9.16%		
	Mode	3							
	Mean	2.83							
	Stdev	1.10							

Table 27: Comparing Participants concern level for pollution with their likeliness to get involved with water resources management activities considering survey question 8 and 16.

Involvement		Concern	
Response	Score	Response	Score
Not at all likely	1	Not at all concerned	1
Not so likely	1	Slightly	1
Somewhat likely	2	Moderately	2
Very likely	2	Very concerned	2
Extremely likely	2	Extremely Concerned	2

U.S. Participants – Concern for water pollution versus likeliness to get involved	
T-test (2-tailed, heteroscedastic)	1.42E-45
T-test (2-tailed, paired)	3.06E-53

Table 28: Results to Question

Age group	Not Disclosed	Not at all	Not so	Somewhat	Very	Already involved	total	mean
Non-stem								
18 to 24	1	2	20	20	7	2	**52**	**2.69**
25 to 34		10	15	22	6	1	**54**	**2.50**
35 to 44		4	14	7	1		**26**	**2.19**
45 to 54		5	16	22	3	4	**50**	**2.70**
55 to 64	1	8	22	27	8	7	**73**	**2.74**
65 to 74		2	7	13	6	1	**29**	**2.90**
75 or older		8	15	17	5		**45**	**2.42**
I prefer not to disclose				1			**1**	**3.00**
Non-stem Total	**2**	**39**	**109**	**129**	**36**	**15**	**330**	**2.62**
Medical, Healthcare								
18 to 24			7	1	1		9	**2.33**
25 to 34		2	6	4	2		14	**2.43**
35 to 44		2	3	3	1		9	**2.33**
45 to 54		1	1	4	2		8	**2.88**
55 to 64			5	3	1	1	10	**2.80**
65 to 74		2		1	2		5	**2.60**
75 or older	1	1	5	3			10	**2.00**
Medical, Healthcare Total	**1**	**8**	**4**	**19**	**8**	**17**	**65**	**2.46**
STEM w/o Medical								
18 to 24		5	18	20	21	12	**76**	**3.22**
25 to 34	1	7	14	16	14	16	**68**	**3.22**
35 to 44	1	1	2	12	2	7	**25**	**3.36**
45 to 54		1	2	10	1	5	**19**	**3.37**
55 to 64		3	8	7	7		**25**	**2.72**
65 to 74			7	7	4	2	**20**	**3.05**
75 or older		3	4	7	2	1	**17**	**2.65**
I prefer not to disclose			1				**1**	**2.00**
NA				1	1		**2**	**3.50**
STEM w/o medical Total	**2**	**20**	**56**	**80**	**52**	**43**	**253**	**3.14**
Not Disclosed								
18 to 24				1	1		**2**	**3.50**
45 to 54				1			**1**	**3.00**
55 to 64			2				**2**	**2.00**
75 or older		1				1	**2**	**3.00**
Not Disclosed Total		**1**	**1**	**3**	**2**	**1**	**7**	**2.86**