Establishing Failure Indicators for Conventional On-site Wastewater Treatment Systems

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ABSTRACT

Conventional On-site Wastewater Treatment Systems (COWTS) are systems used for the treatment of domestic wastewater. These systems comprise of a septic tank that provides primary and secondary treatment in which solids are settled and broken down by biological processes, and a soil absorption trench or field that provides advance treatment for the discharge of effluent, mainly through filtration and adsorption. These systems are used primarily in regions where there is no reticulated wastewater disposal; however, significant increases in population, and poor design and management of these facilities have led to a large number of failing systems throughout the world. Owing to the constituents present in wastewaters and discharged effluent, failure of these systems is a public and environmental concern, as they have the potential to contaminate both surface water and groundwater resources, primarily through the release of pathogenic microorganism and nutrients. This thesis identifies modes of failure for COWTS and establishes indicators that can signal irregularities in their performance before complete failure occurs. It also demonstrates how some parameters can intensify failure.

Design, technical, management and compliance are presented as the four categories of failure modes, and these are further divided into several sub–categories. The ratio of occupancy size, to septic tank volume, and the frequency of use contribute significantly to a system failure during the primary stages of treatment, while poor siting, user inexperience and soil properties within the drainage area largely contribute to failure during the secondary treatment stage. Parameters such as the proximity to a school, surface waterways and nearby dwellings are used to show how failures can be intensified.

A methodology in the form of a monitoring model has proven to be very useful in increasing user awareness of a system’s performance, and can aid in preventing complete failure. Success with this methodology came by combining the failure indicators and intensifying parameters to generate a numerical risk score. This score is compared with examples of the likely occurrences of failures at that particular score. Darfield Township on the South Island of New Zealand is used as the case-study area to demonstrate how the monitoring methodology developed can be applied.

GLOSSARY

Absorption	The uptake of effluent into the soil
Adsorption	The physical or chemical attachment of substances to the surface of soil particles
Effluent	The liquid discharged from the septic tank
Environment	Surrounding, including natural and physical resources, ecosystems, community, and neighbourhood
Groundwater	The body of water in the soil
Impermeable layer	Soil layer with permeability less than 10 % of that of the overlaying soil layer
Infiltration	Passage of water or effluent into soil
Influent	The wastewater flowing into the septic tank
Regulatory authority	An authority or body empowered to by statue to be responsible for managing or controlling an aspect of on-site systems
Risk	An expression of the likelihood of identified hazards causing harm in exposed populations or receiving environments, and the severity of the consequences
Scum	The floating mass of wastewater solids on the liquid surface inside the septic tank
Setback	The distance an on-site system shall be situated from any facility, boundary or body of water
Sludge	The semi-liquid solids settled from wastewater
Wastewater	The discharge from sanitary fixtures and sanitary appliances
Water table	The upper surface of groundwater below which the soil is permanently saturated with water

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CHAPTER 1 INTRODUCTION

The first known waste disposal system with a flushing device was installed in Knossos, Crete, in 1700 BC. Since then, societies and governments have dedicated a lot of time and effort to the disposal of human waste and have implemented mechanisms to treat and dispose of effluent in a careful and engineered manner. Throughout this process, careful attention is paid to minimising threats to humans, while adequately protecting environmental and ecological health (USEPA, 2002). This has resulted in creating systems that have relied on soil for disposal of human waste and wastewaters. Throughout the twentieth century, soil–based disposal systems such as seepage pits and privies were used to isolate human wastes and avoid pollution of the environment (Siegrist, 2007). Although these systems were not designed to achieve a high level of treatment, they remain very important as they provide an economical means for the treatment of sewage, especially in areas where there is no reticulated form of disposal and treatment available (Siegrist et al., 2000b).

1.1. On-site wastewater

On-site wastewater generally includes all liquids, dissolved gases and solid wastes that may be carried by liquids removed from residential, commercial, institutional and industrial establishments (Tchobanoglous et al., 2003). Owing to the significance in quantity of residential wastewater, the focus will be on this category throughout this thesis; however, because of the varying sources from which waste may be generated, wastewater includes a large number of constituents. Failure to contain, treat and dispose of wastewater in the most appropriate method, so that the main constituents of concern can be broken down to acceptable levels can be detrimental to public and environmental health.

The wastewater generated from households are referred to as domestic wastewaters and are separated into two categories:

1. greywater – i.e. wastewater generated for bathrooms and laundry; and
2. blackwater – i.e. wastewaters generated from toilets and kitchen sinks.

Collectively the two categories are referred to as all-wastewaters and should be treated before discharge into the receiving environment. Although there have been significant improvements in technologies to treat wastewaters, the ability to adequately treat domestic wastewaters on-site remains very challenging, especially in rural areas. The development of semi-rural and suburban communities in areas where there is no centralised form of wastewater treatment has also intensified this task (AS/NZS 1547:2012; Sample et al., 2014).

1.2. On-site wastewater treatment systems

On-site wastewater treatment systems (OWTS) are domestic wastewater management systems that receive and treat domestic wastewater before it is discharged to a holding tank or land application system (AS/NZS 1547:2012). These systems have been acknowledged as a feasible, affordable, sustainable and decentralised approach for wastewater management, assuming they are planned, designed, installed, operated and maintained properly. Major developments in OWTS have resulted in the evolution of systems of the primitive kind such as pit privies to systems capable of producing well–disinfected effluents (USEPA, 2002); however, significant increases in population growth along with poor siting and inadequate soil analysis have resulted in a significant number of deteriorating OWTS. A cluster of poorly performing or failing OWTS has the potential to cause serious health problems, since the improperly treated effluent is likely to contain disease–causing microorganisms and nutrients that can contaminate both surface and groundwater (Gunady et al., 2015; Harris, 1995; Lipp et al., 2001; Pang et al., 2004; Young et al., 1999). These contaminants are of serious concern because of the potential health risks involved along with the possible degradation of water resources for drinking, recreation and food gathering (Carroll, Hargreaves, et al., 2005; Hagedorn et al., 1999; Wiggins et al., 2003). Although the potential of these contaminants to severely contaminate ground and surface waters has been fully documented, in-depth understanding of OWTS to predict failure has not been fully studied (Siegrist, 2001a).

1.3. OWTS usages and challenges

Throughout the world, a significant proportion of households use OWTS for the management of household wastewaters. In the US approximately 25 % of households are served by OWTS (USEPA, 2002); in Australia, approximately 20 % (Beal et al., 2005); an estimated 26 % in Europe (Williams et al., 2012; Paul J. A. Withers et al., 2014); and approximately 20 % of the population in New Zealand also use these systems (Dakers et al., 2009). OWTS will continue to be a major means for treatment and disposal of household wastewater in developing countries, mainly because of the high costs associated with implementing a centralised reticulated system. Although there have been significant improvements in the design of OWTSs over the years, which may have resulted in higher levels of treatment, research has shown that many systems experience operational or functional failures; either systems have failed to effectively remove all the wastewater from a home in a timely manner or systems have failed to treat the wastewaters to acceptable levels before discharging to the receiving environment (Angel, 2002).

A large percentage of OWTS failures are due to poor management of these systems by homeowners. In New Zealand, the Ministry for the Environment (MfE) reported in 2008 that failure rates for these systems range between 15 % to 50 %, while in the US, failures in the range from 10 % to 20 % have also been reported (USEPA, 2002). In Australia Gunady et al. (2015) reported that failure rates are approximately 40 %. Failure rates will continue to rise since current forms of management allow maintenance of these systems to be the responsibility of homeowners, who generally have limited knowledge about managing them (Howard, 2003). Improper maintenance of systems has not only led to numerous of failing systems, but is also one of the leading causes of surface and groundwater contamination around the world because of the inadequately treated wastewater being discharged into the environment (Canter et al., 1984; Robertson et al., 1991; Yates, 1985). Maintenance of these systems continues to be challenging for regulatory authorities because of the different sites they are being constructed in, the difficulty in identifying which systems are most likely to fail, and correctly accessing the magnitude of the risk a particular system may pose if it fails (Siegrist et al., 2000a).

Impacts of poorly managed OWTS

Poorly managed OWTS may result in failure that can negatively affect the environment and endanger public health. Due to the constituents of wastewaters, particularly nutrients, the release of untreated or poorly treated effluent can promote rapid algae and macrophyte growth in surface waters and even cause the water body to become eutrophic. This excessive nutrient enrichment has led to the degradation of many recreational waterways because of oxygen depletion, creating anoxic conditions and results in loss of aesthetic value. This eutrophic state along with the continuous input of untreated effluent containing high organic matter from poorly managed OWTS can have a negative effect on aquatic life because of reduced dissolved oxygen levels (Fatta-Kassinos et al., 2011; Penn et al., 2006; Singh et al., 2010; UN Water, 2015).

Many researchers have also expressed concerns about the adverse effects that failing OWTS systems can have on groundwater, mainly due to increased nitrate concentration and microbial contamination (Close, 2010; G. Heufelder, 2012; K. S. Lowe et al., 2008; Nasser et al., 2002;

Wilhelm et al., 1994; Paul J. A. Withers et al., 2014). In developing countries, such as Guyana where more than 90 % of the population live along the Atlantic coast, which is approximately one metre below mean sea level and overlaying a coastal aquifer system from which approximately 90 % of the potable water supply is extracted and distributed without any form of treatment, makes preventing all forms of surface and groundwater contaminations an essential priority (US Army Corps of Engineers, 1998).

Consumption of water containing levels of nitrate beyond the allowable limit has been associated with limiting the oxygen and haemoglobin transport in babies causing methemoglobinemia (blue baby syndrome) and carcinogenic effects in adults. Over the years there has been a significant number of documented cases of waterborne disease outbreaks caused by failing OWTS releasing pathogenic microorganisms and contaminating potable water supply wells (Maine Center for Disease Control and Prevention, 2013). During August, 2016, an outbreak of gastroenteritis occurred in Havelock North, New Zealand and indications showed that some of the district's potable water supply was contaminated with Escherichia coli and Campylobacter bacteria and approximately two thousand persons were affected. Tests also revealed traces of faecal contamination (Water New Zealand, 2016). Although there was no conclusion linking failing OWTSs and this outbreak, there is potential for outbreaks of this magnitude to occur if OWTSs fail.

Some types of failures may result in effluent ponding on the ground surface that can emit an unpleasant odour and act as a breeding ground for mosquitoes. In addition, the presence of some micro pollutants such as pharmaceuticals and personal care products (PPCP), inadequately managed systems leaching untreated effluent into adjacent waterways can cause disruptions in the biological diversity of aquatic ecosystems due to the presence of the various endocrine disrupting chemicals these substances may contain (Colborn et al., 1993; Fatta-Kassinos et al., 2011; Gallert et al., 2005; Godfrey et al., 2007; Kasprzyk-Hordern et al., 2008). For these reasons, it is important that significant focus is placed on managing these systems, and that advanced methods of monitoring system performance are developed so that failures are minimised, especially since OWTS will continue to be a dominant form for domestic wastewater treatment due to their low cost (Nasr et al., 2015).

1.4. Contaminants of concern in wastewaters

Categorising all the constituents present in wastewaters will always be a major challenge because of the different sources from which wastewater is generated and the increasing number of emerging contaminants present in products used within the home; however, it is significant to note the various contaminants and the impacts they can have on the receiving environment and public health if discharged without first being broken down. Table 1-1 below lists some of the major contaminants and the reasons for their importance.

Table 1-1 Important Contaminants of Concern in Wastewaters.

Constituents	**Source and reason for importance**
Dissolved organic matter	Principally digestion of proteins, carbohydrates, and fat cause oxygen depletion and will subsequently affect aquatic life. Commonly measured in terms of BOD (biochemical oxygen demand) and COD (chemical oxygen demand.).
Suspended solids	Mainly insoluble and non-biodegradable matter. May lead to the development of sludge deposits and anaerobic conditions when untreated wastewater is discharged in the aquatic environment.
Nutrients	Nitrogen (N) originates mainly from blackwaters and phosphorus (P), originates mostly from greywater. When discharged to the aquatic environment, they promote excessive growth of aquatic plants. May also pollute groundwater. May cause blue baby syndrome.
Priority pollutants	Organic (e.g. fatty acids,) and inorganic compounds (e.g. sodium chloride) selected on the basis of their known or suspected carcinogenicity, mutagenicity, teratogenicity, or high acute toxicity. Many of these compounds are found in wastewater.
Refractory organics	These organics resist conventional treatment methods. Examples include surfactants, phenols, and agricultural pesticides.
Bacterial, viral, and protozoan pathogens	Disease-causing agents, contaminants of faecal matter.

Adapted from Tchobanoglous et al. (2003)

Researchers have characterised these constituents based on their physical, chemical and biological composition. By doing so, clear distinctions were made for the range of concentration of the main constituents present in residential wastewaters. These are shown in Table 1-2 below.

Table 1-2 Average Mass Loadings and Concentrations in Typical Residential Wastewater.

Parameter	Mass loading (grams/person/day)	Concentration (mg/L)
Total solids (TS)	115–200	500–880
Volatile solids	65–85	280–375
Total suspended solids (TSS)	35–75	155–330
Volatile suspended solids	25–60	110–265
5-day biochemical oxygen demand (BOD_5)	35–65	155–280
Chemical Oxygen demand (COD)	115–150	500–660
Total Nitrogen (TN)	6–17	26–75
Ammonia (NH_4)	1–3	4–13
Nitrates and nitrates (NO_2-N; NO_3-N)	<1	<1
Total phosphorus (TP)	1–2	6–12
Fats, oils, grease	12–18	70–105
Volatile organic compounds (VOC)	0.02–0.07	0.1–0.3
Surfactants	2–4	9–18
Total coliforms (TC)	–	10^8–10^{10}
Faecal coliforms (FC)	–	10^6–10^8

Adapted from USEPA (2002)

These values fluctuate throughout the day because of the different contributing sources, variations in the quantity of wastewater and the concentration of contaminants. However, the primary constituents of concern that have the most devastating effects on the environment and public health are nutrients and pathogenic microorganisms, because of their impacts on surface and groundwater. Recent studies have also linked pharmaceuticals along with other micro pollutants as new contaminants of concern, presenting an emerging challenge for designers and regulatory officials (Larsen et al., 2004; Siegrist et al., 2000a; USEPA, 2002).

1.4.1. Parameter # 1 – biochemical oxygen demand

Wastewater contains a significant amount of biodegradable organic matter composed mostly of carbohydrates and proteins (Penn et al., 2006). Stabilisation of these materials, occurs through two processes: chemical decomposition or biological consumption. However, both of these processes consume the oxygen dissolved in the wastewater; therefore, the higher the concentration of organic matter in the wastewater and discharged effluent, the greater is the rate of oxygen depletion in the receiving waters. For this reason, efforts should always be made to prohibit poorly treated effluent from entering surface waterways because significant amounts of biodegradable organic matter rapidly depletes the dissolved oxygen, and this can be harmful to most aquatic life (Ellis, 2004). Measurement for oxygen demand is done in mg/L. The value obtained gives an indirect indication of the concentration of organic matter in the water (Penn et al., 2006; Water Resources Research Center University of Hawaii, 2008).

1.4.2. Parameter # 2 – nutrients

The nutrients present in septic tank effluent originate mainly from daily activities within a dwelling. The amount of these nutrients varies throughout the year; hence, the level of impact on the environment cannot be accurately determined. Research done by Withers et al. (2012) shows that in spite of the temporal variations and their relatively small contribution to the annual nutrient loads within a catchment (when compared with other activities such as agriculture), septic tank effluent has the potential to influence the ecological responses within a surface water body and this should be of significant concern, especially during periods of low flow. The nutrients of primary concern are nitrogen and phosphorus because of their rate of mobility and the impact they can have on the environment and public health. Both of these nutrients are known to be essential for plant growth, therefore excess levels in surface waters will accelerate aquatic plant growth rate, reduce the amount of light entering the waterway and increase the likelihood for anoxic conditions. This can be very challenging for guardians of surface waterways, especially those used for recreational purposes.

Nitrogen

The nitrogen contained in septic tank effluent is typically in the form of 70–80 % ammonium ion (NH_4^+), while the remaining 10 to 30 % is in the organic form. OWTS, designed and operated in locations, that have favourable conditions such as soil, topography and climate, have the capacity to remove approximately 20 % of the nitrogen contained in the effluent

(Carroll, 2005; Siegrist et al., 2000a). Due to the anaerobic conditions present in the septic tank, organic-N is converted into ammonium-N ($\mathrm{NH_4^+} - N$). As the effluent percolates through the drainage area, the available bacteria within the soil, along with the aerobic conditions, enable the nitrification process to occur. This transforms the ammonium and organic-N into nitrite and nitrate as shown in equations 1-1 and 1-2 below (Carroll, 2005; Van Loosdrecht et al., 1998).

$$\mathrm{NH_4} + 1.5\mathrm{O_2} \rightarrow \mathrm{NO_2^-} + 2\mathrm{H^+} + \mathrm{H_20} \qquad (1\text{-}1)$$

$$\mathrm{NO_2^-} + 0.5\mathrm{O_2} \rightarrow \mathrm{NO_3^-} \qquad (1\text{-}2)$$

The oxidation of nitrites to nitrates occurs in the natural environment; as a result there is a low concentration of nitrites in surface and ground water. The oxidation process yields an abundance of nitrates and this poses a problem because although negatively charged, they are not adsorbed to soil particles and this makes it easier to reach surface and groundwater (Lamb et al., 2014). Further degradation of nitrates to nitrogen gas seldom takes place within the soil column because the anaerobic conditions that would aid this process are seldom present. If the effluent is used for irrigation purposes, and applied correctly, the likelihood of the nitrates being utilised intensifies because as the effluent moves through the upper layers of the soil, nitrates are taken up by vegetation and microorganisms as nutrients (Carroll, 2005; WHO, 2011). Due to the ease with which nitrates are able to move through the subsurface, they easily move into aquifers and gradually increase in concentration. Research has shown that if consumed in high concentrations nitrates can causes “blue baby syndrome” in bottle-fed infants. For this reason, the World Health Organisation has established that the maximum allowable value of concentration for intake should not exceed 50 mg/L (WHO, 2011). Being a major nutrient that supports plant growth, the abundance of nitrates in surface waters can also promote significant algae growth and other biological activities and this can impact the configuration of the aquatic food web (Smith et al., 2006).

Phosphorus

Phosphorus is viewed as one of the main contaminants of concern whenever OWTS are located in close proximity to surface water bodies, particularly because of its ability to encourage algae growth (Arnscheidt et al., 2007; Carpenter et al., 1998; Carroll, 2005; Jarvie et al., 2006;

Robertson et al., 1998). There is vast uncertainty associated with the mobility of this chemical element within the subsurface because it is highly reactive, adsorbs to most soil particles and combines with some metal cations. These soil particles are susceptible to erosion and subsequently transported to surface waters which makes phosphorus a cause for concern because nutrient enrichment promotes algal growth (Robertson et al., 1998). The digestion processes that occur within OWTS convert phosphorus into a more soluble form of orthophosphates. When present in this form, the ability to move in saturated soils and surface waterways increases (Carroll, 2005). Excessive concentrations of phosphorus in surface waters, particularly lakes, has been documented as the main contributing factor for eutrophication. This overenrichment in nutrients not only discolours the waters, but presents the necessary conditions to promote significant increases in the algae and cyanobacteria population that also leads to anoxic conditions. Depleted oxygen levels in surface waters are of great concern because this can result in fish kills and other disturbances in the aquatic ecosystems (Correll, 1998).

1.4.3. Parameter # 3 – microorganisms

There is a wide range of microorganisms present in wastewaters. These include bacteria, fungi, protozoa, rotifers, algae and viruses. The presence and life span of these microorganisms depend heavily on environmental conditions such as temperature and pH. Bacteria constitute the largest percentage of these microorganisms due to their presence in most habitats and all living bodies. They also play a significant role in the biological treatment of wastewaters. Many types of bacteria are harmless and found in abundance in the excretory system of humans; however, some bacteria are of particular interest because they are pathogenic in origin and capable of infecting humans, causing diseases within the gastrointestinal tract. Other types of pathogenic microorganisms found in wastewater are viruses, protozoa and helminths. These are all known to be highly infectious, therefore extreme caution should be taken to contain septic tank effluent (AS/NZS 1547:2012; Crites et al., 1998; Maine Center for Disease Control and Prevention, 2013). Research by Gerba et al. (1975), Viraraghavan et al. (1978) and Stevik et al. (2004) has shown that pathogenic microorganisms can travel extensive distances and potentially cause microbial contamination of surface and groundwater. There have been several outbreaks of waterborne diseases in countries around the world, that have been a result of septic tank effluent contaminating potable water supply wells (Maine Center for Disease Control and Prevention, 2013; Stevik et al., 2004). Research by Kurup et al. (2010) revealed high levels of microorganism in potable water supply taken from sampling points in Guyana’s capital.

Althouugh there is no evidence to link this contamiantion to septic tank effluent, this still remains a cause for concern.

1.4.4. Parameter # 4 – contaminants of emerging concern (CEC)

Several studies have documented failing OWTS as the primary source of contaminants of emerging concern found in surface and groundwater (Carrara et al., 2008; Godfrey et al., 2007; Holloway, 2010; Larsen et al., 2004; Schaider et al., 2010; Singh et al., 2010; Swartz et al., 2006). These contaminants are mainly the result of pharmaceuticals and personal care products (PPCPs) used within the dwelling. The release of these contaminants into the environment is alarming since the ability of OWTS to reduce an endocrine-active substance to tolerable levels has not been established (Stanford et al., 2010). Although analytical techniques allows minute detection of these compounds, their impacts on humans and the environment have not been well researched (G. Heufelder, 2012). Convincing evidence has shown that many pharmaceuticals and chemical compounds have endocrine disruption functions, capable of causing negative developmental effects, particularly in the hormonal structure of animals and humans (Kasprzyk-Hordern et al., 2008). The most common of these effects are decreased fertility and abnormal thyroid function in birds and fish. The most detrimental health defect discovered in fish exposed to endocrine–disrupting chemicals is the defeminisation and masculinisation of the females. Likewise, birds feeding on fish with these defects have shown numerous abnormalities. Among these is the significant reduction in their rate of reproduction and the premature death of their young (Bound et al., 2005; Colborn et al., 1993). Godfrey et al. (2004) conducted experiments on septic tank effluent in some areas of the United States and reported high levels of pharmaceuticals. They further advocated that failing OWTS could create a potential source of pharmaceutical contamination of underlying aquifers especially in areas that have predominantly sandy soils and where the unsaturated layer is less than two metres thick. This alarming discovery has made forecasting of failure in OWTSs to be, potentially of significant importance.

1.5. Categories of OWTS

A large number of diverse designs for OWTS are used around the world, however, Crites and Tchobanoglous (1998), reported four main categories of OWTS:

1. conventional on-site system
2. alternative on-site system
3. modified conventional on-site system
4. on-site system with additional treatment

1.5.1. Conventional on-site systems

The most popular of the four is the conventional on-site system which includes a septic tank and a drain field. Most of the systems in use presently around the world are of this category, however, throughout the years modifications such as elevated drain fields and holding tanks for the discharged effluent have been introduced into older designs. This category will be discussed further in section 1.6.

1.5.2. Alternative on-site systems

Alternative on-site systems incorporate the use of elevated sand mounds, evapotranspiration systems, constructed wetlands and drip dispersal systems. Alternative designs have increased over the years particularly in the older system because although some may have excellent hydraulic and disposal capabilities, they fail to adequately attenuate the contaminants of concern to acceptable levels (Joubert et al., 2005). In some areas, alternative on-site systems such as constructed wetlands are used because of their outstanding phosphorus removal capabilities (Siegrist et al., 2000a; Westholm, 2006). Some alternative designs incorporate the use of elevated sand mounds, evapotranspiration systems, constructed wetlands and drip dispersal systems; however, the most common of these is the constructed wetland (Crites et al., 1998).

1.5.3. Modified conventional on-site systems

Several modifications can be made to the typical, conventional on-site system to improve the quality of the final effluent. These modifications are usually constrained because of the unavailability of adequate land area. One of the most common adjustments made to these systems is to design the septic tank with an additional pressure-dosed system and shallow, elevated trench for effluent discharge. This form of design is used mainly in areas where there is a high water table and treatment of the effluent has to be undertaken in a field located up-gradient of the discharge outlet. It usually requires the use of additional land area (Crites et al., 1998). Panswad et al. (1997) and Sabry (2010) also demonstrated that other modifications to the septic tank, such as air intrusion and including additional baffle walls may also produce better quality effluent.

1.5.4. On-site systems with additional treatment

These systems are used when additional treatment is needed before the effluent is discharged into the environment. The most commonly used mechanism to achieve this additional treatment is the use of low-rate packed bed filters. These are two types: the intermittent single-pass system and the recirculating multipass system. In the single-pass system the effluent is dosed through a packed granular bed once before dispersal, whereas in the multipass, there is repeated circulation of the effluent through the granular filters before discharge. After the initial circulation of one dosage through the filters, a small percentage of the effluent is discharged, while a significant percentage of the effluent is returned to the septic tank for further recirculation. In some instances, if the design includes an intermediate storage area between the septic tank and the bed filters, the effluent may also be reintroduced at this section (Crites et al., 1998; Leverenz et al., 2002)

1.6. Conventional on-site wastewater treatment system (COWTS) design

Conventional on-site systems include three main components: a pre-treatment unit (septic tank), an effluent delivery system (pipes and distribution chamber) and a drain field. The wastewater generated by the dwelling is transported by distribution pipes to the septic tank, distribution chamber and finally to the drain field for final treatment. Generally, the movement of the wastewater is facilitated by gravity; however, in areas where the site conditions do not allow this, a pump is used. All three components are essential for the system to function adequately (Reneau Jr et al., 1998). A schematic of this system is shown in Figure 1-1 below.

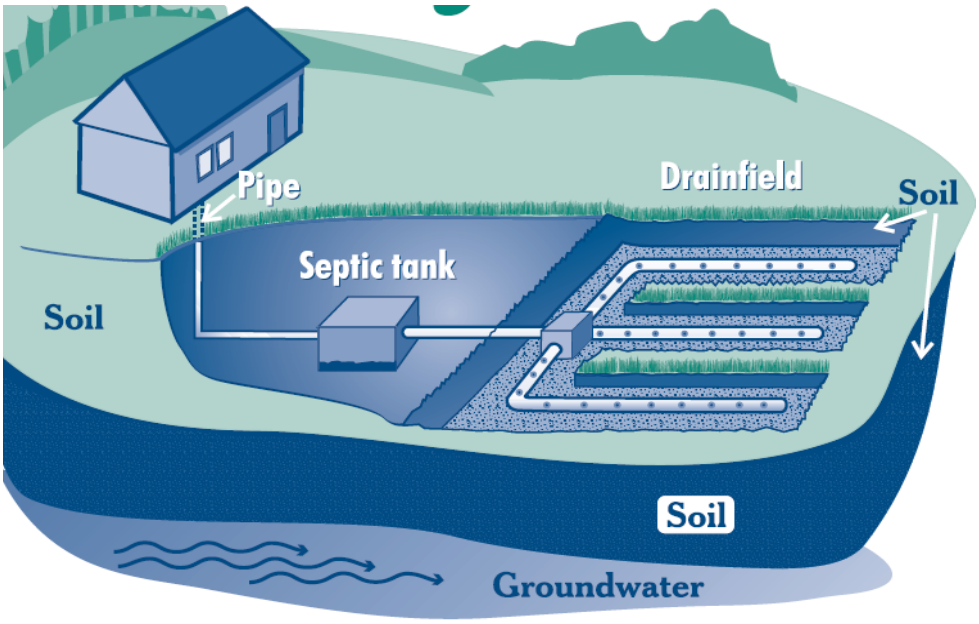

Figure 1-1 Layout of a COWTS (USEPA, 2002b)

Septic tank design

The most common material used for constructing septic tanks is concrete; however, high-density polyethylene (HDPE) or fibreglass are often used in areas impassable for the transport of concrete tanks. Constructed with a 2:1 length-to-width ratio, concrete tanks are usually rectangular, while fibreglass and plastic are typically cylindrical. Some designs include internal walls, referred to as baffle, which partition the tank into separate chambers and optimises the retention of solids. In addition to the tank, the three most important components in designing a septic tank are the inlet tee, the outlet tee and the manhole. The correct placement of the inlet and outlet tees minimises the amount of solids exiting the tank (Howard, 2003). A typical single chamber septic tank is shown in Figure 1-2 below.

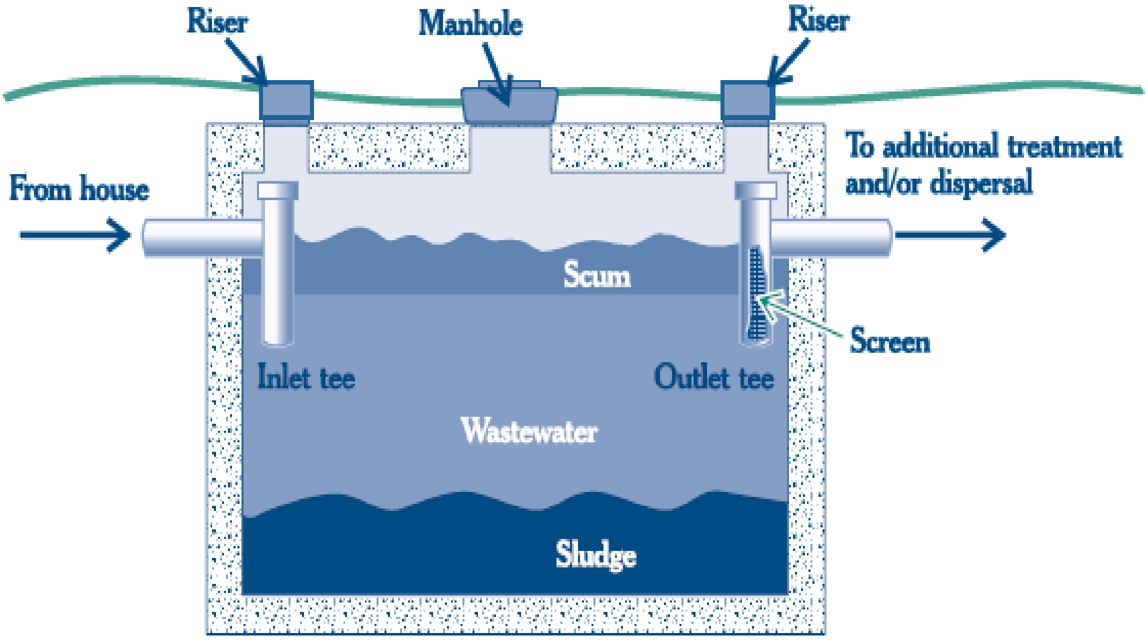

Figure 1-2 Profile of a single compartment septic tank with outlet screen (USEPA, 2002b)

Canter et al. (1984) and Hughes (1993) outlined that COWTS have many advantages over reticulated systems, including:

- the initial cost for the installation of septic tank systems is less than the installation of a reticulated sewage system for small populations
- the level of maintenance required is less when compared to reticulated systems
- it is possible to have long term operation without the components failing, because of the low technology involved
- low energy required for operation

Some disadvantages of COWTS highlighted by Lesikar (1999) and Joubert et al. (2005) are:

- septic tanks are likely to leak if incorrectly installed
- regular inspection and maintenance is required by the dwelling occupant

Adequate sizing of the septic tank is very important, since sufficient volume supports adequate hydraulic residence time. The United States Environmental Protection Agency stipulates that a minimum of 6 to 24 hours residence is best for sufficient sedimentation to occur. The determination for the capacity of the tank is based on the volume of wastewater to be treated, and is usually estimated by the numbers of bedrooms in the dwelling. Several countries have adapted this relationship for the development of design codes and standards.

Similar to many other design standards used around the world, in New Zealand the AS/NZS 1547:2012 stipulates that domestic wastewaters are classified as one of three types:

1. blackwater
2. greywater
3. all-wastewaters

Based on these classifications, the minimum capacities established (based on a settling volume for tanks) are: 200L per person for all-waste tanks, 60 L per person for blackwater tanks, 120 L per person for greywater tanks. Appendix *A* shows the tank capacities adopted by the AS/NZS 1547:2012 for all-wastewaters, greywaters, and blackwaters to be used for designing systems in New Zealand.

1.6.1. Treatment processes in the COWTS

In the COWTS, treatment occurs in two stages. In the first stage, the wastewater entering the septic tank is retained for a period known as the "retention period". This period is crucial, since adequate time must be allowed for sedimentation and anaerobic decomposition to take place. These processes result in an increase in thickness of the sludge and scum layers and are largely dependent on the quantity and strength of the wastewater entering the tank, along with the tank's hydraulic retention time (Brandes, 1978). The organic matter retained at the bottom of the tank further undergoes decomposition, in which the resulting products are gaseous compounds such as carbon dioxide, methane and hydrogen sulphide (Chernicharo, 2007). Although the anaerobic decomposition minimally reduces the volume of deposited, because of the continuous use of the tank, the rate of accumulation is usually greater than the reduction and this results in a net accumulation of sludge.

Favourable environmental conditions such as pH and temperature within the tank are also essential to encourage bacterial growth so that the biological treatment process may commence. The retention period also facilitates the conditions necessary in the tank to enable the sludge and scum formation.

The scum layer that is located on the surface of the effluent contains the buoyant particles. It is usually composed of organic, inorganic and gaseous particles along with all the other low density materials that may have entered the tank (USEPA, 2002). Similarly to the sludge layer, this layer also increases over a period of time. The net accumulation in thickness of these layers reduces the effective volume available to allow for adequate settling to occur. The production of clarified effluent is influenced mainly by tank depth and retention time (Barshied et al., 1974; Canter et al., 1984). Thicknesses of these layers are very important because as they increase, the hydraulic residence time decreases, which further results in a reduction of the biological treatment process. Whenever this occurs, the possibility of poorly treated effluent entering the drain field to cause clogging intensifies; however, because septic tanks are a confined apparatus – often totally or partially buried – information pertaining to the thickness of these layers is only available through manual inspection. This has resulted in failures caused mainly as a result of user negligence, as outlined by Butler and Payne (1995) and can ultimately shorten the operational life of the tank (Nnaji et al., 2011).

In the second stage of treatment, clarified effluent discharged from the septic tank enters the drainage area where it percolates through the soil media. As it moves through this body of soil, further attenuation of the constituents of concern occurs, mainly by filtration, transformation, adsorption and another process referred to as die-off, where the microorganisms become inactive.

In addition, at the interface of the distribution conduits, which are usually perforated pipes, and the upper layer of soil, a clogging layer known as the biomat is formed. This layer comprises mainly of organic matter accumulated over time, and microorganisms (Tomaras et al., 2009). This layer reduces the permeability and aids in a uniform distribution of the effluent. This form of induced clogging also enhances sorption, biogeochemical and die-off/inactivation processes and further aids in promoting unsaturated flow conditions in the underlying layers (Van Cuyk et al., 2001). An extensive clogging mat can entirely block the pores and lead to hydraulic failure of the system.

The soil type and depth of the groundwater table are major factors that influence the size and configuration of this area since the level of treatment the effluent receives is directly related to these parameters. Although several modifications have been made by designers to enhance this stage of the treatment process for such systems, failures such as effluent ponding and leaching to adjacent waterways continue to occur in some areas. For this reason, a proper understanding of both stages is important because failure at either stage can cause an environmental catastrophe (Crites et al., 1998; Galbraith et al., 2015; Neralla et al., 2000).

In addition to settlement and solids separation by gravity and flotation, complex chemical substances are also broken down in the absence of oxygen, while releasing mineralised nutrients from the wastewater within the septic tank (Tanner et al., 2012). The level of clarification the wastewater receives is influenced primarily by the duration of the retention time and the availability of microorganisms to consume the organic materials present. Quiescent conditions in the septic tank and extensive residence times facilitates better sedimentation. These longer times also allow suspended and settled organic matter to undergo further anaerobic decomposition forming finer particles. The production of gases, notably methane, carbon dioxide and hydrogen sulphide are other by-products resulting from the reactions that occur during the operation of the septic tank. For this reason, it is recommended that septic tanks be designed with air vents to allow the release of these gases (Butler et al., 1995; Chernicharo, 2007; Howard, 2003; Maine Center for Disease Control and Prevention, 2013). Two other notable by-products of the operation of a septic tank, are the sludge and scum layers. The accumulation rate and amount of sludge and scum often exceed the rate of decomposition, therefore periodic removal of these layers are necessary to maintain the effective volume of a tank. The primary reason for the removal of these layers is that as they increase, the detention time decreases (Butler et al., 1995; Howard, 2003). Gardner et al. (1997), Eliasson (2004) and USEPA (2009) reported that wastewater within a properly functioning septic tank with adequate hydraulic residence time and favourable environmental conditions such as pH and temperature, may result in approximately 50 % removal of biochemical oxygen demand (BOD_5), 75 % removal of suspended solids, 10 % removal of total nitrogen and 15 % removal of total phosphorus.

Drain field operation and design

Partially treated effluent discharged from the septic tank is further treated by the soil in the "soakaway" area, also referred to as the "drain field" or "soil absorption field". In this area, as the effluent percolates through the unsaturated layer of soil, biological stabilisation and pathogen removal take place mainly by adsorption and filtration (Ahmed et al., 2005; Butler et al., 1995; P. J. A. Withers et al., 2011).

Effluent discharged from the septic tank contains microorganisms such as bacteria and viruses along with nutrients, and if not adequately attenuated these may be transported to contaminate nearby surface or groundwater. The potential for contamination is highly influenced by the soil type and depth of groundwater (Gerba et al., 2005). A reduction in the concentration of these microorganisms and nutrients is thought to happen at each stage of the four-component transport process: the septic tank, the disposal field, the unsaturated zone and the groundwater layer (Moore et al., 2010). Figure 1-3 below depicts the transportation process for contaminants in typical septic tank effluent.

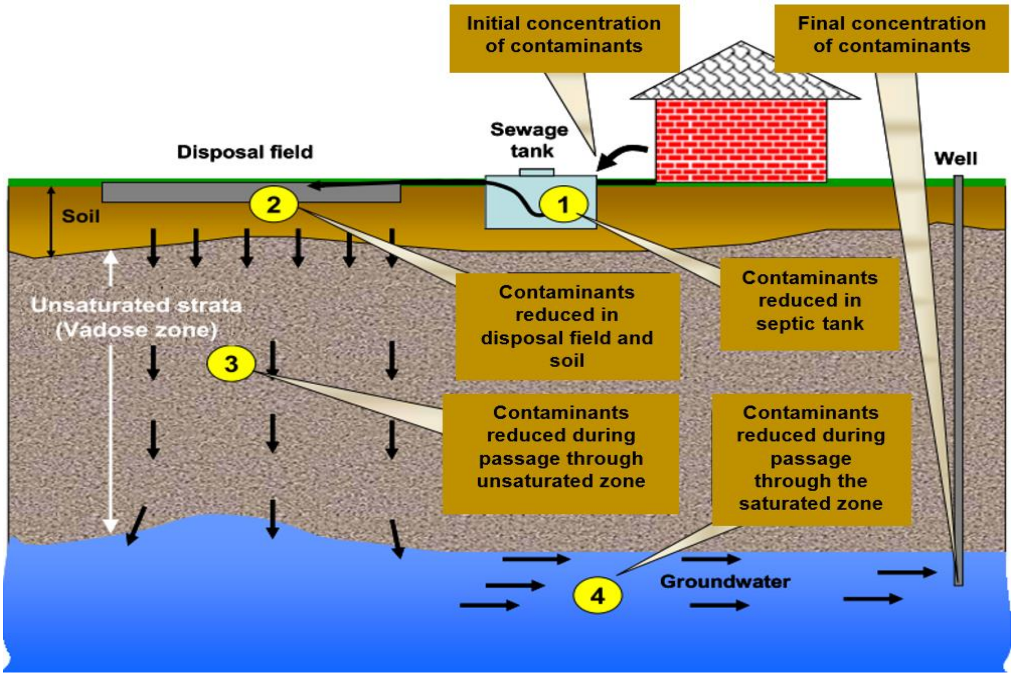

Figure 1-3 Stages of contaminants removal between disposal and abstraction point (Moore et al., 2010)

The depth of underlying strata below the drainage area is very important since this region acts as the final level of treatment the effluent receives before it recharges groundwater, whenever present. One important feature in designing a drain field for COWTS is to maintain an adequate distance between the bottom of the drain field and the groundwater table so that unsaturated flow conditions can be maintained at all times (Brown, 1998). Treatment of the effluent is dependent mainly on the infiltrative surface characteristics, the soil's hydraulic conductivity, and the depth of the unsaturated zone. The treatment processes that occurs within this zone are filtration, adsorption, sedimentation, and inactivation of the contaminants, therefore the thickness of the unsaturated layer is very importance. The depth of the unsaturated zone affects the hydraulic and purification functions of a system (Bremer et al., 2012). Generally, the infiltrative surface is usually 150 to 300 mm thick and located below the existing ground level. Factors such as the soil moisture content, hydraulic conductivity, aeration and surface area in contact with the effluent are also directly related to how effectively these functions can be performed (Van Cuyk et al., 2001). These systems are sized based on the design loading rates of soil, which is determined from the on-site soil characteristics. In the absence of such information, known values are assigned from published guidelines or design codes. These values are assigned depending on the soil category. For example, typical values for sandy loams are within the range of 20 to 30 mm/d. Based on these values, it is expected that the discharged effluent will be adequately attenuated within the confines of the property. In areas where there are low permeability soils, alternative designs such as evapotranspiration-absorption (ETA) trenches should be considered since these systems rely mostly on evapotranspiration for effluent quality reduction, rather than absorption, because percolation through low permeable soils will be very slow and this results in very low effluent infiltration rates. With an ETA design, effluent uptake will be supported by evapotranspiration of the vegetation within the topsoil. This type of design also promotes aeration of the soil because there is usually an increase in the rate at which the moisture in the soil is reduced. This further aids the biological treatment process by reducing the number of microorganisms (AS/NZS 1547:2012). Figure 1-4 below shows a typical cross section of an ETA bed. Trenches have the designed with the same configuration but are shorter in with.

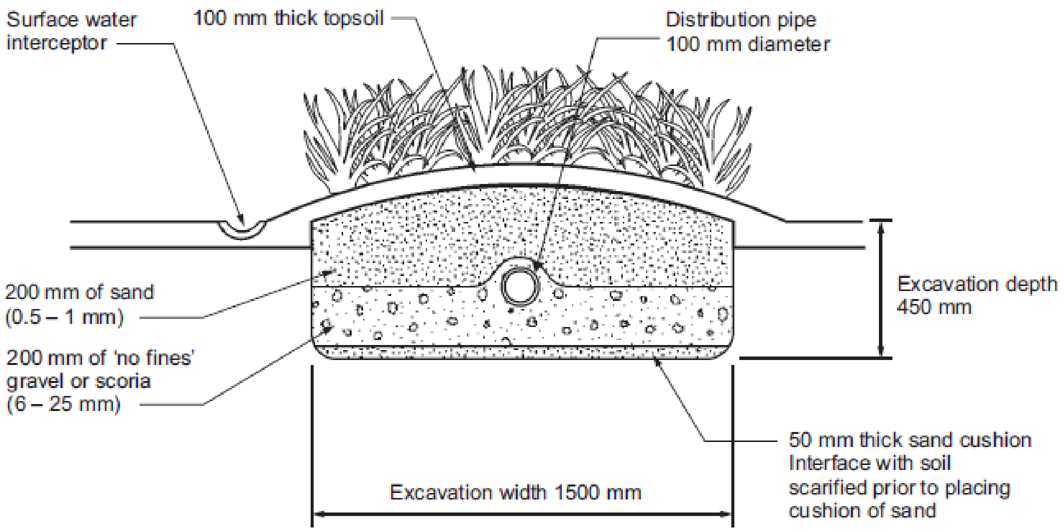

Figure 1-4 Cross section of a typical ETA (AS/NZS 1547:2012)

In locations where the land surface has a shallow gradient and the site exhibits unfavourable properties, an alternative design such as a mound system may be used. These systems are constructed with the drain field elevated above the natural soil surface, creating an increased thickness of the unsaturated layer. Due to the difference in elevation, pumps are required to distribute the effluent to the drainage area. This can be a disadvantage because during power failures treatment will not occur. Other site and soil restrictions that require mound designs are high-groundwater tables, poorly drained soils, and areas that have a thin, permeable layer of soil overlaying a less permeable layer, such as rock or hardpan (AS/NZS 1547:2012; Hygnstrom et al., 2002). An example of a mound system is shown in Figure 1-5 below.

Figure 1-5 An example of a mound system at Ladbrooks School, Ladbrooks, Canterbury, New Zealand.

Importance of maintaining unsaturated flow

Maintaining unsaturated conditions in the underlying layer is very important since these conditions reduce the rate at which the contaminants travel through the soil. As the effluent flow velocity decreases, the residence time of the effluent interaction with the soil particles increases, and this further increases the potential for the main contaminants of concern to be reduced primarily through biodegradation, sorption, filtration, chemical precipitation and natural die-off. Additionally, unsaturated conditions increase the likelihood for aerated conditions. This is very important since aerobic conditions aid in the conversion of nutrients, particularly nitrogen in the form of ammonium-nitrogen to nitrate, in which form, it is easily taken up by plants but can also be easily leached out. Unsaturated conditions also increase the potential for the phosphate ions to interact with the soil particles. These interactions enhance the mechanisms of adsorption, precipitation and plant uptake to occur and reduces the transport to groundwater (Brown, 1998).

The potential for a number of microorganisms to decrease also increases with unsaturated conditions. A moisture-deficient environment is important because the availability of pore spaces increases the likelihood of bacteria becoming inactive as the effluent moves through the soil. In these conditions, the soil acts as a filter and removes these single-cell organisms. Although viruses are smaller than bacteria, they are also removed by filtration during unsaturated flow conditions (Brown, 1998; Howard, 2003; Whitehead et al., 1999)

Many contaminants of emerging concern found in septic tank effluent are also removed during unsaturated flow below a drain field (Montana Environmental Health Association, 2016). Heufelder et al. (2014) reported that drain fields demonstrated higher removal efficiencies for these compounds when compared with wetlands. They further noted that a comprehensive understanding of the mechanisms involved in the removal of these contaminants as the effluent passes through the soil is not fully understood, mainly due to the scarcity of data in this area of study (Du et al., 2014).

1.7. Failures of OWTS

The performance of any OWTS involves its hydraulic and purification functions and their connections. If a system can adequately process its wastewater without causing any blockage in the dwelling, without ponding or surfacing of effluent, in addition to reducing the concentration of the main contaminants of concern at the point of assessment, and without threatening the receiving environment, the system can be considered an adequately operative system (Siegrist et al., 2000a; Watts et al., 2005).

AS/NZS 1547:2012 stipulates that the key performance objectives for any OWTS are:

- to protect public health;
- to maintain and enhance the quality of the environment;
- to maintain and enhance community amenity; and
- to protect resources.

Whenever an OWTS fails, nutrients and pathogens are released into the environment, which may result in serious public health and environmental consequences (Gunady et al., 2015). MfE (2008) "Proposed National Environmental Standard for On-Site Wastewater Systems", reported that a significant number of OWTS are not providing adequate levels of treatment to domestic wastewaters, which has resulted in deleterious effects on the environment and potential risks to human health. MfE further noted that the overflow and ponding of effluent presents a situation that allows direct contact with humans and the contamination of surface and groundwater. Gunady et al. (2015) reported that failure of most OWTS is not due to innate imperfections in system technology, but rather to inappropriate siting and construction, or their operation and management.

1.8. Impacts of failing OWTS

1.8.1. Public health impacts

Failing OWTS increases the risk of septic tank effluent entering surface and groundwater. USEPA (2002) in "Onsite wastewater treatment systems manual", emphasised that nitrogen and microbial pathogenic organisms are the main contaminants associated with groundwater contamination from these systems. Prolonged exposure to nitrate in humans results in biological effects that stimulate the oxidation of normal haemoglobin in the blood to methemoglobin, which diminishes the transport of oxygen. This has been shown to result in a medical disorder termed methaemoglobinemia (blue baby syndrome) and other illnesses such as cyanosis, and even asphyxia when exposed to higher concentrations. Some studies have also linked nitrate or nitrite intake to a potential escalation in the risks of cancer, along with other adverse reproductive effects (Gill et al., 2009; Shuval et al., 1972; WHO, 2011).

Pathogenic microorganisms such as campylobacter and cryptosporidium contained in poorly treated effluent from failing OWTS have the potential to contaminate drinking and recreational waters and pose serious health problems. Ingestion of water contaminated with this bacteria can cause gastrointestinal infections (WHO, 2003).Other microorganisms such as salmonella typhi and hepatitis A virus may also increase the risk of diseases such as typhoid fever and infectious hepatitis (Crites et al., 1998; Gunady et al., 2015). These risks intensify whenever there are system failure and high rainfall events because their ability to be transported increases (Carroll & Goonetilleke, 2005)

1.8.2. Environmental impacts

The two main nutrients – nitrates and phosphates – present in septic tank effluent have been shown to be the major cause for eutrophication in surface water. Although they have different rates of mobility, whenever both nutrients are present in abundance their potential to have a negative impact intensifies. Excessive nutrients are a major concern because they stimulate the rapid growth of macrophytes and enhance the production of autotrophs such as algae and cyanobacteria (Correll, 1998). Although macrophytes play a major role in the productivity and biogeochemical processes in freshwater ecosystems, when present in excess, they can cause a water body to lose its aesthetic values (Carpenter et al., 1986; Thomaz et al., 2010). Nutrient enrichment from failing OWTS intensifies the productivity of cyanobacteria mats. This high-bacteria population depletes the water body of dissolved oxygen, creating anoxic conditions and further threatening the survival of aquatic organisms (Arnscheidt et al., 2007; Carpenter et al., 1998; Correll, 1998; Jarvie et al., 2008; Palmer-Felgate et al., 2010). Effluent ponding on the surface of the drainage area, which may have resulted from a failing OWTS is known to emit unpleasant odours and provide ideal conditions for the reproduction of mosquitoes and flies.

1.9. Maintenance of OWTS

For the successful maintenance of any OWTS, all parties involved must have an understanding of the necessary procedures that should be followed for these systems to function effectively. For this reason, owners should be knowledgeable about the routine maintenance requirements for optimising performance so that adequate levels of wastewater treatment can be achieved. A stringent maintenance schedule must be employed to ensure that these systems are functioning as intended by outlining visual, physical, chemical and microbiological parameters that should be monitored (Howard, 2003). Some of the benefits associated with this form of monitoring are an extended lifespan for the system, reduced likelihood for system failure to occur, the potential for adverse effects on the environment and public health are minimised, and the cost associated with repairs to system components resulting from neglect are reduced (AS/NZS 1547:2012; Auckland Regional Council, 2004).

Emphasis should also be placed on the types, amount, and frequency of use of household products, such as antibacterial products and detergents used within the dwelling, since these substances can have a direct impact on the pH of the wastewater. Excessive use of these substances may cause the pH to fluctuate and this will have a direct effect on the growth and survival of the microorganisms. Maintaining a stable environment so that adequate amounts of bacteria are present in the septic tank is very important since microorganisms, predominantly bacteria, are responsible for metabolising the organic matter present. A reduced bacterial population will affect the performance of the septic tank and this will further affect treatment in the drain field because effluent that contains high organic matter will intensify clogging in the upper layer. Reduced levels of bacteria may also increase the likelihood for obnoxious odours to be emitted from the system (Crites et al., 1998; Maine Center for Disease Control and Prevention, 2013; Roberts, 2016; Wellington Regional Council, 2000).

Systems should be inspected to determine if there are any deficiencies in the structure and also to establish the sludge and scum accumulation rate. By doing so, early signs of leaks can be detected and decisions on whether the desludging frequency needs to be adjusted can be determined. Design codes, maintenance manuals, and management guidelines have outlined that pump out should be conducted every three to five years; however, conditions such as frequency of use, and number of occupants within the dwelling can impact the sludge and scum accumulation rates in the septic tank and this can have an influence on the performance of a system. In addition, regular inspections of the depth of the groundwater level below the drain field must be conducted, since natural processes such as climate variability may influence the seasonal variations of the groundwater table. Early detection of any drop in this level, to a value lower than the recommended stipulated depth for adequately treating the effluent, can indicate the potential for ground or surface water contamination (Gurdak et al., 2009; Howard, 2003; Kumar, 2012).

1.10. Some existing management models and frameworks

Current risk-based models such as Trench 3.0^{TM} developed by Cromer (1999) and On-site Sewage Risk Assessment System (OSRAS) developed by Hillier et al. (2001) are used to assess site suitability and for evaluating the risks associated with OWTS on the surrounding and downstream environments. According to Carroll (2005), these and other models are able to provide creditable results, but some major deficiencies are that (a) they are largely dependent on the volume and type of data accessible to the user, and (b) they are unable to accurately highlight risk levels in areas containing existing OWTS. This causes a huge deficiency because the ability to properly highlight the cumulative risks associated with a collection of OWTS located within close proximity of each other cannot be accurately forecasted. This uncertainty in highlighting these potential risks led to the development of management frameworks such as the "Site Evaluation, Design and Engineering of On-site Technologies Within a Management Context" developed by Hoover (1998), and site suitability alternatives decision support systems such as SANEX^{TM} developed by Loetscher et al. (2002). Carroll (2005) noted that most of these models and frameworks are very sophisticated and lack the required flexibility in assessing the overall risk associated with an OWTS at a particular location.

1.11. Summary of literature and need for this research

The reviewed literature has shown the impact that poorly treated effluent from failing OWTS can have on the environment and public health, mainly through the contamination of surface and groundwater resources. Although there are systems that have been in use for decades and good design and management practices should be inseparable, very often this does not occur. In addition, many of these systems are privately owned. Property owners or dwelling occupants have the responsibility of maintaining these systems, but very often this is neglected. Such negligence increases the likelihood of failure, and whenever a system fails, the potential for contaminants entering surface and groundwater increases.

During the operational life of these systems, there are certain changes that occur within the septic tank and the surrounding environment, and these changes can have a negative effect on how these systems function. By recognising these changes and monitoring their variation, it will be possible to establish if a system is at a high risk of failing. Available resources in the form of models and frameworks enable some control measures to be established, but Carroll (2005) outlined that these are very complex.

This research is geared towards identifying modes of failure for OWTSs and parameters that may signal irregularities in a performance of a system. These will be combined to create a monitoring tool that is less complexed than the existing models and frameworks. In developing such tool, the identification of failures can be achieved before they become disastrous. This tool will be applied to a case study area to demonstrate its effectiveness.

CHAPTER 2 RESEARCH AIM, OBJECTIVES AND METHODLOGY

Failing to effectively detect OWTSs that are performing below the required standard can result in devastating impacts on the environment and on public health. Research has shown that one of the leading causes of surface and groundwater contamination around the world is from failing OWTSs. Existing management models and frameworks provide information that can assist in managing these systems; however, Carroll (2005) outlined that these existing tools have several major deficiencies. Identifying the modes of failure, and using a management tool that combines failure indicators and intensifying parameters has been selected as an effective form of managing these systems.

This tool will allow regulatory authorities to detect areas within a community where a failing system or groups of systems are located. This can be achieved by incorporating the information with available catchment data such as property addresses, location of surface waterways, location of schools and of play parks, and using ArcGIS software to display a geographic representation of the systems that are most likely to fail.

2.1. Aim

This research aims to identify modes of failure for OWTS and to establish indicators that signal irregularities in the performance of a system before complete failure occurs. The development of indicators will allow gradual changes occurring in a system to be detected before they become uncontrollable. These indicators will be used in conjunction with parameters that may increase the intensity of a failure. The two will be combined to develop a management methodology that will give all stakeholders with responsibilities for managing COWTS an idea of the potential risks associated with a particular mode of failure and the level of impact this failure may have on a particular area.

2.2. Objectives

The following are the main objectives of this research:

1. to determine the major modes of failure for COWTS
2. to determine what indicators change before total failure occurs
3. To identify what parameters may intensify failure whenever they occur
4. to develop a management tool that COWTS stakeholders can use to detect failures before they become uncontrollable
5. to apply this tool to Darfield Township in New Zealand as a case study.

2.3. Methodology

2.3.1. Approach

In order to achieve the objectives outlined above, the following steps were undertaken:

- a thorough literature review of the design specifications and operating procedures to be followed when constructing a COWTS, and the major modes of failure which are often experienced by these systems
- an examination of the indicators that can be measured to evaluate the performance of a system during its operational life, along with the parameters that may intensify failure whenever they occur (used to develop a management tool)
- visit sites around Canterbury, to have an assessment of COWTS and to observe some of the modifications made by designers to meet the relevant site conditions

2.3.2. Investigating the different modes of failure (objective 1)

In addition to reviewing literature relating to the different modes of failure, discussions were held with practising professionals within the field in Canterbury to identify which modes are most frequently occurring. Site visits were also conducted around Canterbury to have direct observations of the different modes of failure and how they vary, depending on the differing site conditions. These observed failures were compared with published modes to distinguish whether there were any similarities.

2.3.3. Development of failure indicators (objective 2)

Failure indicators (FIs) can provide pertinent information in evaluating the effectiveness and efficiency of a system by providing both quantitative and qualitative assessment. Additionally, they can provide crucial information that can facilitate a more pre-emptive approach to management, rather than reacting to system failures (Matos et al., 2003). Deficiencies and uncertainties in assessing the performance capabilities of any COWTS can create high risk situations and potentially threaten the receiving environment; therefore the establishment of FIs and effective monitoring is essential (Siegrist et al., 2000a). This was accomplished by examining literature relating to the main contaminants of concern contained in domestic wastewaters, the different treatment processes in COWTSs and the conditions that are necessary to safeguard the environment and public health. Collectively these were assigned values based on the information provided in the literature and instances where there was no information, an estimation was used.

2.3.4. Identifying intensifying parameters (objective 3)

Factors that will intensify the magnitude of a particular type of failure were examined since the potential for a failure to inflate can be determined by these factors. This was achieved by examining the factors specified in the literature and assigned weights. Examples of these include a system's proximity to a school, play park, nature resort and recreational waterway. The failure indicators and intensifying parameters were combined to develop a management tool to assess the risk of a particular system failing.

2.3.5. Creating a management tool (objective 4)

The management tool was developed in the form of a model with the desired outcome to be in two phases. The first phase aids in forecasting the dwellings that will present the highest risk if they fail. This enables regulatory authorities to be aware of the locations that monitoring is required. The second phase, referred to as the analysis phase, shows the areas that will have the greatest impact is failure should occur. To achieve these outcomes the user is required to input the values obtained from the failure indictors, along with the possible intensifying parameters for that particular system, based on its location. The model produces a risk score as its output and this score is categorised within a failure range of either low, medium or high failure. Examples of the possible failure types that are likely to occur within these ranges are also presented.

2.3.6. Darfield as a case study (objective 5)

Located in the South Island of New Zealand in the Selwyn District at latitude 43.5º S and longitude 172.1º E, Darfield is the main town between Christchurch and the West Coast (Selwyn District Council, 2016). See Figure 2-1 below. With a recorded population growth of 15.8 % between 2006 and 2013 and a population currently of 1935 (Statistics New Zealand, 2013), this makes it the largest town in New Zealand without a reticulated wastewater treatment system (Burbery, 2014). Residents of this area rely on OWTS for the disposal of their wastewaters.

Waste management and the provision of a potable water supply in Darfield is undertaken by the Selwyn District Council; however, because this area overlies the unconfined alluvial gravel aquifer that lies beneath the central Canterbury Plains, from which Darfield and the surrounding areas drinking water supply is extracted, it is imperative that OWTS function appropriately to avoid potential contamination of the aquifer and surface waters (Burbery, 2014; Mulrine, 2014). Data retrieved from the Koordinates database (Koordinates database, 2015) showed that there are 1308 houses located in the study area. The tool developed was applied to this area using values obtained from the literature and instances where information was unavailable, realistic values were substituted for the failure indicators and intensifying parameters. The properties that have the highest impact potential and the locations that have the highest risk of failing are presented using an ArcGIS map displaying the geographical representation of these locations. Figure 2-1 below shows the location of the study area.

Figure 2-1 Map showing case study area

2.4. Summary

An overview of the methodology and the approach for achieving the objectives has been presented in this section. A description of the area that will be used for the application of the monitoring methodology was also presented. Reference was also made about the failure modes and the failure indicators. These terms will be further developed in the following chapters.

CHAPTER 3 OWTS FAILURE MODES

This chapter is centred on the literature pertaining to the modes of failure and some examples that are likely to occur at these respective modes. Information pertaining to this area of research was limited and those instances where information was available, the results were disjointed. There was no cohesiveness in the information presented in the literature; hence the need for this research. In this section the emphasis is placed on identifying the available information and identify existing gaps where additional work needs to be undertaken.

Rausand et al. (1996) outlined that failure is an event that occurs whenever a required function is compromised within a system. AS/NZS 1547:2012 defines OWTS failure as "unsatisfactory performance of a system which may cause an undesirable and unfavourable impact on the environment or public health." Dakers et al. (2009) have categorised on-lot failures for OWTS into four comprehensive modes:

1. design failures
2. technical failures
3. management failures; and
4. compliance failure.

Several examples for failure modes are presented in the literature but a substantial amount of information was focused on the design, technical and compliance modes. The instances where management failure modes are referenced, the most common example referred to was "failing to pump out the septic tanks" at the stipulated time so that the required residence time for the wastewater can be maintained. The USEPA (2002) and AS/NZS 1547:2012 recommends that this should occur once every three to five years to reduce the risk of hydraulic failure and in areas where systems are managed by a stringent monitoring programme, desludging or pump out cycles should be determined from monitoring inspections and installed alarm devices. There is a need for more research to demonstrate that other factors, such as intensity of use and the number of persons within the dwelling, can reduce the times between pump out in the schedule. Bremer and Hater (2012) noted that older, and poorly maintained systems, are more likely to experience deficiencies in the conditions that support proper effluent treatment. Another distinct absence from this category found in the literature was the absence of extensive research showing that a significant number of dwelling occupants having limited knowledge of OWTS operating procedures.

3.1. Examples of design failures

Poor siting

The amount of treatment the septic tank effluent receives is largely dependent on the topography of the land and the volume of unsaturated soil below the soil treatment area, therefore choosing the best location for the system is very important. Poor siting may eventually cause failure, for example, systems that are sited in locations with severe depressions will increase precipitation run-off and encourage flooding. This will reduce the level of treatment the effluent receives, resulting in greater transport of pathogenic microorganism and nutrients to the surface and groundwater (Cooper, 2016). Both USEPA, (2002) “Onsite wastewater treatment systems manual” and the Australian/New Zealand Standard, “On-site domestic wastewater management”, (AS/NZS 1547:2012), stress the importance of siting systems away from drainage swales, slopes and shallow rocky soils.

Incorrect sizing of septic tank

Primary treatment of the influent in a septic tank is achieved by maintaining quiescent conditions, which is accomplished by an extended wastewater residence time. Having inadequate volume, geometry and compartmentalisation can affect the hydraulic residence time. Whenever any of the factors mentioned above occur, the available time for settling and bacterial breakdown is limited and this will lead to failure (USEPA, 2002). Bounds (1997) referenced earlier works that recommended hydraulic residence times of 6 to 24 hours; however, according to the USEPA (2002), this amount varies significantly owing to differences in geometry and entrance/exit configurations. Minimal hydraulic residence time may also allow solids to be discharged direct to the drain field which may lead to clogging of the drainage pipes (Holt, 2015). Incorrect sizing of septic tanks may also lead to “hydraulic overloading”, which occurs when the amount of water leaving the septic tank exceeds the soil’s infiltration rate. This usually results in wastewater backing up in the dwelling or effluent ponding on the surface of the soil treatment area (Lee et al., 2010; Ready, 2008). Another consequence of inadequate sizing and hydraulic overloading is the reduction of bacteria present in the tank to treat the incoming waste. Having a very small amount of bacteria available results in less of the solids being broken down (Holt, 2015).

Incorrect sizing of drain field

As the discharge effluent percolates through the drain field, treatment of the contaminants occurs by means of sorption, filtration, biodegradation and die-off, before ground water recharge (Conn et al., 2012; USEPA, 2002). Therefore drainage fields should be sized adequately to facilitate the design flow of the discharged effluent so that it can be adequately attenuated. This is very important, because although it has been proven that microorganisms can be entirely removed from the effluent as it percolates through the unsaturated zone, improperly designed systems may allow these microorganisms to migrate long distances (Stevik et al., 2004). Gerba et al. (1975) outlined that once these organisms have entered the groundwater, they can travel several hundred metres. Conn et al. (2012) further reported that groundwater quality beneath drain fields was severely impacted by septic tank effluent because of failures that occurred as a result of inadequate sizing.

Limited knowledge of a soil's hydraulic conductivity

Having a detailed and well informed understanding of the soil's hydraulic conductivity is very important, because this determines the loading rates and size of the absorption area (Hall, 2001). The amount of time the effluent is in contact with the soil particles during unsaturated flow conditions will determine the level of treatment received. By limiting the hydraulic loading rate (HLR) to a small fraction of the soil's saturated hydraulic conductivity, unsaturated flow conditions can be achieved (Siegrist et al., 2001b); therefore if a system is designed without adequate consideration of the soil's hydraulic conductivity, inadequate levels of treatment and system performance deficiencies will occur.

Both Siegrist et al. (2001b) and Beach et al. (2005) emphasised that these deficiencies can manifest themselves in both hydraulic and purification dysfunctions and amplify the risks of unfavourable public health and environmental effects. Failures such as surfacing of effluent or inadequately treated effluent percolating and contaminating the groundwater are of particular concern, because of the difficulty in detecting and mitigating them. The long-term performance of the soil's ability to adequately treat the effluent can be predicted by having an informed understanding of the soil chemistry, the soil's physical characteristics and its drainage ability (Dawes et al., 2003); therefore, detailed soil analysis and hydraulic conductivity tests should be conducted during the design stages to minimise the chances of failure (Amador et al., 2012).

Incorrect selection of treatment unit

The appropriate selection of an OWTS should be based on the local codes and regulations for that specific area, and systems should be and designed to meet the specific site conditions (Ready, 2008). Widespread failures have resulted from insufficient scientific knowledge of these systems. Very often systems are designed for a small, single family and are later used for larger families or commercial application. In addition, systems that were designed to handle domestic wastewaters are subsequently fed with influent from restaurants and other commercial facilities that produce higher strengths of effluent. One of the major consequences of having higher strength septic tank effluent than the system was designed for is the increase of clogging in the drainfield, which results in a reduction in the infiltration rate. Research has shown that effluent discharged from systems fed by restaurants and other commercial institutions containing elevated concentrations of BOD, TSS, fats, oils and grease increases the likelihood of clogging and hydraulic failure (Eliasson, 2004; Laak, 1970; Siegrist, 2001a).

3.2. Examples of technical failures

Leaking septic tanks

Leaking septic tanks allow raw untreated effluent to flow into surface and groundwater. According to Verhougstraete et al. (2015), microbial contamination from the failure of these systems presents one of the highest health risks to areas used for potable water intake, recreation and fishing or shellfish harvesting. Identifying nonpoint sources of faecal contamination such as raw untreated effluent from leaking septic tank systems can be very challenging; therefore significant efforts should be made to prevent leaks from occurring (Bernhard et al., 2000).

Storm water intrusion and blocked drainage fields

Wastewater entering septic tanks should remain within the tank for a specific length of time so that the solids can be settled. Effluent loads entering the tank that are within the design limits facilitate this process. However, whenever storm water intrusion occurs, the retention time of the effluent within the tank decreases and untreated effluents containing high organic matter enters the drain field, which will cause clogging and subsequently failure (Taranaki Regional Council, 2006). Effluent containing high percentages of organic matter are likely to clog the entrance of the drainage area and further prevent an even distribution of the effluent across the entire drain field area. This results in ponding on the surface and could create an environment that promotes the breeding of flies, mosquitoes, and rodents (Wellington Regional Council, 2000).

3.3. Examples of management failures

It is essential that stringent management practices are adapted in order to have long-term sustainability of OWTS. A strict management programme will aid in the prevention of inefficiencies and failure of these systems (AS/NZS 1547:2012). Watts and King (2005) emphasised that failures, especially of older systems, have mainly occurred as a result of inadequate maintenance. They further noted that these failures are not necessarily the fault of the homeowner but rather a result of poor guidance on maintenance requirements. Crites et al. (1998) also mentioned that although OWTS require an insignificant amount of maintenance, they seldom receive any and this has resulted in high rates of failure.

Failure to pump out septic tank

Septic tanks are designed for the denser solids present in the influent to be settled and stored as sludge and the less dense solids to be stored as buoyant scum. However, after some time the settleable and buoyant materials become excessive. Due to the continuous use of the tank, the sludge and scum accumulation rates usually exceed the rate of decomposition and this results in a net accumulation of solids. With this excess the available space for clarified wastewater decreases, which further reduces the retention time within the tank. When this scenario occurs, the likelihood of poorly treated effluent flowing into the drainfield increases and the possibility for clogging to occur intensifies (Ontario Ministry of Municipal, 2000; Taranaki Regional Council, 2006; USEPA, 2002). Butler and Payne (1995) reported that numerous failure of septic tanks occur as a result of owners' negligence or ignorance of desludging. They further highlighted that although some persons are aware of the maintenance requirement, attempts are only made to desludge after noticeable signs of failure such as sewage backing-up in the dwelling, or overflowing of the septic tank.

Blocked outlet filter

Performance of the septic tanks can be enhanced with the installation of outlet filters since these have been proven to effectively decrease the amount of solids discharged into the drainage area (Crites et al., 1998; Stafford et al., 2005). Lowhorn (2001) established that when filters are installed during construction/fabrication of the tank or retrofitted after installation, they are capable of reducing the amounts of BOD, TSS, greases, fats, and oils leaving the tank.

However, over a period of time solids accumulate within the septic tank at differing rates and these increases are likely to cause blockages and hinder the effluent from leaving the tank, which may result in blockages occurring within the dwelling. Therefore regular cleaning of the filter at least one every six months is necessary to avoid failure of this nature (Byers et al., 2001).

3.4. An example of compliance failure

Failure to meet prescribed territorial local authority rules and regulations

Regulatory codes and consents are developed by authorities to protect the longevity of OWTS, and to protect the environment and public health (Auckland Regional Council, 2004; Hill et al., 1980). Due to the large variation in standards and regulations in different local authorities, systems are often designed and constructed inappropriately, which results in failure (Crites et al., 1998). This is a result of the variations in standards established by different authorities. Some authorities may specify dimensions of minimum lot size or establish setback distances to determine the selection of drainage area, whether bed or trench, and the method of application of the effluent, gravity or pumped. These decisions are made so as to ensure satisfactory attenuation of the effluent before it enters groundwater; however, consideration is rarely given to understanding the varying infiltration capabilities of different soil categories and how this may affect their attenuation process. In addition, the cumulative impacts of having very large clusters of OWTS in one location is often neglected (Carroll & Goonetilleke, 2005). Several researchers (Lipp et al., 2001; Perkins, 1984; Whitehead et al., 2000) have demonstrated that high densities of OWTS in one area can increase the likelihood of groundwater contamination. Further, Perkins (1984) and Yates (1985) suggested that OWTS constructed in areas where cluster densities are lower than 15 systems/km2 can also have harmful impacts on groundwater and adjacent surface waters.

3.5. Summary and analysis of findings

Several guidelines are available outlining the methodologies that should be used to ensure systems are adequately designed, installed and managed; however, dwelling occupants often ignore the management of these systems, and the need for management only appears relevant after failure has become visible. In most cases, by the time a failure is recognisable, surface and groundwater resources may have already become contaminated with nutrients and pathogenic microorganisms, and the potential for adverse effects on the environment and public health would have already escalated. It is essential that stringent management practices are adapted in order to have long-term sustainability of OWTS. This will also aid in the prevention of inefficiencies and failure of older systems. Crites et al. (1998) mentioned that although OWTS require an insignificant amount of maintenance, they seldom receive any and this has resulted in high rates of failure. This further re-emphasises the fact dwelling occupants need to be educated about the factors that may lead to failure.

If the likelihood for a system to fail and the level of impact that particular failure is likely to cause can be forecast, then informed decisions can be made pre-failure to remedy the systems that are at a high risk of potentially failing. The absence of a robust, all-inclusive monitoring programme in municipalities and regional councils has also resulted in failures, particularly in developing countries such as Guyana. Most times, establishing such programmes for an entire community can be very costly; however, if homeowners and dwelling occupants are informed of the negative impacts associated with failure, and know of the indicators that may signal irregularities within a system, then monitoring can be done independently. This will also reduce the overall cost of a monitoring programme for the entire community. The following chapter outline some of the indicators can be assessed and provide an indication of a system's performance.

CHAPTER 4 FAILURE INDICATORS

USEPA (2002) outlines that the failure of a system may occur whenever the performance requirements are not achieved; however, because of the varying performance expectations of OWTS, a wide range of unfavourable conditions may be considered as failure and this makes it improbable to clearly identify all the factors that may lead to failure. Additionally, because the quantity and quality of wastewaters may vary widely because of the different sources along with other factors such as time of day, day of week and season of the year, these will add to the challenges of identifying failures. Another notable factor is, because the natural soil structure that is used for attenuating the effluent before it reaches groundwater is neither homogeneous nor isotropic, the difficulties of identifying failures is further compounded; however, there are some similarities in conditions within a system and its environs that will change, which may indicate a system performance and aid in highlighting failures. This chapter highlights some of these indicators that can be monitored to highlight a system's performance so that timely interventions can be made before failures escalate to uncontrollable levels

4.1. Failure indicator 1 – sludge and scum layers

Residential wastewater entering a septic tank is known for the varying amount of constituents it contains. During this part of the treatment process, the wastewater entering (influent) is separated into three separate layers, namely the scum, wastewater, and sludge layers. After some time, the volume of the sludge and scum layers will increase because of the sedimentation and decomposition processes, resulting in a reduction of the wastewater layer.

Using the thickness of both the sludge and scum gives a good approximation of a septic tank's performance. AS/NZS 1547 (2012) outlined that for effective settling and scum formation to occur, there should be at least a 24-hour hydraulic residence time for the wastewater entering the tank and a pump out every three to five years. This conservative frequency timeline was intended for the protection of older tanks (Seabloom et al., 2004); however, the USEPA (2002) recommends that the combined sludge and scum volume should not exceed 30 % of the tank's volume. It further states that pumping is recommended if the difference between the elevation of the bottom of the scum layer and the outlet is within 3 inches (75 mm), or the difference in elevation of the top of the sludge layer and the bottom of outlet tee is less than or equal to 18 inches (460 mm). Once theses limits are exceeded, failure is likely to occur. This factor is key in the operation and maintenance of an OWTS, because in addition to highlighting potential failure, it also impacts on the operating cost, along with giving an indication of the overall efficiency of the system (Lossing et al., 2010).

In developed countries such as New Zealand, sensors installed within the septic tank are used to indicate if the tank is full and requires pumping out. This method is efficient but, having these devices installed in tanks located in developing countries such as Guyana can be very costly. Homeowners and dwelling occupants in these countries can use less expensive methods. Appendix *B1*, outlines one method that can be used for this process.

4.2. Failure indicator 2 – wastewater chemical properties

The wastewater layer is the thickest of the three layers. It is located between the sludge and scum layers and contains significant amounts of dissolved solids and other minute particulates. Within this zone the biodegradation of particulate matter takes place. However, this process is influenced significantly by the characteristics of the wastewater entering the tank. Wastewaters are highly influenced by the occupancy ratio, home activities, and methods of water use (Anderson et al., 1989; Crites et al., 1998; Howard, 2003). Furthermore, other parameters such as the occupancy age, health and annual time spent at the residence can heavily impact the constituents present in the wastewater and thus impact the anaerobic digestion, which relies on the presence of microorganisms – primarily bacteria – for this process to occur (Howard, 2003; Tchobanoglous et al., 2003; USEPA, 2002). The presence of a healthy microbial population is vital for effective treatment of the wastewater, particularly for the removal and digestion of both the settled and buoyant solids. It also has a direct impact on the system performance and contributes to the general lifetime of the system (Alhajjar et al., 1989).

The chemistry of septic tank effluent is highly variable during a 24-hour period owing to the different water use activities and the number of persons within the dwelling. According to Patterson (2003), activities such as laundering and lengthy baths are the main contributors to these variations. It is well documented (Crites et al., 1998; Hickey et al., 1966; Patterson, 2003) that conditions such as temperature and pH have a direct impact on the survival of bacteria within a tank. It was further noted that that minimal variation of these parameters are preferable for optimum growth to occur. Research has shown that pH between 6.5 and 7.5 are preferable for optimum bacterial growth.

Monitoring for these parameters presents a difficult challenge because of the number of activities by which they may be influenced. The different activities occurring during a day within the home will have a direct impact on these parameters; however, by establishing a monitoring programme that occurs during a period in which septic tank inputs are negligible may present the best option. In these conditions the microbial activities would be less affected by external factors, therefore, implementing a monitoring programme which allows for sampling to be conducted during the least active periods of the day such as early in the mornings may provide an excellent indication of a septic tank's performance.

Measurements of pH for septic tank effluent can be done using pH meters or pH paper. The simplest and least expensive of the two listed above is the use of pH paper. A methodology for conducting this test is described in Appendix *B2*.

4.3. Failure indicator 3 – depth of groundwater below drain field

The height of groundwater below the drain field area provides an indication of the thickness of the unsaturated layer available for the effluent to percolate through before coming into contact with groundwater. Since the level of treatment the effluent receives is significantly dependent on this thickness, efforts should be made to monitor this height, since the movement of microorganisms is less in unsaturated soils (Viraraghavan, 1978). Thicker, unsaturated layers provide longer travel times and promote conditions for more extensive interaction between the effluent and the soil. Longer contact times between the effluent and the soil reduces virus transport; therefore, efforts should be made to ensure these conditions are always present (Lance et al., 1984; K. S. Lowe et al., 2008). However, because of changing seasons and climatic conditions, some weather patterns may promote periods of intense precipitation which will result in fluctuations of the groundwater levels. Whenever the groundwater level rises, the unsaturated layer becomes thinner and conditions that favour maximum treatment of the effluent are diminished since shallower ground water reduces the available percolation zone and impedes the contaminant removal process (Water Resources Research Center University of Hawaii, 2008). Prolonged saturation of the soil within the drain field area also hinders the aerobic conditions necessary to attain the maximum possible treatment for the effluent before it enters the groundwater. Campbell et al. (1976) and Stevik et al. (2003) established that saturated conditions are preferred by microorganisms and increase their longevity. Wetter conditions also increase the likelihood of clogging of the openings on the drainage pipes, especially in systems that are drained by gravity (Wellington Regional Council, 2000).

Monitoring of the groundwater levels within the drain field area is of significant importance. This can be achieved by installing a piezometer within the area or for temporary purposes the augur-hole method can be used. This will aid in highlighting any fluctuation of the ground water table and provide information for occupants within the dwelling to limit their water usage during periods when the groundwater level is less than the preferred elevation. By observing these elevations, regulatory authorities will also be provided with information pertaining to these systems, so that better decision making can be incorporated during the design phase of these systems. Methodologies for measuring groundwater depth conducting this test is discussed Appendix *B3*.

4.4. Failure indicator 4 – slow draining of effluent to drainage area

This parameter is perceived as one of the most common failures in an OWTS. The slow draining of effluent entering the drain field area may be a result of blockages of the screen located within the outlet tee (see Figure 1–2) or within the distribution box. In addition, whenever sludge and scum levels exceed the levels at which the tank was designed to operate efficiently, normal flow conditions may force these solids into the drain field area and cause undesirable blockages. Although many researchers (De Vries, 1972; Gill et al., 2007; Rice, 1974; Tomaras et al., 2009) suggested that the total elimination of biomat formation is highly unlikely, the unnecessary delivery of solids can accelerate the formation of this layer, which may further reduce the life span of the system. Therefore, it is important that monitoring of the effluent's flow rate into the drain field area be conducted, so that potential irregularities can be corrected promptly. One methodology for measuring flow rates is outlined in Appendix *B4*.

4.5. Failure indicator 5 – rapid vegetative growth in nearby waterways

Aquatic plants flourish in waterways that are enriched with nutrients, particularly nitrogen and phosphorus. Since poorly treated septic tank effluent is known to have high concentrations of these nutrients, all measures should be employed to avoid leaching to nearby waterways. Plants take up the nutrients as food; therefore any waterway adjacent to an OWTS that has effluent flowing directly into it will exhibit excessive macrophyte growth. Observations of rapid increase in growth of these aquatic plants can be an indication of effluent leaching into the waterway. In addition to macrophytes, another noticeable sign that effluent can be entering nearby waterways is the blue-green discolouration of the water caused by algal blooms. The presence of excessive suspended algae may also act as an indicator of nutrient enrichment, particularly if the area where the freshwater body exists is not part of a catchment that is surrounded by agricultural land. This rapid blue-green algae production is also fuelled by increased nutrient supplies. Appendix *B5* outlines one method that can be implemented for assessing vegetation growth rate.

4.6. Failure indicator 6 – high concentration of nutrients and pathogens in groundwater

A properly functioning septic tank will discharge effluent that is marginally brown in colour and devoid of any suspended solids (Maine Center for Disease Control and Prevention, 2013). While the effluent may be free of suspended solids, it will be rich with pathogenic microorganisms. The removal of these organisms happens as the effluent percolates through the unsaturated zone below the drainage layer. The depth and characteristics of this layer is important because it determines the extent of treatment the effluent receives before it mixes with the ground and surface waters. Several researchers (Bouma et al., 1975; Gerba et al., 1975; Hagedorn et al., 1981; Stevik et al., 2004) have shown that microorganisms can be retained, and in some cases completely eliminated by percolation through the unsaturated zone; however, leaks from failing systems, which causes effluent to leach directly into groundwater, have the potential to permit transport of bacteria over distances greater than 400m in some soil types. This potential for microbial transport intensifies whenever there are saturated conditions existing below the soil treatment area (Stevik et al., 2004). Yates et al. (1985) reported that, although factors such as virus type, climatic conditions, and soil type may have an impact on the survival and mitigation of viruses in the subsurface, once favourable conditions are present, viruses can penetrate to depths of 67 m and migrate to horizontal distance as great as 408 m from their source. Appendix *B6* outlines areas where sampling should occur.

4.7. Failure indicator 7 – surface flow of effluent around septic tank area

Effluent ponding on the surface around its perimeter or in close proximity to a septic tank gives an indication of potential failure developing within the system. In most instances, overflowing septic tanks may be the result of a design or management failure mode. Poorly designed systems, especially those made of concrete, have the tendency to crack and this allows untreated effluent to leak through the walls. It is very important, therefore, that during the construction stage of these systems, emphasis is placed on maintaining the designed specifications to ensure that these systems are structurally sound. In addition, during installation care should be taken to prevent damage to these systems. Surface flow resulting from poor management usually occurs either by failing to pump out the septic tank at the stipulated time or by damage to the subsurface pipe network, which can be the result of roots from trees planted within the vicinity. In some instances, failures resulting from either a poorly designed or managed system are difficult to detect because the effluent does not always flow to the surface; there is no visible sign of leakage, especially if the soil is highly permeable and the septic tank is buried (E. Beach, 2015). Description of ways surface flow can be assessed is outlined in Appendix *B7*

4.8. Summary

Identifying the indicators and implementing useful methods and techniques for assessing and measuring them have been presented. Although some of measuring techniques do not provide precise results, timely observations can aid in assessing failure. In addition, the presence of additional factors that can intensify failure makes it improbable to accurately determine which specific indicator will contribute to the failure modes, however, it should be noted that the combination of all the indicators are the main causes of system failures.

CHAPTER 5 INTENSIFYING PARAMETERS

Although a COWTS can be performing poorly and all the factors identified may have exceeded their thresholds, the location of the system relative to other systems and water bodies may prevent failures from escalating. Likewise, if the same system is located within a school compound, or in close proximity to a nature reserve or a recreational park the effects of failure can be intensified because there is a greater probability that persons may come into contact with the effluent (Moore et al., 2010). Parameters such as the proximity of a failing system to surface/groundwater bodies or the type of drainage the soil facilitates – whether poorly drained or well drained – may influence the extent at which a failure occurs. For this reason, it should be noted that some parameters can intensify the magnitude of a failure caused by a poorly functioning COWTS. Failing to identify these parameters and appropriately evaluating them can cause failures to escalate. Identifying parameters that are visually noticeable or easily measurable may highlight and signal irregularities within a system and aid in assessing the system's performance and prevent surface and groundwater contamination and disease out breaks. This chapter highlights some of these parameters that can be monitored to prevent failure from escalating.

5.1. Proximity to potable water supply and groundwater table

Contamination groundwater for drinking purpose is either microbiological or chemical. The focus is usually on chemical contamination, even though there have been a minimal number of out breaks of groundwater-related illnesses caused by chemical contamination (Yates, 1985). Microbiological contamination is considered of lesser importance, because of the wide range of mechanisms by which these contaminants can be attenuated before they recharge groundwater (Ministry of Health, 2016). Yates (1985) reported that this is unfortunately not the case, since there has been an increase in the number of reported cases of diseases caused by groundwater contamination from bacteria and viruses present in domestic sewage. Yates (1985) further stated that the likelihood for contamination to occur increases with the septic tank density per unit area. This continues to be a point for concern, because septic tanks contribute significantly to groundwater recharge from domestic wastewaters when compared to effluent discharged from reticulated systems. The effects of microbiological contaminants is significant because of their fast acting capabilities, ability to multiply within the host, capability to be transmitted to person-to-person, and their potential to cause fatal illnesses (Nokes, 2008). Failures such as a leaking septic tank may result in poorly treated wastewater percolating through the subsurface and intersecting with the abstraction points of potable water supply wells. For this reason, Moore et al. (2010) advocated that a separation distance must be established between wastewater discharge point and groundwater abstraction locations to reduce the likelihood for contamination. They further emphasised that OWTS regulatory authorities, drinking water supply authorities, manufacturers and public health agencies should include proximity to drinking water supplies and groundwater resources as an important factor when constructing and developing policies, and implementing guidelines for these facilities. Home owners and dwelling occupants should also be cognisant of the increased likelihood of a failing system to contaminate potable water supply. In some rural communities in developing countries, a significant number of properties that have COWTS also have private domestic wells and in many instances, the two facilities are in close proximity to each other. The level of awareness should be further heightened in these countries, because most of these wells abstract water from shallow aquifers. In some instances, wells are abstracting from deeper groundwater, usually an unconfined aquifer. Both situations should be of concern because water quality in these locations is most vulnerable to contaminants from failing COWTS and in many instances, the water abstracted from these locations does not undergo any form of treatment before consumption (Moore et al., 2010).

5.2. Proximity to surface waterways, recreational waters and nature reserves

The potential for contaminants entering surface waterways intensifies if the COWTS is in close proximity to a waterway. The reason for this is because soils in close proximity to waterways are often saturated, and this creates preferential flow pathways for contaminant transport. The transport of contaminants in these saturated conditions is usually faster than in the preferred, unsaturated conditions. Conditions that create preferential flow paths for effluent also limit the interaction between the effluent and soil particles, and this reduces the contact time necessary for proper attenuation of the contaminants (Nimmo, 2006). Other factors, such as changes in the physical and chemical composition of the soil, reduce the rate for effluent attenuation (Dawes et al., 2003). The development of urban communities that will be highly dependent on COWTS use, and when these systems are to be located in close proximity to recreational waterways or nature reserves, emphasis should be placed on maintaining appropriate distances from these surface waters. Failing to integrate this aspect into the design can result in high concentrations of contaminants entering these waterways.

5.3. Proximity to schools

Locating COWTS in public areas where they are least likely to cause devastating consequences if failure occurs will always present a challenge for regulatory authorities, especially if the areas in which they are to be located are accessed regularly by children. Managing these systems in school compounds or in close proximity to schools needs to be of high importance because if failure occurs, the spread of illness among children can be difficult to contain, particularly since most diarrhoeal illnesses in children occur when they become infected by pathogenic microorganisms. These types of illness continue to be a cause for concern, because of their significant contribution to childhood mortality and morbidity (Thapar et al., 2004). Borchardt et al. (2003) stated that a poorly functioning COWTS that allows ponding on the drain field area increases the risk for persons to be exposed to enteric pathogens. Within close proximity to schools the risk and likelihood for an illness to occur increases because there is a potential for higher rates of exposure for children.

5.4. Proximity to nearby dwellings (septic tank density)

The effects of a failing COWTS can be greatly intensified if the systems is located close to other dwellings. Additionally, if many systems in a high density area are failing simultaneously then the likelihood for ground and surface water contamination increases. Although the failure modes discussed in Chapter 3 may contribute to ground and surface water contamination, Yates (1985) emphasised that the density of systems in an area is one of the most important factors contributing to groundwater contamination. The impacts will be greater if a collection of failing systems are located in a densely populated area compared to having the same number of systems in a low density area because there will be an increased likelihood for persons or animals to come into contact with the effluent. In addition, multiple systems failing in a high density area will compound the effects of failure and increase the likelihood for groundwater contamination, especially if the drain fields are located in high permeability soils with a shallow groundwater table. With multiple systems failing simultaneously, the soil’s capacity to adequately attenuate the effluent will be diminished (Yates, 1985).

5.5. Proximity to play parks and sports fields

Similar to the situation with surface waters, and nature reserves, failing COWTS located close to recreational areas also present a risk to the environment and public health. Having poorly performing systems with defective drainage fields will create boggy areas and promote rapid vegetation growth within the boundaries of the fields. These highly vegetative areas will create an unsightly appearance and diminish the aesthetics of the area. In addition, it is likely that these areas will be stagnant and will potentially emit obnoxious odours, and may also provide habitats for rodents, reptiles and insects. This can be dangerous, particularly for persons using the parks, because these are areas traversed frequently by the public, and it is highly likely that persons may come into contact with these animals. There will also be an increase in the likelihood of persons coming into contact with contaminated waters, and the potential for virus infections will be increased.

5.6. Intensity of use and the period persons occupied the dwelling

The frequency at which a COWTS is used and the number of persons using it may impact the performance of the system in both positive and negative way. Systems are designed for households of a particular size, therefore once they are used correctly and frequently, they will provide the necessary conditions to enable bacterial growth for the anaerobic decomposition of the organic matter. Conversely, having infrequent usage of the system will diminish the bacterial growth within the tank. The variability in usage of both quantity and quality of wastewater has a direct impact on the treatment stages of the COWTS. For example, septic tanks of COWTS installed at holiday dwellings will be void of bacteria during periods of no occupancy; however, during periods of high occupancy there will be a sudden increase in organic matter and water use. This dramatic increase in usage can cause failure, especially during periods of high rainfall in areas where the groundwater table is shallower than the required depth. This may result in hydraulic overloading, and the likelihood for poorly treated effluent contaminating ground and surface waters would increase. For this reason, it is recommended that adjustments be made to water-use activities within the dwelling once environmental conditions are not favourable to promote adequate attenuation of the effluent (Dakers et al., 2009).

5.7. Subsoil drainage

Soil characteristics, particularly subsoil drainage, play a major role in the successful performance of a COWTS. For optimum treatment to occur, soils must be able to (a) absorb the effluent, (b) retain the effluent for an appropriate time to allow attenuations by the chemical reactive processes, and (c) facilitate drainage of the treated effluent to the lower strata. Once these three conditions are fulfilled, the drain field area should perform satisfactorily. In some instances these systems may be located in areas with low permeability soils and this restricts the effective acceptance, treatment and disposal of the effluent. These restrictions may result in poorly treated effluent ponding on the surface of the drainage area and effluent being retained in the septic tank. Although ponding is easily recognisable, in many instances the likelihood for potential seepage pathways that allow microorganisms, nutrients and other contaminants to enter surface and groundwater may have occurred before these visible signs. Identifying soil before constructing a drainage area is very important because some soils exhibit severe constraining properties that are not favourable for drain field construction and are more likely to cause failure (Epp, 1984); however, this may not always be achievable because of a lack of choice. In areas where these constraints are present efforts should be made to adapt designs such as ETA's and mound systems to suit these soil conditions.

5.8. Summary

Some of the key parameters that may intensify failures of COWTSs have been explored in this chapter. While much emphasis was concentrated on highlighting how these parameters can determine the magnitude of a failure, the most significant point that needs to be observed is the relationship between the failure indicators presented in the previous chapters and the intensifying parameters presented in this chapter. For example, rapid vegetative growth in surface waterways can be influenced by the failing systems located in close proximity to these waterways. Having a management tool that can combine these two factors and also present examples of the likely modes will aid in alerting dwelling occupants of failures before they become uncontrollable.

CHAPTER 6 MANAGEMENT APPROACH

The three previous chapters outlined the modes of failure and the ways in which failure indicators and intensifying parameters can affect the extent to which a system fails if their combined effects are ignored. It is, therefore imperative that significant focus needs to be placed on the management of COWTSs in order to highlight failures before they become uncontainable and this will limit the likelihood of poorly treated effluent leaching to surface and groundwater. The emphasis towards achieving this is important, because of the adverse health effects associated with constituents contained in the effluent, especially since some products such as pharmaceuticals and personal care products have been linked to emerging contaminants.

6.1. Concept for monitoring COWTS

This research outlines the likely impacts failing COWTS can have on the environment and public health. While many regulatory authorities have developed strategies or systems for managing COWTS, especially in developed countries, little effort seems to have been placed on developing management methodologies that involves collaboration between regulatory authorities and dwelling occupants. This seems to be one of the major issues affecting the efficiency and longevity of COWTS. Indeed such collaborative mechanisms would be particularly useful in developing countries, due to the large dependence on surface and groundwater for domestic usage. Existing management models and frameworks unable to highlight which systems have the highest risk and which areas are likely to have the greatest impact, so this creates a huge gap in the ability to clearly identify the areas that needs urgent corrective works or areas where monitoring should be done.

6.2. Monitoring tool

The sequel presents a tool that will highlight the forecasting phase and the analysis phase. The failure indicators and intensifying parameters outlined in chapters 4 and 5 are combined to generate a risk score. In this way, not only does the model conveys the risks associated with the combinations of failure indicators and intensifying parameters, but the score associated with the risk presented, also relates to the potential for failure of the system. The eight indicators were selected after a review of the literature, where it was shown that the selected indicators are generally the main causes of system failures.

These selected failure indicators were assigned values based on the information provided in the literature and an estimated range. The values were arranged from the worst condition, through to the more favourable conditions on the right as shown in Table 6-1 below. This arrangement was adopted for all the indicators except pH, because, values in the range of 6.5 and 7.5 are ideal for bacterial growth.

For each indicator, the ranges selected were also ranked numerically from 1 to 8. This ranking system was selected for this model, however, alternative ranking systems can be assigned. The greater score was assigned to the parameter representing the worst range and the lowest score assigned to the parameter in the most favourable range. Table 6-1 below shows the failure indicators that were selected.

Table 6-1 *Failure Indicators and the Selected Ranges*

<table>
<tr><th>Failure Indicators</th><th colspan="8">Range</th></tr>
<tr><td>Sludge and scum Levels (% of tank volume)</td><td>>30</td><td>25–30</td><td>20–25</td><td>15–20</td><td>10–15</td><td>5–10</td><td>3–5</td><td>1–3</td></tr>
<tr><td>Depth of ground water below drainage area (m)</td><td><1</td><td>1–2</td><td>2–3</td><td>3–4</td><td>4–5</td><td>5–6</td><td>6–7</td><td>>7</td></tr>
<tr><td>pH of tank effluent</td><td>2.5–3.5</td><td>3.5–4.5</td><td>4.5–5.5</td><td>5.5–6.5</td><td>6.5–7.5</td><td>7.5–8.5</td><td>8.5–9.5</td><td>9.5–10.5</td></tr>
<tr><td>Drainage rate of effluent from septic tank to drainfield</td><td colspan="4">low</td><td colspan="2">medium</td><td colspan="2">high</td></tr>
<tr><td>Rate of vegetation growth in surface waters adjacent to drainage area</td><td colspan="4">high</td><td colspan="2">medium</td><td colspan="2">low</td></tr>
<tr><td>Concentration of nutrients in potable water supply</td><td colspan="4">high</td><td colspan="4">low</td></tr>
<tr><td>Concentration of pathogens in potable water supply</td><td colspan="4">high</td><td colspan="4">low</td></tr>
<tr><td>Surface flow of wastewater around septic tank area caused by leaking tank</td><td colspan="4">flow</td><td colspan="4">no flow</td></tr>
</table>

The ten intensifying parameters that were selected were also assigned ranges to illustrate the required objective of the model. As with the failure indicators, each intensifying parameter was also assigned a numerical weight corresponding to its intensity or adversity, and the overall intensity was determined by summing the weights of the selected parameters. The parameters selected are shown in Table 6-2 below.

Table 6-2 *Intensifying Parameters and the Selected Ranges*

Intensifying Parameters	Range							
Proximity to potable water supply (m)	0–10	10–50	50–100	100–200	200–300	300–400	400–500	>500
Depth of groundwater table (m)	0–5	5–10	10–30	30–50	50–100	100–150	150–200	>200
Proximity to surface waterways, springs (m)	0–5	5–10	10–30	30–50	50–100	100–150	150–200	>200
Proximity to schools (m)	0–5	5–10	10–30	30–50	50–100	100–150	150–200	>200
Proximity to nearby dwellings (m)	0–3	3–6	6–9	9–12	12–15	15–18	18–21	>21
Proximity to play park (m)	0–5	5–10	10–30	30–50	50–100	100–150	150–200	>200
Proximity to recreational waters, nature resorts, sports fields, golf courses (m)	0–5	5–10	10–30	30–50	50–100	100–150	150–200	>200
Intensity of use (yr.)	all	11/12	5/6	3/4	2/3	7/12	1/2	<1/2
Period number of persons occupied dwelling (yr.)	all	11/12	5/6	3/4	2/3	7/12	1/2	<1/2
Subsoil drainage	Poorly drained				well drained			

The scores generated for the intensifying parameters were combined with the failure indicators' score to form a risk score. Three risk levels were established, which were arranged in three different categories:

- Low – i.e. scores less than 35
- Medium – i.e. scores greater than 35 but less than 70 and
- High – i.e. scores greater than 70 and less than or equal to 100

The categories and failures likely to occur are shown in Table 6-3 below.

Table 6-3 *Categories of Risk Levels and Some Examples of Failures that are Likely to Occur*

Risk Score
48.4

RISK LEVEL	Failures likely to occur at different levels of risk score
Low (<35)	Slow draining of sinks and toilets
	Unpleasant odours being emitted from system
	Partial overflowing of septic tank
	Wet patches in drainage field
Medium (35-70)	Minimal retention of effluent in tank. Direct flow to drain field
	Effluent ponding on surface
	Completely overflowing septic tank
	Sewage backing up in dwelling
High (>70)	Effluent flowing directly into surface waters
	Effluent flowing directly to groundwaters
	Direct contact of untreated effluent with pets
	Direct contact of untreated effluent with humans

Each risk category was designed to represent the likelihood of failure of the system based on the observed indicators and intensifying parameters entered into the model. The total risk score was determined as the weighted average of the intensity and failure indicators scores proportions, in relation to the worst-case scenario in both intensity and failure – i.e. the worst possible case for failure and intensity respectively. The weights used were:

- Intensifying parameters proportion – 0.3, and
- Failure indicator proportion – 0.7

This weighting was used in order to reflect the intuition that failure indicators should have a greater impact on the overall risk score than the intensifying parameters. For example, suppose a system is observed to have failure indicators at their highest levels but intensifying parameters at their lowest levels, it would be expected that the risk of failure of such system would be at least moderately high (i.e. high medium). Correspondingly, if a system is observed to have failure indicators at their lowest but intensifying parameters at their highest, the risk of failure in such a system would be expected to be most moderately low (i.e. low medium). After a series of experiments, it was observed that the above weights not only gave an adequate representation of these expectations but also reflected the intuition entailed in other combinations of failure and intensity scores. The weighted sum of the proportions of the failure give rise to the overall risk score as follows:

$$R = 100 * \left[\left(\frac{w_{ip} * s_{ip}}{x} \right) + \left(\frac{w_{fi} * s_{fi}}{y} \right) \right] \tag{6-1}$$

Where: R = overall risk score; w_{ip} = intensifying parameter weight; s_{ip} = observed intensity score and x = maximum (obtained by summing over the worse cases) intensity score respectively; and w_{fi} = failure indicator weight; s_{fi} = observed failure indicator score and y = maximum (obtained by summing over the worse cases) failure scores respectively; all of which are unit less.

6.3. An example of the tool

An example of how the scores are generated for the failure indicator and intensifying parameters is shown in Tables 6-4 and 6-5 below.

Table 6-4 *Example of Selected Failure Indicators Range and the Scores Assigned*

Failure Indicators	Range	Indicator Score
Sludge and scum Levels (% of tank volume)	5–10	3
Depth of ground water below drainage area (m)	2–3	6
pH of tank effluent	6.5–7.5	1
Drainage rate of effluent from septic tank to drainfield	high	1
Rate of vegetation growth in surface waters adjacent to drainage area	medium	2
Concentration of nutrients in potable water supply	low	1
Concentration of pathogens in potable water supply	high	2
Surface flow of wastewater around septic tank area caused by leaking tank	no flow	1
TOTAL		**17**

Table 6-5 *Example of Selected Intensifying Parameters Range and the Scores Assigned*

Intensifying Parameters	Range	Parameter Score
Proximity to potable water supply (m)	>500	1
Depth of groundwater table (m)	50–100	4
Proximity to surface waterways, springs (m)	>200	1
Proximity to schools (m)	5–10	7
Proximity to nearby dwellings (m)	>21	1
Proximity to play park (m)	10–30	6
Proximity to recreational waters, nature resorts, sports fields, golf courses (m)	>200	1
Intensity of use (yr.)	<1/2	1
Period number of persons occupied dwelling (yr.)	3/4	5
Subsoil drainage	Poorly drained	2
TOTAL		**29**

An example of the risk score calculated from parameters and indicators depicted in Tables 6-4 and 6-5 is shown in Equation 6-2 below.

$$R = 100 * \left[\left(\frac{0.3 * 29}{74}\right) + \left(\frac{0.7 * 17}{32.5}\right)\right] = 48.4 \qquad (6\text{-}2)$$

Examples of the failures likely to occur at this risk score are shown in Table 6-3.

6.4. Implementation of tool

It is important to note that although the risks associated with a system cannot be totally eliminated, efforts should always be made to keep them to a minimum. This research showed that combining the failure indicators and intensifying parameters gives an estimation for the likelihood for a COWTS to fail. The designed tool evaluates the potential for failure of a system and also shows how the failure can be magnified, based on the usage rates, surrounding features and structures. The risk score generated can be compared to the three risk levels to identify the risk category to which the evaluated system corresponds. The examples for the failures that are likely to occur for each category of risk level will assist the evaluator to assess the necessity for remedial or maintenance work. This can be very helpful, especially for homeowners or dwelling occupants, because simple observations and tests can be done on a system, and the potential for failure can be easily evaluated. Additionally, regulatory authorities can use the information to identify the potential hot spots in an area, so that informed decisions can be made.

6.4.1. Case study: Darfield

The town of Darfield, on the South Island of New Zealand, was used as a case study area to demonstrate how the model can be applied. Four intensifying parameters – proximity to school, proximity to surface waters, proximity to play parks and proximity to nearby dwellings – were assigned similar weights used for the model. Radii of *10m, 50m, 100m and 250m* were used to create buffer zones around schools, play parks and waterways.

Weights were assigned to dwellings located within distances of one metre–10 m, 10 m–50 m, 50 m–100 m, 100 m–250 m and >250 m, and the dwellings that had at least three adjacent dwellings located within the one metre – 10 m radius were assigned the greatest weight.

The intensifying parameters were also used. The different ranges used for each of the parameters were assigned to an arbitrary number of dwellings and the impact levels for all the indicators were calculated based on these numbers. This was done by generating random numbers is excel. All the impact levels for each indicator were summed to obtain the total impact for each dwelling.

These results from the four intensifying parameters and failure indicators were assigned weights and used in ArcGIS to generate maps showing areas of highest impact potential and areas with the highest risk of failing. These are shown in Figures 6-1 and 6-2 below.

6.4.2. Locations with highest impact potential

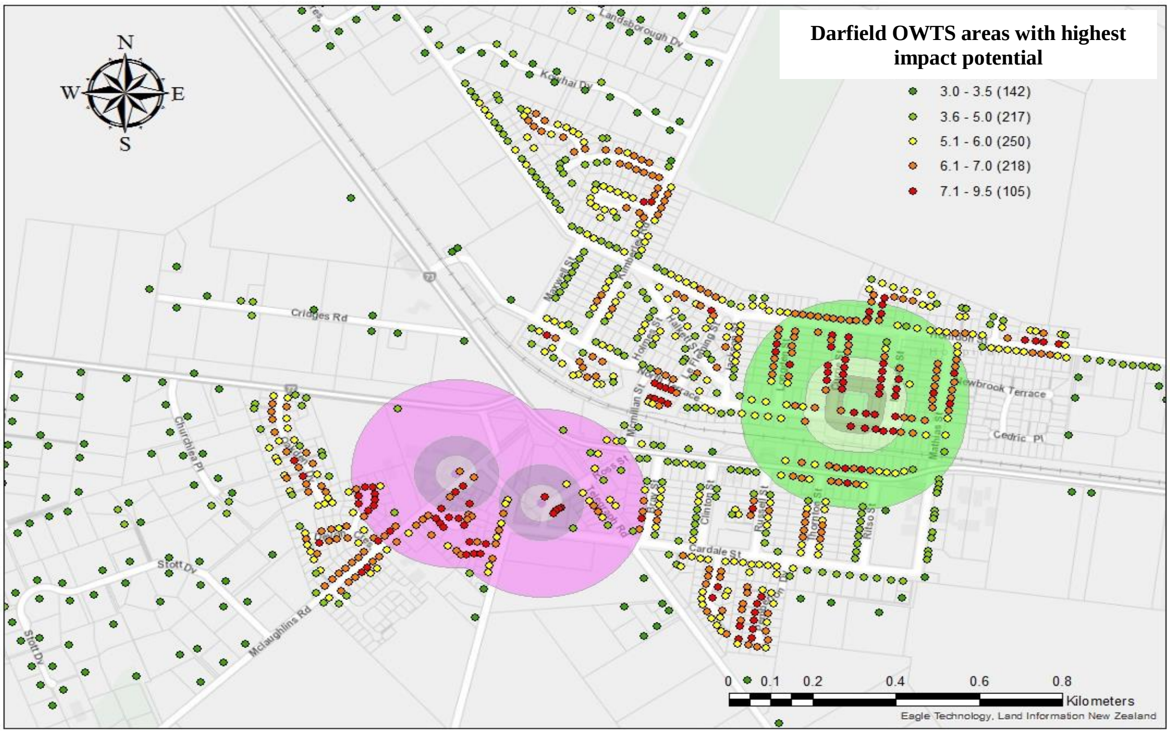

Figure 6-1 Geographical representation of the areas with highest potential impact

In Figure 6-1 above, the areas enclosed by the purple circles are the schools, and the green circle is the play park. Dwellings that will have the highest impact if they fail are depicted by the red dots. This map is very useful since it provides a clear representation of the locations where the systems should be adequately maintained because of the impacts these systems may have if failure occurs. This map also shows a significant number of dwellings within the buffer zones, which further emphases the concept that proximity to schools, play parks and nearby dwelling are key parameters when assessing the possible impacts of different failure modes. This also emphasises that emphasis should be placed on such locations during monitoring or assessment.

6.4.3. Locations with the highest risk of failing

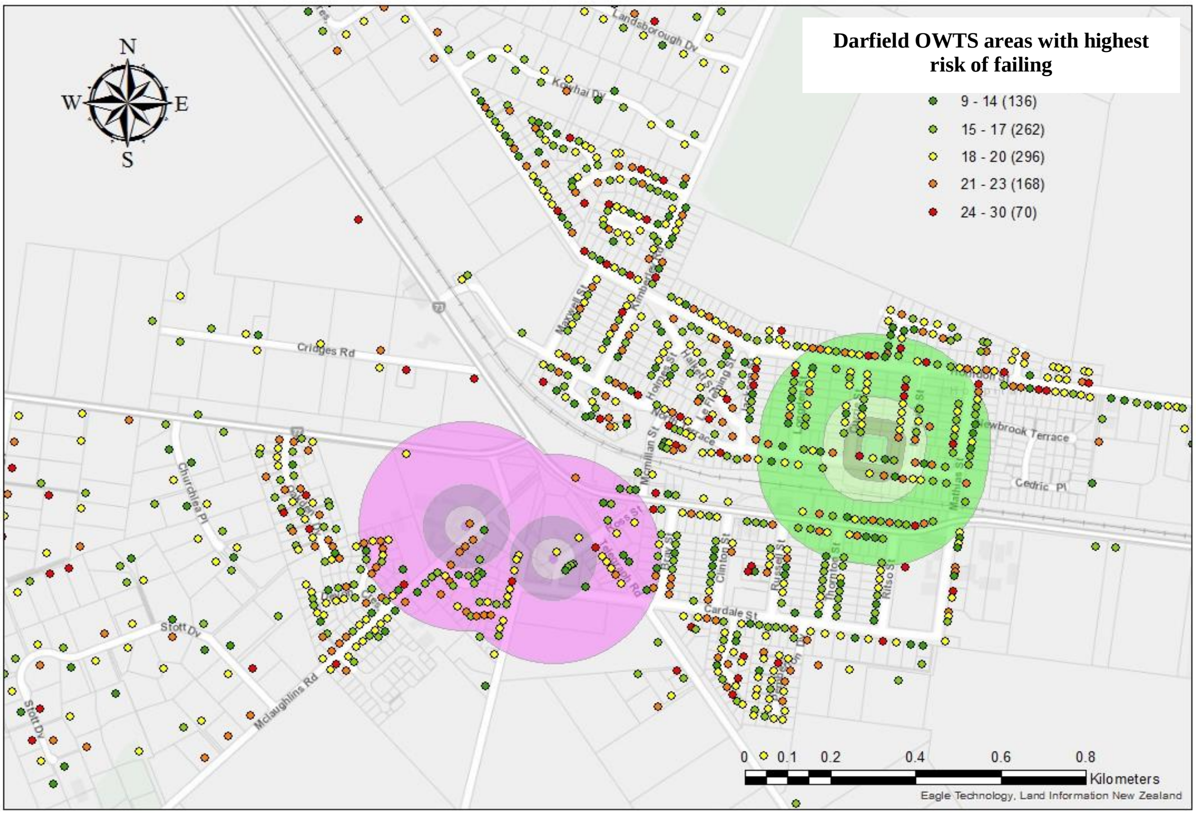

Figure 6-2. Geographical representation of locations with the highest risk of failing

In Figure 6-2 above, the dwellings with the highest risk scores are depicted by the red dots. It can be observed that the cluster of red dots is less when compared to those of Figure 6-1. This justifies the intuition used for assigning the higher weights to the failure indicators because, although some locations in Figure 6-1 have a high impact if they fail, they are not actually at the stage where urgent corrective works need to be administered. However, this map clearly shows the locations that are at the highest risk of failing and also the highest impact if they fail. Therefore, dwelling occupants and regulatory authorities can identify the locations where urgent maintenance work should be undertaken.

6.5. Discussion

The intended concept described in section 6.1 and 6.2 was to develop a management tool that can be used collaboratively, by dwelling occupants and regulatory authorities so that failures of COWTSs can be identified before they become uncontrollable. The possibilities of achieving this significant goal were clearly demonstrated in the example of the model presented and its application to the study area. The developed model is the first of its kind that combines failure indicators and intensifying parameters to highlight failure. It was shown in the literature that these very factors, when combined, are precisely the primary drivers of failure in COWTS, making the developed model, not only useful but novel.

Some major advantages of this model are the ease at which data can be entered and the flexibility it provides. The underlying design of the system allows the user to add additional parameters they consider necessary, without causing any interference with the designated outcome. This is very convenient, particularly since climatic conditions vary, and parameters can be added to correspond to the characteristics of the relevant site, e.g. its location. Additionally, the ease at which the data can be integrated with ArcGIS will be advantageous to persons in the management sector because it highlights the areas of high impact.

The information that the tool provides is also helpful for planners in the recreation and entertainment sectors. For example, if someone is interested in holding an even at a fun park, they can identify which parks should be avoided so that the possibilities of persons coming into close contact with contaminated waters can be reduced. Another key benefit of this model is that it can provide credible evidence of the areas that are at the highest risk, which is valuable information in its own right, and which can be utilised by regional councils or municipalities to, for example petition central governments for the financing of monitoring programmes. The ability to implement monitoring programmes in areas where risks are of the highest in beneficial to governments also because this can reduce the economic implications that can result from the cumulative impacts of disease outbreaks and environmental disasters.

6.5.1. Limitations of model

Like many other models and frameworks, the model developed is unable to determine the precise magnitude of the risks associated with COWTS. Variations in daily water use practices and usage rates within the dwelling and the time at which testing is conducted will influence the results obtained for pH. Systems that do not have flow and moisture content measuring apparatus installed will make failure indicators such as effluent drainage rate and the surface flow around the septic tank dependent on visual observations, and a precise representation of these can be hindered by rainfall events. Further, the failure indicators and intensifying parameters were assigned values obtained from peer-reviewed literature, however, most of these research were conducted in countries with varying soil types and climatic conditions. Therefore, there is no guarantee that these values will be constant for all the different locations.

Additionally, because the information required for the intensifying parameters is largely dependent on existing data, the possibility of having these data available in most developing countries is unlikely, so this will create large gaps in the information required for the model to function accurately. However, in areas where this information is available, informed decisions about the likelihood of a system failing can be achieved, and the likelihood of possible failures can be assessed promptly.

The numbering ranges used to differentiate the different categories of risk levels were based purely on assumption. This may present one potential source of error since there is no definite description that only failures of one particular kind can occur within these ranges. Another potential source of error is the absence of a clear, well defined method of calculating the level of uncertainty in the risk scores generated.

6.6. Summary

In this chapter, a new approach was presented for managing COWTSs. While much emphasis was placed on literature pertaining to the impacts of failure, types of systems, design and operation of OWTS, some existing management models, modes of failure, failure indicators and intensifying parameters, in the previous chapters; this section showed how all that information was combined to develop a user friendly, very flexible and less sophisticated approach to managing COWTS. The case study also demonstrated how the model can be used as a monitoring and planning tool for identifying the potential hotspots in an area.

CHAPTER 7 CONCLUSION AND RECOMMENDATIONS

7.1. Conclusion

Conventional on-site wastewater treatment continues to be a significant form of domestic wastewater treatment, particularly in developing countries and areas of developed countries that do not have reticulated forms of wastewater treatment. This study explored the major modes of failure for these systems and some of the measurable or visible parameters that change before failure occurs. A management methodology in the form of a computer model was developed to indicate a system's performance; this can be evaluated and aid in remedying failures before they become uncontrollable. The tool was applied to Darfield, New Zealand as a case study but can also be applied to Guyana.

The research showed that the major failure modes are (i) design, (ii) technical, (iii) management and (iv) compliance. Of the four, management was found to be the mode of most concern because most of the factors that contribute to the other modes can be controlled during the design and construction stages of these systems. Detailed site assessment, an extensive subsurface soil investigation and a review of design standards for a particular area, will provide pertinent information on a site's topography, the soil's hydraulic conductivity and the standards adopted by regulatory authorities in a particular area. Conducting this research will highlight factors that may contribute to design, technical and compliance failure modes and if properly identified and assessed, necessary adjustments and corrections to avoid failure can be made by designers and other technical personnel.

A significant point to note is that the factors that contribute to management failure modes can only be adjusted during the operation of these systems and in many instances, particularly in developing countries, management of these systems is exclusively the responsibility of the homeowner or dwelling occupant. However, a large percentage of these individuals have limited knowledge of how these systems should function, the necessary maintenance procedures that need to be undertaken and the potential risks associated with their failure. Additionally, the need for monitoring is often ignored, because in many areas both the septic tank and drain field are located below ground level, therefore some failures only become noticeable after poorly treated effluent begins to pond on the surface or when influent begins to back-up within the dwelling. At this stage of failure, it is highly likely that water resources may have already been contaminated, therefore, recognising failures before they advance to such levels is very important. Since residential wastewater contains nutrients such as nitrogen and phosphorus, along with pathogenic microorganisms, and whenever these constituents enter surface or groundwater the resulting effects can be devastating to environmental and public health. One aspect of research that was lacking in the conventional on-site wastewater treatment sector was a less complex model for managing these systems. This research was able to fill this gap and present a robust method that can be applied throughout the world.

In developing countries, it is important that this methodology is implemented to recognise COWTS failures, especially since approximately 90 % of the potable water supply is extracted and distributed without any form of treatment and consumption of contaminated water can result in waterborne disease outbreaks similar to that experienced by residents of Havelock North, New Zealand, in August, 2016.

The tool developed will provide all COWTS stakeholders a user-friendly model to monitor these systems at minimum cost. Measurements of the failure indicators identified in this study, along with the intensifying parameters, will be used to provide information on a system's performance and this will aid in identifying failures before they become uncontrollable. This collaborative approach to system monitoring will also reduce the uncertainties associated with the performance of these systems because the scores generated from the model will give the user examples of failures that are likely to occur at that particular risk score. Application of the results shows that regulatory authorities, developmental personnel's, entertainment entities and central government can use the model to identify and avoid areas of high risk and high impact in a particular district along with using this information for financing monitoring programmes. This is very valuable for countries like Guyana where accuracy in budgeting is important because of the low GDP when compared to more developed countries such as New Zealand.

7.2. Recommendations

Identifying additional failure indicators and intensifying parameters, and an understanding of how they may impact the performance of a COWTS and contribute to failure should be investigated, since this research only focused on those that were most common in the literature reviewed.

Further research should be undertaken to establish more realistic values for different soil types since contaminant transport will vary for different areas. There should also be additional investigations to determine which of the two (failure indicator or intensifying parameter) will have a greater impact on the performance of these systems and if this difference should be standardised or it show be adjusted for different climatic conditions.

It is also recommended that regulatory authorities place greater emphasis on improving the knowledge of the users of COWTS through user education. Information on how some household activities can impact a system’s performance, and how failures can affect environmental and public health should be disseminated. Regulatory authorities should also establish a database to store information collected by users so that the performance of these systems during different seasons and climatic conditions can be better understood.

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APPENDIX A – Design capacities for all-waste, greywater and blackwater septic tanks

All- waste Septic Tank Operational Capacities

Population equivalent (persons)	Number of bedrooms	Design flow (L/day)	Tank capacity (L)
1–5	1–3	1000	3000
6–7	4	1000–1400	3500
8	5	1400–1600	4000
9–10	6	1600–2000	4500

Note. Retrieved from Australian/New Zealand Standard, (AS/NZS 1547:2012), Appendix J, p. 127.

Greywater Septic Tank Operational Capacities

Population equivalent (persons)	Number of bedrooms	Design flow (L/day)	Tank capacity (L)
1–5	1–3	600	1800
6–7	4	600–840	2100
8	5	840–960	2400
9–10	6	960–1200	2700

Note. Retrieved from Australian/New Zealand Standard, (AS/NZS 1547:2012), Appendix J, p. 127.

Blackwater Septic Tank Operational Capacities

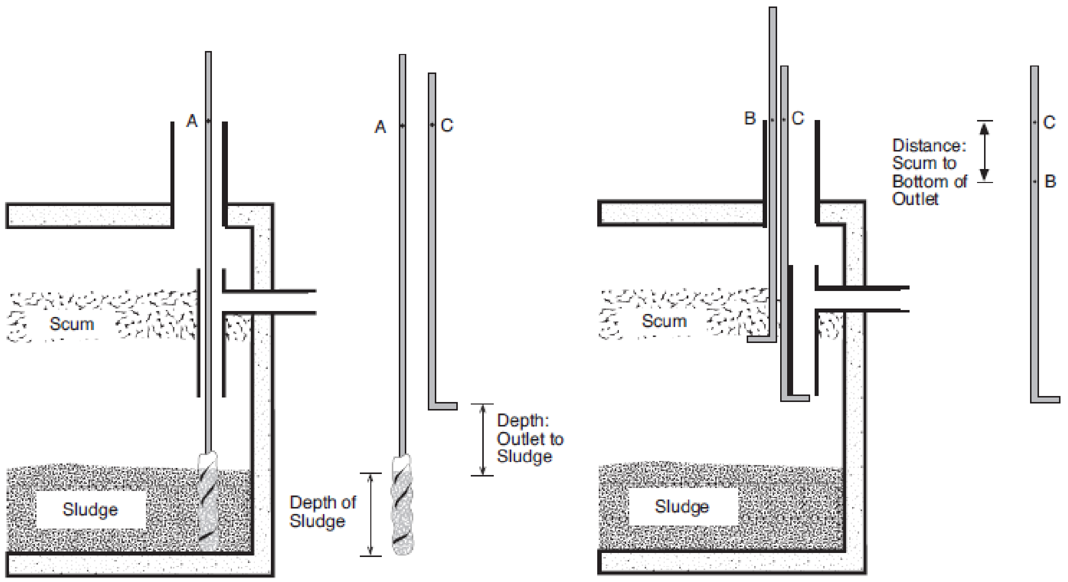
Population equivalent (persons)	Number of bedrooms	Design flow (L/day)	Tank capacity (L)
1–5	1–3	300	1500
6–7	4	300–420	1800
8	5	420–480	2100
9–10	6	480–600	2500

Note. Retrieved from Australian/New Zealand Standard, (AS/NZS 1547:2012), Appendix J, p. 127.

APPENDIX B – Measuring intensifying parameters

B1. Measuring sludge and scum thicknesses

- obtain a piece of wooden rod with approximate dimensions of 50 mm x 50 mm x 2400 mm and firmly wrap a light-coloured cloth around it, covering approximately one-third its length at the bottom end.
- remove the riser (refer to figure below) closest to the outlet tee and insert the rod through the scum and sludge layers until it reaches the bottom of the tank.
- place a mark on the rod relative to a fixed reference point on the tank opening. For example, "A" as shown in the figure below. Measurement of the dark sludge particles collected on the cloth gives an indication of the thickness of the sludge layer.
- obtain a second piece of rod of similar width and thickness, but approximately 600mm shorter than the previous.
- attach an additional 75mm piece of rod to one end of the rod forming the shape of the letter "L" as shown in figure below.
- insert the end with the attached piece through the same opening as before, until it reaches the wastewater layer, then gently lift the rod upwards until it reaches the bottom of the scum layer. This will be indicated by a slight change in resistance while pulling upwards.
- place a mark on the rod, for example "B" as shown in figure below using the same reference point that was used for reference "A" above.
- lower the rod further in the tank until it touches the bottom of the outlet tee and place another mark, for example "C" as shown in figure below, using the same reference point as "A" and "B".
- the distance between points "B" and "C" indicates the difference in elevation of the bottom of the scum layer and the outlet tee.
- place the two rods adjacent to each other and align points "A" and "C". The distance from the bottom of the projection to the top of the sludge particles indicates the distance between the sludge and the bottom of the outlet tee (Willingham et al., 2010).

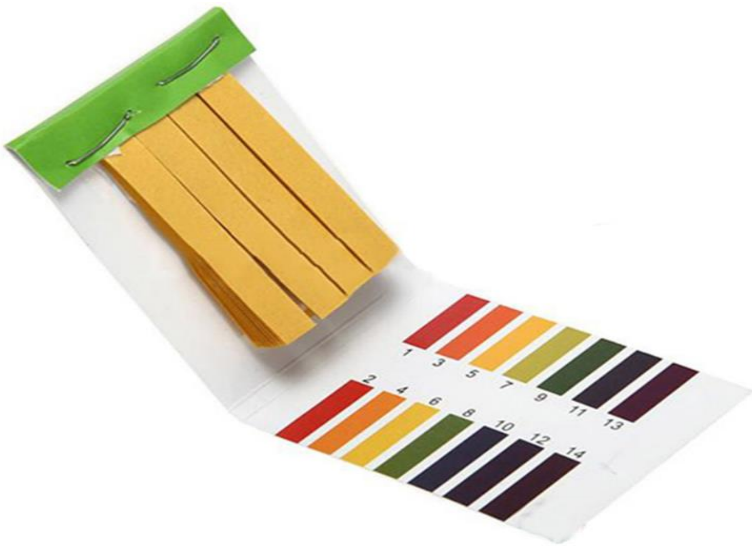


Appendix B1: Illustration on how to determine thickness of sludge and scum layers. Willingham et al (2010)

B2. Measuring pH of septic tank effluent using pH paper

These are special strips of paper that change colour when submerged in a solution. The changed colour is compared with the pH colour indicator chart that is sold with the strip (Heger, 2015).

- acquire pH paper with the desired pH range. Usually for wastewaters, strips within the ranges of pH 4 to 10 will be appropriate.
- using a sampling rod attached to a container, obtain a grab sample of approximately 100mL of the wastewater. The sample should be taken through the opening located above the inlet tee.
- submerge one end of the strip in the sample for approximately 5 seconds then allow to dry.
- compare the changed colour of the strip to the colour chart provided, and record the pH.



Appendix B2: An example of pH paper and colour chart.

B3. Measuring groundwater levels

The most reliable method for obtaining groundwater levels is by measuring water levels in a shallow well. In the absence of wells, surface geophysical methods that utilise electric or acoustic probes may be used, depending on the accessibility of the area (USGS, 2016). Regulatory authorities can also install piezometers to monitor the level of groundwater in a particular area, or dwelling occupants can observe changes in elevations of any neighbouring groundwater-fed stream; however, one simple method for temporary measurements of groundwater elevations is by using an auger as described below.

Steps for measuring groundwater level using the auger-hole method (Van Beers, 1958).

- acquire a hand held auger or any other apparatus capable of making a excavating a hole in the ground
- excavate a hole into the soil to at least one metre below the drain field
- if the water table is encountered at this depth, allow the groundwater within the hole to reach equilibrium state
- measure the depth of the water level

B4. Measuring effluent drainage rate between septic tank and drain field

Effluent discharge flow rates can be measured using magnetic flow meters. These devices are excellent for measurements of this form because they have no moving parts, are available in a variety of sizes, are not affected by variations in flow rates, are insensitive to a fluid's chemical properties, and flow reading are not affected by solid particles (ICENTA, 2017).

B5. Measuring vegetative growth rates

Growth rates for aquatic plants in a surface waterway are significantly influenced by factors such as contributing sources to the waterway and the surrounding land use activities. Nutrients in particular impact the growth rate of floating aquatic plants. Whenever there are limited nutrients in the water column, plants growth rates are limited also; however, temporal changes in nutrient loadings result in nuisance plant growth. By observing any changes in the growth rates for these aquatic plants, an indication of nutrient enrichment will be given (Madsen et al., 2012; Swistock et al., 2008). A possible method of achieving this is by taking photographs at four week intervals to observe and rapid increase in vegetation. Examples of pictures showing different stages of nutrient levels

Nutrient deficient stream | Nutrient enriched stream

Appendix B5: Examples of streams with different nutrient levels (Georgia Wildlife Resources Division, n.d; Manie Department of Environmental Protection, 2016).

B6. Measuring nutrient and pathogen concentration

Concentrations of nutrients and microorganisms in groundwater can be conducted by sampling nearby wells at strategic points within the water distribution network. It is important that regulatory authorities have a stringent monitoring programme for water quality because pathogenic microorganisms pose the greatest risk to human health. When designing a monitoring programme, it is important that sampling points are uniformly distributed throughout the network and samples are taken from areas that are sourced for human consumption (WHO, 2004). Areas where groundwater is entering surface waterways can also be used as sampling points.

B7. Measuring surface flow around septic tank

Effluent leaking from septic tanks is not always noticeable because the effluent would generally flow vertically downwards, as a result of gravity, along preferential flow paths. The flow path will occur particularly if the soil is unsaturated. For this reason, techniques for measuring subsurface flow can be used to give indications of effluent flow rates. Ground-based techniques such as remote sensing for soil moisture monitoring at a particular point of observation are possible (Pan et al., 2012); however, establishing such programmes to identify changes in a soil's moisture content around the perimeters of septic tanks can be very costly. If dwelling occupants and homeowners make observations of these areas, at least once per week, visible changes in the soil's moisture content can be identified; however, at this stage contamination may have already occurred.

APPENDIX C – Lookup table for intensifying parameters

Intensifying Parameters		Code	Lookup value	Rank	Weight	Weight x Rank
Proximity to potable water supply (metres)	0 to 10	A	0 to 10_A	8.0	1	8
	10 to 50	A	10 to 50_A	7.0	1	7
	50 to 100	A	50 to 100_A	6.0	1	6
	100 to 200	A	100 to 200_A	5.0	1	5
	200 to 300	A	200 to 300_A	4.0	1	4
	300 to 400	A	300 to 400_A	3.0	1	3
	400 to 500	A	400 to 500_A	2.0	1	2
	>500	A	>500_A	1.0	1	1
Depth of groundwater table (metres)	0 to 5	B	0 to 5_B	8.0	1	8
	5 to 10	B	5 to 10_B	7.0	1	7
	10 to 30	B	10 to 30_B	6.0	1	6
	30 to 50	B	30 to 50_B	5.0	1	5
	50 to 100	B	50 to 100_B	4.0	1	4
	100 to 150	B	100 to 150_B	3.0	1	3
	150 to 200	B	150 to 200_B	2.0	1	2
	>200	B	>200_B	1.0	1	1
Proximity to surface waterways, springs (metres)	0 to 5	C	0 to 5_C	8.0	1	8
	5 to 10	C	5 to 10_C	7.0	1	7
	10 to 30	C	10 to 30_C	6.0	1	6
	30 to 50	C	30 to 50_C	5.0	1	5
	50 to 100	C	50 to 100_C	4.0	1	4
	100 to 150	C	100 to 150_C	3.0	1	3
	150 to 200	C	150 to 200_C	2.0	1	2
	>200	C	>200_C	1.0	1	1
Proximity to schools (metres)	0 to 5	D	0 to 5_D	8.0	1	8
	5 to 10	D	5 to 10_D	7.0	1	7
	10 to 30	D	10 to 30_D	6.0	1	6
	30 to 50	D	30 to 50_D	5.0	1	5
	50 to 100	D	50 to 100_D	4.0	1	4
	100 to 150	D	100 to 150_D	3.0	1	3
	150 to 200	D	150 to 200_D	2.0	1	2

	>200	D	>200_D	1.0	1	1
Proximity to nearby dwellings (metres)	0 to 3	E	0 to 3_E	8.0	1	8
	3 to 6	E	3 to 6_E	7.0	1	7
	6 to 9	E	6 to 9_E	6.0	1	6
	9 to 12	E	9 to 12_E	5.0	1	5
	12 to 15	E	12 to 15_E	4.0	1	4
	15 to 18	E	15 to 18_E	3.0	1	3
	18 to 21	E	18 to 21_E	2.0	1	2
	>21	E	>21_E	1.0	1	1
Proximity to play park (metres)	0 to 5	F	0 to 5_F	8.0	1	8
	5 to 10	F	5 to 10_F	7.0	1	7
	10 to 30	F	10 to 30_F	6.0	1	6
	30 to 50	F	30 to 50_F	5.0	1	5
	50 to 100	F	50 to 100_F	4.0	1	4
	100 to 150	F	100 to 150_F	3.0	1	3
	150 to 200	F	150 to 200_F	2.0	1	2
	>200	F	>200_F	1.0	1	1
Proximity to recreational waters, nature resorts, sports fields, golf courses (metres)	0 to 5	G	0 to 5_G	8.0	1	8
	5 to 10	G	5 to 10_G	7.0	1	7
	10 to 30	G	10 to 30_G	6.0	1	6
	30 to 50	G	30 to 50_G	5.0	1	5
	50 to 100	G	50 to 100_G	4.0	1	4
	100 to 150	G	100 to 150_G	3.0	1	3
	150 to 200	G	150 to 200_G	2.0	1	2
	>200	G	>200_G	1.0	1	1
Intensity of use	all yr.	H	all yr._H	8.0	1	8
	11/12 yr.	H	11/12 yr._H	7.0	1	7
	5/6 yr.	H	5/6 yr._H	6.0	1	6
	3/4 yr.	H	3/4 yr._H	5.0	1	5
	2/3 yr.	H	2/3 yr._H	4.0	1	4
	7/12 yr.	H	7/12 yr._H	3.0	1	3
	1/2 yr.	H	1/2 yr._H	2.0	1	2
	<1/2 yr.	H	<1/2 yr._H	1.0	1	1
Period number of persons occupied dwelling	all yr.	I	all yr._I	8.0	1	8
	11/12 yr.	I	11/12 yr._I	7.0	1	7
	5/6 yr.	I	5/6 yr._I	6.0	1	6
	3/4 yr.	I	3/4 yr._I	5.0	1	5
	2/3 yr.	I	2/3 yr._I	4.0	1	4

	7/12 yr.	I	7/12 yr._I	3.0	1	3
	1/2 yr.	I	1/2 yr._I	2.0	1	2
	<1/2 yr.	I	<1/2 yr._I	1.0	1	1
Subsoil drainage	Poorly drained	J	Poorly drained _J	2	1	2
	well drained	J	well drained_J	1	1	1

APPENDIX D – Lookup table for failure indicators

Failure Indicators		Code	Lookup value	Rank	Weight	Weight x Rank
Sludge and scum Levels (% of tank volume)	>30	A	>30_A	8.0	1	8
	25 to 30	A	25 to 30_A	7.0	1	7
	20 to 25	A	20 to 25_A	6.0	1	6
	15 to 20	A	15 to 20_A	5.0	1	5
	10 to 15	A	10 to 15_A	4.0	1	4
	5 to 10	A	5 to 10_A	3.0	1	3
	3 to 5	A	3 to 5_A	2.0	1	2
	1 to 3	A	1 to 3_A	1.0	1	1
Depth of ground water below drainage area (metres)	<1	B	<1_B	8.0	1	8
	1 to 2	B	1 to 2_B	7.0	1	7
	2 to 3	B	2 to 3_B	6.0	1	6
	3 to 4	B	3 to 4_B	5.0	1	5
	4 to 5	B	4 to 5_B	4.0	1	4
	5 to 6	B	5 to 6_B	3.0	1	3
	6 to 7	B	6 to 7_B	2.0	1	2
	>7	B	>7_B	1.0	1	1
pH of tank effluent	2.5 to 3.5	C	2.5 to 3.5_C	4.5	1	4.5
	3.5 to 4.5	C	3.5 to 4.5_C	3.0	1	3
	4.5 to 5.5	C	4.5 to 5.5_C	2.3	1	2.25
	5.5 to 6.5	C	5.5 to 6.5_C	1.8	1	1.8
	6.5 to 7.5	C	6.5 to 7.5_C	1.0	1	1
	7.5 to 8.5	C	7.5 to 8.5_C	2.0	1	2
	8.5 to 9.5	C	8.5 to 9.5_C	3.0	1	3
	9.5 to 10.5	C	9.5 to 10.5_C	4.0	1.125	4.5
Drainage rate of effluent from septic tank to drainfield	low	D	low_D	3.0	1	3
	medium	D	medium_D	2.0	1	2
	high	D	high_D	1.0	1	1
Rate of vegetation growth in surface waters adjacent to drainage area	high	E	high_E	3.0	1	3
	medium	E	medium_E	2.0	1	2
	low	E	low_E	1.0	1	1
Concentration of nutrients in potable water supply	high	F	high_F	2.0	1	2

	low	F	low_F	1.0	1	1
Concentration of pathogens in potable water supply	high	G	high_G	2.0	1	2
	low	G	low_G	1.0	1	1
Surface flow of wastewater around septic tank area caused by leaking tank	flow	H	flow_H	2.0	1	2
	no flow	H	no flow_H	1.0	1	1