Establishing Failure Indicators for Conventional On-site Wastewater Treatment Systems

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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 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.

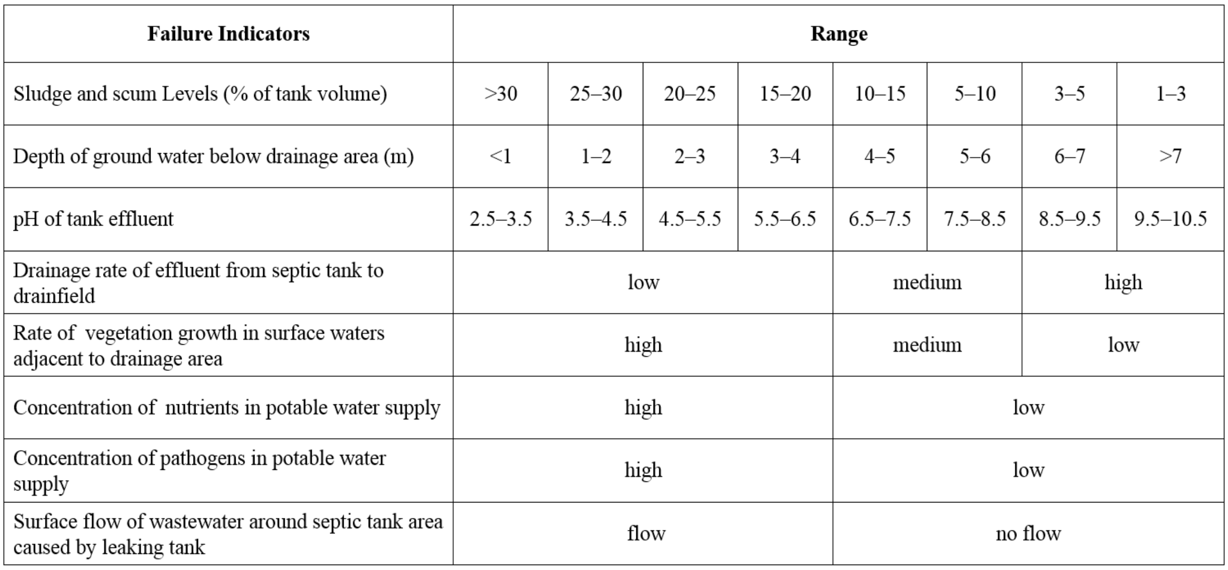
6.2. Monitoring tool

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*



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

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.