The University Of Queensland

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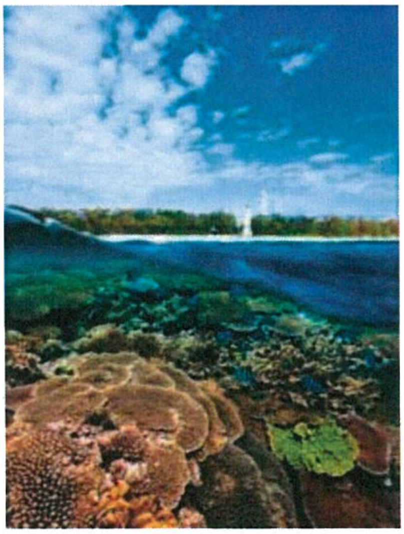
"Effects of urbanisation on water quality and inshore coral reefs of Eli Creek Catchment"



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Declaration of Authorship

I certify that the work presented here is, to the best of my knowledge and belief, original and the result of my own investigations, except as acknowledged, and has not been submitted, either in part of whole, for a degree at this or any other institution.

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Abstract

Coral reefs, which are exceptionally susceptible to rapid changes in ocean temperature and acidity due to climate change, are predicted to experience more frequent bleaching events in the future. The resilience of coral to bleaching can be influenced by many other factors such as overfishing, nutrient enrichment, increased sedimentation, diseases and non-indigenous invasive species. These manmade stresses reduce the regenerative capacity of coral reefs, which in turn, make reefs less able to recover from bleaching. Within the coastal zone of Queensland, urbanisation has resulted in a deterioration of water quality within heavily urbanised catchments. Urbanisation usually results in increased pollutant loads in stormwater runoff, which can threatened the health of inshore coral reefs and their resilience to bleaching if these pollutants reach critical threshold levels. The objective of this research was to attempt to quantify the relationship between urbanisation and water quality within the Eli Creek Catchment, and assess the potential effect of urbanisation on inshore coral reefs. This was done by building a Bayesian Network model to show how urbanisation has influenced water quality within the Eli Creek Catchment of Hervey Bay, Queensland, over the last decade. Bayesian networks are a useful tool for developing models where uncertainty is high and data are missing. They consist of qualitative and quantitative parts, the qualitative part being a graphical model (made up of nodes and links) and the quantitative part being probabilities that quantify the relationships between variables. Results from the study found no definite link between increasing urbanisation and water quality within Eli Creek Catchment, however, it is clear that median total nitrogen, phosphorous and suspended solids levels are higher than the recommended critical levels for estuaries, and for constructed lakes and reservoirs. This can potentially degrade inshore reefs. Additionally, the sensitivity analysis conducted using the Bayesian network model indicated that urbanisation was more influential than monthly rainfall on water quality (total phosphorous in particular) over the last decade, however, the mode of influence is not clear.

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1. Introduction

1.1. Background to the research problem

Greenhouse gas concentrations are gradually increasing in the earth's atmosphere and exceeding the capacity of oceans and the biosphere to absorb them. This has been linked to global warming and climate change, which have the potential to lead to serious ecological impacts such as the loss of species diversity and disturbance of ecological process (Munday et al. 2008). One of the predicted impacts of climate change will be the loss of coral reefs, which are exceptionally susceptible to rapid changes in ocean temperature and acidity (Pomerance 1999; IUCN, n.d). Since the 1970s, coral reefs around the world have frequently suffered from rising ocean temperature, which causes bleaching of coral reefs through the loss of algal cells or zooxanthellae (Riegl et al. 2009). In some areas, reefs have died due to excessive bleaching caused by long-term higher ocean temperatures (Hardy 2003).

In 1998, coral reefs around the world appeared to have suffered the most extensive and severe bleaching and subsequent mortality in modern records. Thirty percent of reefs were killed in the Western Indian Ocean as a result of an increased summer ocean surface temperature and El Nino – Southern Oscillation impact (Grimsditch & Rodney 2006). Even though the situation was not severe in Australia, 42 to 60 percent of the reefs on the Great Barrier Reef were bleached (Hardy 2003). They suffered greater in 2002 when another devastative bleaching event occurred. It is predicted that bleaching events are likely to reoccur rapidly because of global warming (Riegl et al. 2009). This is a global issue and it seems that climate change in future will create even greater stresses on the health and resilience of reefs. This in turn will increase the frequency and severity of coral bleaching.

Previous research has shown that the resilience of coral to bleaching can be influenced by many other factors such as overfishing, nutrient enrichment, increased sedimentation, diseases and non-indigenous invasive species (Bellwood et al. 2004). These manmade stresses reduce the regenerative capacity of coral reefs. For example, in the Caribbean, overfishing of herbivorous fish caused macroalgae to dominate reefs. This made reefs less able to recover from bleaching (Grimsditch & Rodney 2006). Similar manmade stresses are occurring on the Great Barrier Reef, where terrestrial runoff, overfishing and climate change are changing the dynamics and stability of reefs. Inputs of sediment and nutrients from the land have increased fourfold since European settlement, while the numbers of turtles, dugongs and other macrofauna have greatly decreased

(Bellwood et al. 2004). Even though it has not suffered severe damaged from coral bleaching, the Great Barrier Reef is being threatening because mass bleaching events have occurred repeatedly over the past 30 years (Hoegh-Guldberg 2008). Fortunately, mortality rates of bleached reefs have been quite low on the Great Barrier Reefs in comparison to other places. Nevertheless, a number of reports show that recovery rates have been slow (Hoegh-Guldberg 2008). The severity of bleaching can be reduced if other stressors, particularly those caused by human activities, are managed.

There are many stressors caused by human activities that affect the health and resilience of the Great Barrier Reef. Waters discharged from Great Barrier Reef river catchments contain increasing quantities of pollutants, sediments and nutrients. The reason for this is that the east coast of Queensland has been developed for agricultural, industry and residential use over the last 150 years (Brodie & Fabricius 2008; Lawrence et al. 2002). This has led to high inshore turbidity in the Great Barrier Reef lagoon. Sources of pollutants are mainly from agriculture in the form of herbicides, pesticides and fertilizers from growing bananas, sugarcane, cotton and other crops and increasing soil erosion from beef grazing (Brodie & Fabricius 2008). Nutrients and sediments increase phytoplankton growth which reduces photosynthesis of reefs (Wilkinson 2008). An indirect effect of this is that it may lead to disease and increase coral predation from crown-of-thorns starfish. High turbidity also forces corals to use their energy to clean and repair themselves (Hutchings et al. 2008), which slows their growth. Overfishing is another threat to coral reefs in the Great Barrier Reef. A decrease in fish populations makes coral reefs susceptible to overgrowth of macroalgae, plagues of coral predators, and increases in disease (Riegl et al. 2009). Hutchings et al. (2008) states that "the removal of species near the top of a food chain by fishing can lead to an increase in abundance of their prey .....similarly, the addition of nutrients can stimulate growth of species at the bottom of the food web (primary producers such as phytoplankton and fleshy algae". Fortunately, the Great Barrier Reef has not faced overfishing because most reefs are tens of kilometers offshore and there is no recreational or commercial fishing of tropical reef herbivorous fishes.

Moreover, the expansion of urban can affect local environments and conditions, particularly water environment, which is most adversely affected by urbanisation. Any type of activity in a catchment that changes the existing land use will have a direct impact on its quantity and quality characteristics. In particular, land use modifications associated with urbanisation significantly affect water environments resulting in deterioration of water quality, increased stormwater runoff, and increase in flooding (Carter et al. 2009; Wenger et al. 2009). When urban impervious surfaces are constructed, it leads to overland flows. Moreover, urbanisation usually affects the quality of stormwater runoff through contamination by biological chemical and physical pollutants resulting from anthropogenic activities common to urban areas. For example, local government officers within Southeast Queensland reports that waterbodies regularly fail to meet their design water quality objectives, especially nutrient concentrations were found to far exceed the standard (Newton 2007). Furthermore, urban development also introduces toxic contaminants that are not found at all in undeveloped catchments (Walsh et al 2004). This in turn will increase the rate of severity of coral bleaching, especially when combined with other stressors caused by human activities.

This research project focuses on Eli Creek Catchment, which covers approximately 3,460 ha in Hervey Bay. The Hervey Bay area is the southernmost extent of the Great Barrier Reef and is home to some unique coral species Hervey Bay. It is also an area that has undergone rapid urban development, and in the Eli Creek Catchment alone the level of urbanization is expected to reach 60 percent (Scheltinga & Moss 2010). Consequently, this is expected to reduce water quality in inshore coral reef areas.

1.2. Research aims and objectives

The objectives of this research were to quantify the relationship between urbanisation and water quality within the Eli Creek Catchment, and assess the potential effect of urbanisation on inshore coral reefs. This was done by building a model to show how urbanisation influenced water quality within the Eli Creek catchment over the last decade from 1999 to 2011.

In order to achieve the objectives above, the research tried to answer the following questions: What are the main stressors that impact on reef health in Hervey Bay? How has urbanisation and water quality within Eli Creek changed over time? What influence has urbanisation had on water quality within Eli Creek over time? Does the quality of water within Eli Creek have the potential to degrade inshore coral reefs?

2. Urban development and water quality

Land use change within a catchment has the potential to change both the quantity and quality of water. Urbanisation in particular can significantly affect water within a catchment by clearing vegetation and replacing natural, pervious surfaces with impervious paved roads and roofs (Brilly et al. 2006). The result can be deterioration of water quality, increased stormwater runoff, and an increase in flooding.

Generally, a great amount of rainfall goes back to the atmosphere through evaporation. "In naturally vegetated catchments, a large proportion of rainfall is evaporated by being transpired through plants drawing water from the soil and releasing it through their leaves" (Walsh et al. 2004). Less rainfall can get into the soil due to the fact that it is difficult to infiltrate into impervious surface. Moreover, the capacity of rainfall to infiltrate into soil is further reduced because permeable topsoil from the catchment is frequently removed during the construction of impervious surface. Furthermore, conventional stormwater drainage makes it harder for infiltration as water is transported to watercourses directly (Walsh et al. 2004). As a result, the water table is not replenished due to the fact that less water penetrates to groundwater. This in turn reduces baseflow levels in watercourses.

Urbanisation also has an influence on the quality of stormwater runoff through contamination by biological chemical and physical pollutants resulting from anthropogenic activities common to urban areas. An increase in the amount of contaminants carried by the flow was responsible by increased flood volumes peak discharges and water flow velocities in urban waterways (Department of Environment and Resource Management 2010). Major sources of nutrients and sediments are from land development which exposes soils to wind and water erosion. In addition, transportation and industrial activities also lead to many other contaminants. These pollutants are carried by runoff into waterways. Even though their concentrations might be diluted during a runoff event, the environmental quality of downstream aquatic habitats can be affected by the total load.

It is interesting to note that among different urban forms, stormwater runoff from areas with detached housing in large suburban blocks demonstrated the highest concentration and variability of pollutants (Goonetilleke & Thomas 2004). According to research done on Gold Coast, mean values and standard deviations for water quality parameters were generally found to increase with increasing urbanization (Goonetilleke & Thomas 2004). Furthermore, urban and industrial development in estuarine areas has impacted mangroves, seagrass, and saltmarshes through land clearing and waterfront development. These will have detriment effects on aquatic ecosystem.

Constructed urban water bodies or lakes' are a popular feature of urban development in many countries, including Australia. Such water bodies may be created for a variety of social, economic and environmental reasons (Bayley et al 2007). From the perspective of land developers, urban water bodies can provide scenic amenity as well as recreational opportunities and wildlife habitat, which commonly lead to higher land values in surrounding areas. Whilst constructed urban water bodies may confer many benefits upon their local communities, poor water quality in constructed urban water bodies is commonly observed and can potentially result in a range of environmental problems (Bayley et al 2007). Many reports from local government officers within South East Queensland indicate that many of these water bodies regularly fail to meet their design water quality objectives. Nutrient concentrations in existing water bodies were found to exceed relevant water quality objectives, particularly for phosphorus (Newton 2007). This often results in poor ecological function and the degradation of the water body, including excessive algal blooms and high turbidity. This appears to be the case in many of the artificial urban water bodies in South East Queensland because of relatively high temperatures that increase the productivity of algae. It was found that a median value of Total Nitrogen concentration was 0.55 mg/L, with a maximum of 3.3 mg/L. This median is greater than the Queensland Water Quality Guidelines of 0.35 mg/L (Bayley et al. 2007), meaning that eutrophic conditions generally dominate urban water bodies. In addition, a median Total Phosphorus concentration of 0.1 mg/L has been observed in urban water bodies in South East Queensland, which is higher than the Queensland Water Quality Guidelines of 0.01 mg/L (Bayley et al. 2007 and John Wilson and Partners Pty Ltd 2003). It is interesting to note that only 2 out of 28 urban water bodies tested in South East Queensland met the Queensland Water Quality Guidelines (Bayley et al. 2007). Similar research done in the USA by US NAWQA also found that inorganic nutrient levels are higher in urban waterways compared to forested waterways (Bayley et al. 2007).

Urban development also increases the variety of contaminants in catchments. It introduces a large number of potentially toxic contaminants that are not found at all in undeveloped catchments (Walsh et al 2004). Human activities produce new contaminants that may have been absent or present in trace amounts before the land was urbanized. For example, zinc drains off galvanized iron roofs; other metals, oils and rubber build up on roads from vehicles; fertilizers and pesticides applied to gardens; herbicides applied to paths and other surfaces.

3. Water Quality and Coral Reefs

There is a significant concern about the impact of runoff of nutrients, sediments and agrochemicals on the Great Barrier Reef (GBR). According to Moss et al. (1992) and McCulloch et al. 2003, sediment and nutrient input have increased several-fold since European settlement. It is estimated that current annual inputs of phosphorous and nitrogen from land are 43,000 and 7,000 to11,000 tonnes per year respectively. The following sections discuss the influence of water quality on coral health.

3.1. Sedimentation

According to Cooper and Fabricius (2007), "Sedimentation is the deposition of particulate material onto the benthos, with the origin of the particles being either resuspension from the seafloor or new imports through terrestrial runoff". Generally, levels of sedimentation are largest near the coast due to the re-suspension of wind waves on old seafloor sediments, and close to river mouths (Lirman et al. 2003). In addition, Wolanski et al. (2005) believes that sedimentation is regularly highest sheltered, wave-protected lagoons, bays, or deeper reef slopes. On the other hand, it is lowest in shallow wave-exposed areas. Furthermore, rates of sedimentation vary from time to time. They are usually high after particular events namely, strong waves, winds and terrestrial runoff.

An increase in concentrations of particulate materials can have both advantageous and disadvantageous effects on corals. Cooper and Fabricius (2007) claim that coral growth in some species may be improved by feeding on find sediment particles. However, Anthony and Fabricius (2000) believe that the ability of corals to convert those particulate organic matters to nutrition varies depending on types of sediment and coral species. "Some species gain a substantial proportion of their energy budgets from heterotrophic feeding on suspended particulate matter while others obtain most of their nutrition from phototrophy regardless of the availability of particulate matter" (Anthony & Fabricius 2000). In addition, the energy lost from a reduction of light at deeper depths is likely to be compensated by the energy gained from suspended particulate matter (Fabricius 2005). According to Cooper and Fabricius (2007), corals have an ability to photo-acclimatise to changes in light levels because they can adjust the concentration of photosynthetic pigments and the density of their symbionts. Hence, Symbionts can increase concentrations of photosynthetic pigments to adapt to low irradiance. Likewise, they can reduce the concentrations to have less photosynthetic pigments to adapt to high irradiance.

3.2. Nutrients

The major causes of nutrients namely nitrogen and phosphorous in the the Great Barrier Reef are upwelling from terrestrial runoff and the Coral Sea (McKergow et al. 2005). Nutrients are introduced to corals in various forms including particulate matter, dissolved inorganic and dissolved organic nutrients. Nitrogen and phosphorous are dissolved inorganic nutrients that are absorbed easily and rapidly by phytoplankton. Only small proportion of dissolved organic nutrients is bio-available (Furnas 2003). Most nutrients in the coastal zone released in terrestrial runoff are bio-available form of nutrients for corals. Nutrient concentrations on coral reefs fluctuate greatly with diverse spatial and temporal scales. For instance, concentrations of nutrients are usually higher in summer than in winter, and greater on coastal than offshore reefs (Brodie et al. 2007).

Similar to sedimentation, nutrients can have both positive and negative effects on coral reefs depending on levels of concentration. Rates of gross photosynthesis can be improved with reasonable levels of particulate nutrients and dissolved inorganic nutrients. In addition, it can also increase symbiont density and enhance tissue thickness, but undermine rates of calcification (Cooper & Fabricius 2007). In contrast, high concentrations of nutrients can promote outbreaks of corals' predator such as crown-of-thorns starfish population. They can also increase macroalgal cover and greatly reduce rates of calcification (Hutchings et al. 2008), which can slow coral growth.

3.3. Limits for coral

Fabricius (2009) found that macroalgal cover increased about four-fold as suspended solids increasing from 1.2 to 2.0 mg/L. Macroalgal cover also increased by >50% with increasing particulate nitrogen and by 40% with increasing particulate phosphorus. Hard coral richness steeply declined with increasing suspended solids, with highest richness at <0.8 mg/L and low richness at >2.0 mg/L suspended solids. Hard coral richness also decline with increasing particulate nitrogen and particulate phosphorus, with highest richness at <1.0 µmol/L particulate nitrogen and <0.06 µmol/L particulate phosphorus and low richness at >1.8 µmol/L particulate nitrogen and >0.10 µmol/L particulate phosphorus. The declines in phototrophic octocoral richness were much steeper than those of the hard corals. Richness was highest at <1 mg/L suspended solids, 1.0 µmol/L particulate nitrogen and 0.05 µmol/L particulate phosphorus. Richness was up to 50% lower at 2.0 mg/L suspended solids, 1.6 µmol/L particulate nitrogen and 0.10 µmol/L particulate phosphorus. Heterotrophic coral richness did not respond much to suspended solid and particulate phosphorus, and only weakly declined with particulate phosphorus increasing above 0.08 µmol/L. Therefore, Fabricius (2009) purposed the following maximum annual means as guideline values for coral: 1.5 mg/L suspended solids, 1.5 µmol/L (= 0.020 mg/L) particulate nitrogen and 0.09 µmol/L (0.0028 mg/L) particulate phosphorus.

The critical levels of nitrogen and phosphorous identified by research in the Caribbean and in the Great Barrier Reef (Goreau & Thacker 1994) are 0.014 mg/L nitrogen and 0.003 mg/L phosphorous. It is interesting to note that the median concentrations of total nitrogen and total phosphorous reported for urban water bodies in South East Queensland (0.55 mg/L and 0.1 mg/L respectively) far exceed these critical levels for coral.

4. Modelling the influence of urbanisation on water quality

Models are often used to predict the influence of land use change on water quality and quality within catchments. They are used to predict future trends or to assess the potential impacts of alternative catchment management plans or scenarios. MUSIC is an example of one model developed specifically for assessing the impact of urbanisation on changes in water flow and quality (eWater Cooperative Research Centre, n.d; Scheltinga and Moss 2010). One important limitation of models like MUSIC is that they require specific expertise and large data sets to use. Where data are limited and patchy, models like MUSIC can be difficult to apply. In response to this many researchers have utilised alternative modelling methods. One of the emerging methods in catchment management is the application of Bayesian Network models.

Bayesian networks are graphical models consisting of nodes, links and a set of probabilities called conditional probability tables (Bashari et al. 2009; Liedloff & Smith 2010; Nadkarni & Shenoy 2004). Nodes represent variables which can be physical, social or economic factors (Cain et al. 2003; Smith et al. 2007). Links indicate causal or cause-effect relationships between variables. Probabilities are used to specify how the relationships between the variables operate (Cain 2001). In other words, Bayesian networks consist of qualitative and quantitative parts, the qualitative part being graphical model (made up of nodes and links) and the quantitative part being probabilities that quantify the relationships between nodes.

Bayesian networks attempt to combine expert knowledge and empirical data to development models in situation where there are uncertainties. They are increasingly used to model uncertainties in complicated domains, particularly environmental management where there are many variables and information is missing (Uusitalo 2007). Bayesian networks have a number of advantages over traditional deterministic models. One advantage is that they can be used to develop models where uncertainty is high and data are missing (Nadkarni & Shenoy 2004). They also allow model builders to integrate knowledge and expert opinion with empirical data (Uusitalo 2007). Another advantage is that because they are graphical, Bayesian networks are easier for non-specialists to use and understand. Consequently, they can improve understanding of situations and leave decision-makers to come up with their own conclusion (Cain et al. 2003). As with all modelling tools, Bayesian networks are without their disadvantages. One important disadvantage is that they are acyclic models and do not support feedback loops, making it difficult to model cyclical processes over time (Bashari et al. 2009). Another disadvantage is that the number of probabilities needs to populate a Bayesian network increases rapidly as the number of variables in the model increases. Consequently, it is important to omit less significant variables and make a model simple (Cain et al. 2003; Uusitalo 2009). Another challenging is that it might be difficult to obtain knowledge from experts when building a Bayesian network. There might be disagreement among experts about definition of variables and the probabilities in the model if they are obtained from expert opinion.

Recent studies have used Bayesian networks to integrating expert knowledge and empirical data to water quality and quantity in catchments and also to model the impacts on coral reefs. Shenton et al. 2010, for instance, used Bayesian network model to predict the effects of nitrogen fertiliser management strategies in the Tully River catchment (northern Queensland) on the condition of inshore coral reefs of the Great Barrier Reef. Pollino et al. (2010) used Bayesian networks to assess the risk posed by alternative water management strategies and climate change to water quality and environmental flows within catchments of the Murray Darling Basin. Hart et al. (2009) also used Bayesian networks to model the affect of climate change on environmental flows and fish populations in Victorian and Northern Territory water catchments. Wooldridge and Done (2004) used Bayesian networks to understand the influence of water temperature, and habitat type on coral bleaching on the Great Barrier Reef.

Developing a Bayesian network involves several steps. The first step is conceptual model development, which aims to capture the key variables that influence modelling outputs or objectives and the causal relationships among them. Smith et al (2007) recommended that first step in conceptual model development should be a review of literature followed by meetings or workshops with experts. Keeping the structure of the conceptual model as simple as possible is important because this will make the model easier to understand and populate with probabilities (Cain 2001). The next step is to identify data that can be used to obtain probabilities for the model. This is not straight forward because models often do not fit available data sets easily and knowledge from experts is often the only available source of probabilistic information for Bayesian networks (Burgman et al. 2006). This means that models often have to be adjusted to utilise available data and probabilities may also need to be elicited from experts. Elicitation of probabilities form experts can be a major obstacle in building Bayesian networks because expert opinion is subject to bias (Australian Centre of Excellence for Risk Analysis 2010). To limit bias there are several key factors that should be taken into account. Firstly, it is important to define variables in the model well. Having clear understanding of definition of variables is crucial in order to avoid differences in understanding among experts (Burgman et al. 2006). Secondly, selection of experts is important. Ideally, it is best to choose experts who have local experience or who have published literature in domain of interest (Australian Centre of Excellence for Risk Analysis 2010). Renooij (2001) also recommended that experts used to obtain probabilities for a Bayesian network should also be involved in building the structure of the Bayesian networks so that they have a clear understanding of what the variables and relationships in the model mean.

Once all of the conditional probability tables have been populated, a Bayesian network is ready for use. Bayesian Networks can be used for two main types of analysis – scenario and sensitivity analysis. Scenario analysis is performed by selecting particular states of nodes within the network and observing how this changes the probabilities for states in other nodes (Smith et al. 2007). Sensitivity analysis is performed by varying the state selected particular nodes in the network and observing how this varied the probabilities for states in other nodes within the network. Nodes that are sensitivity to change will have a large change in probability for their states under different scenarios while nodes that are insensitive to change will have a small change in probability for their states. Scenario analysis is used to determine the probability of outcomes under different scenarios while sensitivity analysis is used to determine the relative influence of variables within the network on outcomes.

5. Methods

5.1. Study Area

Eli Creek Catchment covers approximately 3,460 ha and is located within the Hervey Bay area (Scheltinga and Moss 2010) (Figure 1). Its waters flow into Hervey Bay and the Sothern most end of the Great Barrier Reef. One of the major changes in Eli Creek Catchment over the past decade has been expanding population growth and urbanisation. Although most of the catchment area is still rural, the level of urbanization has increased significantly from 17 percent in 2003 to 26 percent in 2010 (John Wilson and Partners Pty Ltd 2003 and Scheltinga and Moss 2010). More areas are being converted to commercial, residential and industrial land uses and the level of urbanisation is eventually expected to reach 60 % (Scheltinga and Moss 2010). This is expected to change water flows within the catchment, increasing peak flows due to increases in impervious surfaces, which in turn will increase pollutant loads from urban storm water into waterways. This will ultimately affect water quality in Eli creek and inshore ecosystems such as coral reefs, which are adjacent to Eli Creek near Point Vernon and further south along the foreshore of Hervey Bay (Scheltinga and Moss 2010).

5.2. Model development

5.2.1. Conceptual model development

On the 6th and 7th of May 2010 a reef resilience workshop was held in Hervey Bay, which aimed to bring together specialist and local knowledge and link catchment and coastal zone management to reef health and resilience. The goal of this workshop was to support knowledge-building and decision-making (particularly in relation to urban stormwater management, urban planning, and conservation) by identifying priority catchment and coastal management actions that will reduce human pressures and increase the resilience of the local nearshore reefs (Patterson et al 2010). An important output of this workshop was an influence diagram outlining the key stressors influencing coral health (toxicants, nutrients, sediments and freshwater), the key issues contributing to these stressors (such as rural, urban and marine point and non-point source pollution) and key human activities influencing these issues (such as urban development and stormwater discharge) (see Appendix A). This influence diagram was used as the starting point for the development of a conceptual model of the influence of urbanization on water quality in

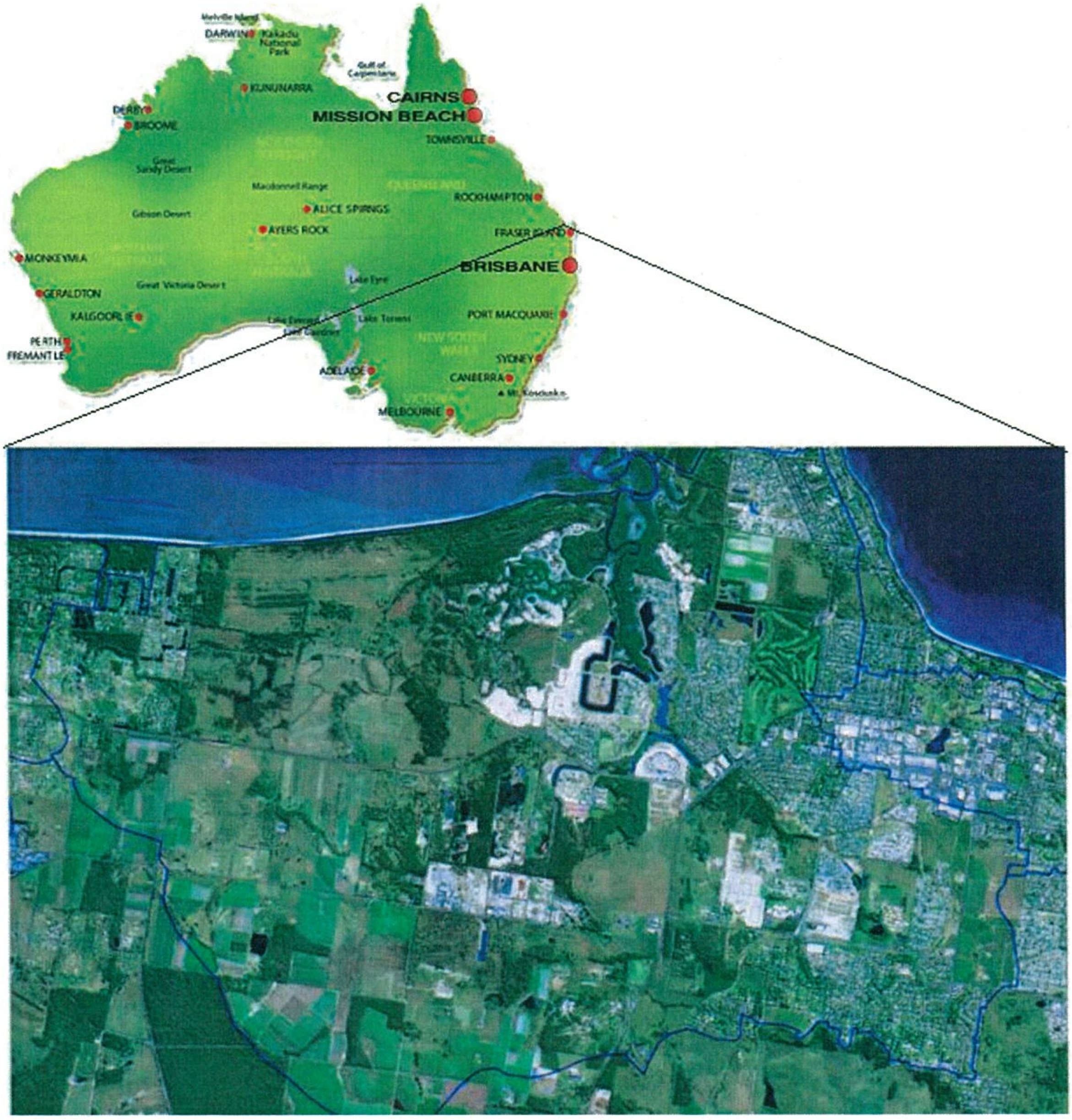


Figure 1: Eli Creek Catchment (blue line indicates catchment boundary)

Eli Creek. Another important study used in conceptual model development was that reported by Ames and Neilson (2001). This study a Bayesian network was used to model nutrient loads in East Canyon Creek, Northern Utah, USA, and their influence on fish habitat (see Appendix B).

Besides reports from previous studies, a meeting was held in June 2011 with staff from the Department of Environment and Resource Management (DERM) in Hervey Bay to discuss to scope of the modelling exercise and identify data that could potentially be used to develop a model. The result of this meeting was to focus on the Eli Creek Catchment as this catchment has experienced rapid urbanization over the last decade a water quality records did exist for Eli Creek over this period.

5.2.2. Data collection

Data collection was based on secondary data resources. The basic data required to model the influence of urbanisation on Eli Creek water quality were water quality records, creek flow records and trends in urban area. Monthly water quality records from 2001 to 2011 were obtained from Wide Bay Water Corporation, which is owned by the Frazer Coast Regional Council and provides water and waste water services to Hervey Bay. Water quality records were available for two points in Eli Creek – upstream and downstream of the waste water treatment point discharge point into Eli Creek (Figure 2). The records contained data on the following water quality parameters: total nitrogen (mg/L), total phosphorous (mg/L), suspended solids (mg/L), Biological Oxygen Demand (mg/L), pH and Faecal Coliforms (cfu/100mL). Total nitrogen (mg/L), total phosphorous (mg/L), suspended solids (mg/L) were used a water quality indicators for model development because critical levels for coral were available for these parameters.

While some flow modelling had been conducted for Eli Creek in the past (John Wilson and Partners Pty Ltd 2003), these flow predictions did not correspond to the same period at the available water quality data. Direct flow data for Eli Creek was also not available for the Wide Bay Water water quality monitoring points. Therefore, in the absence of flow data, total monthly rainfall records for the period 1999 to 2011 were source from the Australian Bureau of Meteorology and were used as a surrogate for flow data. The rainfall records were obtained Hervey Bay Airport, which is the closest weather station to Eli Creek. Some monthly rainfall records were missing from the data set, especially for early 1999.

The trend in urban development for Eli Creek was obtained from a mixture of reported data, GIS data and satellite imagery. Hervey Bay City Council: Eli Creek Catchment Management Plan and a Waterbody Monitoring Strategy for the Fraser Coast Regional Council reports contained figures of urbanization percentage for Eli Creek in 2003 and 2010 for 17% and 26% respectively. The 1999 land use map of Queensland (produced using the Australian Land Use and Management Classification (Australian Bureau of Agricultural and Resource Economics and Sciences 2011) was obtained from DERM and use to estimate the percentage urban development of Eli Creek Catchment in 1999. A satellite image of Eli Creek Catchment taken 2009 was obtained from the

Burnett Mary Regional Group (BMRG). This satellite image, along with the Digital Cadastre Data Base obtained from DERM, was used to map the urban area of Eli Creek Catchment in 2009 using ArcGIS and determine the percentage urbanization for that year. For those years between 1999 and 2011 with no records of urban area, the urban area was interpolated by drawing a line of best fit between those years with known urban growth percentage (1999, 2003, 2009 and 2010) and using this to estimate urban percentage for years with missing data.

Figure 2: Point on Eli Creek monitored for water quality by Wide Bay Water Corporation (1 = downstream water quality monitoring point; 2 = upstream water quality monitoring point).

5.2.3 Bayesian Network development

Netica (Norsys Corporation 1998) was the software used to construct the Bayesian network. The network structure (nodes and links) was based on the conceptual model. States were then defined for each node according to the data available (Table 1).

Table 1: Definitions for nodes and their states in the Bayesian Network.

Node	Definition
Season	This node represents seasons of the year. Its states are: • Summer: December to February • Autumn: March to May • Winter: June to August • Spring: September to November.
Year	This node represents years with states from 1999 to 2011.
Rainfall	This node represents the amount of rainfall per month (mm). It's states are: • 0 - 38.35: rainfall less than the first quartile for the period 1999 to 2011. • 38.35 - 69.5: rainfall between the first quartile and median for the period 1999 to 2011. • 69.5 - 108.05: rainfall between median and the third quartile for the period 1999 to 2011. • Greater than 108.05: rainfall greater than the third quartile for the period 1999 to 2011.
Urbanisation	This node represents the percentage of Eli Creek Catchment covered by urban area. It's states range between 16% and 28%, broken into 2% intervals.
TN Upstream	This node represents total nitrogen (TN) concentration (mg/L) in Eli Creek upstream of the waste water treatment plant outlet. It's states are: • 0 - 0.014: TN concentration below the limit acceptable for coral. • 0.014 - 0.4575: TN concentration between the limit acceptable for coral and the overall up and downstream median for the period 2001 to 2011. • Greater than 0.4575: TN concentration greater than the overall up and downstream median for the period 2001 to 2011.
TN Downstream	This node represents total nitrogen (TN) concentration (mg/L) in Eli Creek downstream of the waste water treatment plant outlet. It's states are: • 0 - 0.014: TN concentration below the limit acceptable for coral. • 0.014 - 0.4575: TN concentration between the limit acceptable for coral and the overall up and downstream median for the period 2001 to 2011. • Greater than 0.4575: TN concentration greater than the overall up

	and downstream median for the period 2001 to 2011.
TP Upstream	This node represents total phosphorous (TP) concentration (mg/L) in Eli Creek upstream of the waste water treatment plant outlet. It's states are: • 0 - 0.003: TP concentration below the limit acceptable for coral. • 0.003 - 0.056: TP concentration between the limit acceptable for coral and the overall up and downstream median for the period 2001 to 2011. • Greater than 0.056: TN concentration greater than the overall up and downstream median for the period 2001 to 2011.
·TP Downstream	This node represents total phosphorous (TP) concentration (mg/L) in Eli Creek upstream of the waste water treatment plant outlet. It's states are: • 0 - 0.003: TP concentration below the limit acceptable for coral. • 0.003 - 0.056: TP concentration between the limit acceptable for coral and the overall up and downstream median for the period 2001 to 2011. • Greater than 0.056: TN concentration greater than the overall up and downstream median for the period 2001 to 2011.
SS Upstream	This node represents total suspended solids (SS) concentration (mg/L) in Eli Creek upstream of the waste water treatment plant outlet. It's states are: • 0 - 0.8: SS concentration below the limit acceptable for coral. • 0.8 – 17.3: SS concentration between the limit acceptable for coral and the overall up and downstream median for the period 2001 to 2011. • Greater than 17.3: SS concentration greater than the overall up and downstream median for the period 2001 to 2011.
SS Downstream	This node represents total suspended solids (SS) concentration (mg/L) in Eli Creek downstream of the waste water treatment plant outlet. It's states are: • 0 - 0.8: SS concentration below the limit acceptable for coral. • 0.8 – 17.3: SS concentration between the limit acceptable for coral and the overall up and downstream median for the period 2001 to 2011. • Greater than 17.3: SS concentration greater than the overall up and downstream median for the period 2001 to 2011.
TN Coral Upstream	This node represents the total nitrogen concentration (mg/L) in Eli Creek upstream of the waste water treatment plant outlet in relation to the acceptable limit for coral (less than or greater than 0.014 mg/L).

TN Coral Downstream	This node represents the total nitrogen concentration (mg/L) in Eli Creek downstream of the waste water treatment plant outlet in relation to the acceptable limit for coral (less than or greater than 0.014 mg/L).
TP Coral Upstream	This node represents the total phosphorous concentration (mg/L) in Eli Creek upstream of the waste water treatment plant outlet in relation to the acceptable limit for coral (less than or greater than 0.003 mg/L).
TP Coral Downstream	This node represents the total phosphorous concentration (mg/L) in Eli Creek downstream of the waste water treatment plant outlet in relation to the acceptable limit for coral (less than or greater than 0.003 mg/L).
SS Coral Upstream	This node represents the total suspended solid concentration (mg/L) in Eli Creek upstream of the waste water treatment plant outlet in relation to the acceptable limit for coral (less than or greater than 0.8 mg/L).
SS Coral Downstream	This node represents the total suspended solid concentration (mg/L) in Eli Creek downstream of the waste water treatment plant outlet in relation to the acceptable limit for coral (less than or greater than 0.8 mg/L).
Coral Health Upstream	This node represents the overall water quality in Eli Creek upstream of the waste water treatment plant outlet in relation to coral health.
Coral Health Downstream	This node represents the overall water quality in Eli Creek downstream of the waste water treatment plant outlet in relation to coral health.

To populate the model with probabilities, a data file (called a case file) was created. This file contained data for each node in the Bayesian network for each month from 1999 to 2011 (except the TN Coral Upstream, TN Coral Downstream, TP Coral Upstream, TP Coral Downstream, SS Coral Upstream, SS Coral Downstream, Coral Health Upstream and Coral Health Downstream nodes) (see Table 2 for an extract from the case file and Appendix C for the full case file). The case file was then used to learn the probabilities for the Bayesian network using counting-learning algorithm (Lauritzen & Spiegelhalter 1988) available in Netica.

The probabilities for TN Coral Upstream, TN Coral Downstream, TP Coral Upstream, TP Coral Downstream, SS Coral Upstream, SS Coral Downstream, Coral Health Upstream and Coral Health Downstream nodes were set manually using deterministic probability tables. For example, the probability table for TN Coral Upstream is shown in Table 3, while the probability table for Coral Health Upstream is shown in Table 4.

Table 2: Extract from the case file used to learn probabilities for the Bayesian network.

ID	Year	Season	Rainfall	Urbanisation	TN Upstream	TN Downstream	TP Upstream	TP Downstream	SS Upstream	SS Downstream
56	x_2004	Summer	321	18.31	0.625	0.107	0.197	0.223	87	22
57	x_2004	Summer	271	18.31	1.28	1.1	0.275	0.266	64	70
58	x_2004	Autumn	223.7	18.31	0.904	1.44	0.212	0.255	46	15
59	x_2004	Autumn	69.6	18.31	1.15	0.548	0.132	0.095	41	17
60	x_2004	Autumn	35.6	18.31	0.777	1.94	0.132	0.43	22	10
61	x_2004	Winter	17.6	18.31	0.56	2.69	0.138	0.55	19	11
62	x_2004	Winter	5.6	18.31	0.769	2.38	0.135	0.403	18	15
63	x_2004	Winter	0.4	18.31	0.711	0.209	0.092	0.055	23	33
64	x_2004	Spring	55.4	18.31	1.02	0.212	0.135	0.054	19	9.6
65	x_2004	Spring	134.8	18.31	0.784	0.314	0.122	0.071	39	35
66	x_2004	Spring	39.4	18.31	0.806	0.579	0.106	0.091	29	27
67	x_2004	Summer	52.4	18.31	0.329	0.264	0.066	0.057	64	69

Table 3: The probability table for TN Coral Upstream

TN Upstream	0 to 0.014	>=0.014
0 to 0.014	100.00	0.00
0.014 to 0.1	0.00	100.00
>=0.1	0.00	100.0

Table 4: The probability table for Coral Health Upstream

TN Coral Upstream	TP Coral Upstream	SS Coral Upstream	Coral Health Upstream
0 to 0.014	0 to 0.003	0 to 0.8	OK
0 to 0.014	0 to 0.003	>=0.8	Degraded
0 to 0.014	>=0.003	0 to 0.8	Degraded
0 to 0.014	>=0.003	>=0.8	Degraded
>=0.014	0 to 0.003	0 to 0.8	Degraded
>=0.014	0 to 0.003	>=0.8	Degraded
>=0.014	>=0.003	0 to 0.8	Degraded
>=0.014	>=0.003	>=0.8	Degraded

5.3. Model use

Both scenario and sensitivity analysis were performed using the Bayesian network in order to assess the influence of urbanisation on water quality in Eli Creek. Eight basic scenarios were investigated (see Table 5). These were urbanisation at 2003 (low urbanisation) and 2010 (high urbanisation) for each season of the year (summer, autumn, winter and spring). Sensitivity analysis was performed using the sensitivity to findings function available in Netica. This function calculated sensitivity as the percent variance reduction (Pearl, 1988), which is a unit-less measure of the reduction in uncertainty of a target node (for example TN Upstream) due to findings at a findings node (for example Urbanisation or Rainfall) and is calculated as Vr, which is the expected reduction in variance of variable Q with q states due to a finding at variable F with f states. The greater the variance reduction of a target node due to findings at a findings node, the more sensitive the target node is to a change in the findings node.

$$Vr = V(Q) - V(Q \mid F)$$

Where V(Q) is the variance of the value of Q before any new findings and V(Q|F) is the variance of the value of Q after new findings for variable F.

Sensitivity analysis was performed on TN, TP, SS upstream and downstream nodes to test the relative influence of urbanisation and rainfall on these water quality parameters.

Table 5: Scenarios tested using the Bayesian network.

Scenario	Season	Year
1	Summer	2003 – low urbanisation
2	Summer	2010 – high urbanisation
3	Autumn	2003 – low urbanisation
4	Autumn	2010 – high urbanisation
5	Winter	2003 – low urbanisation
6	Winter	2010 – high urbanisation
7	Spring	2003 – low urbanisation
8	Spring	2010 – high urbanisation

6. Results

6.1 Conceptual model

The conceptual model for Eli Creek Catchment water quality and the impact of water quality on inshore coral reef health is presented in Figure 3. The conceptual model represents logic that the season and the year determine monthly rainfall, while the year determines the percent urbanisation within Eli Creek Catchment. The monthly rainfall and percent urbanisation in turn influence Eli Creek water quality indicators, such as TN, TP and SS, and these water quality indictors influence coral health. In the conceptual model, rainfall is used as a surrogate for Eli

Creek flow because flow data were not available. Rainfall and creek flow can not only wash pollutants into Eli Creek but also dilute them, so it is an important determinant of water quality. The conceptual model does not include dilution of pollutants that would occur as water leaves Eli Creek and enters Hervey Bay; therefore, the impact on coral health is based purely on Eli Creek water quality.

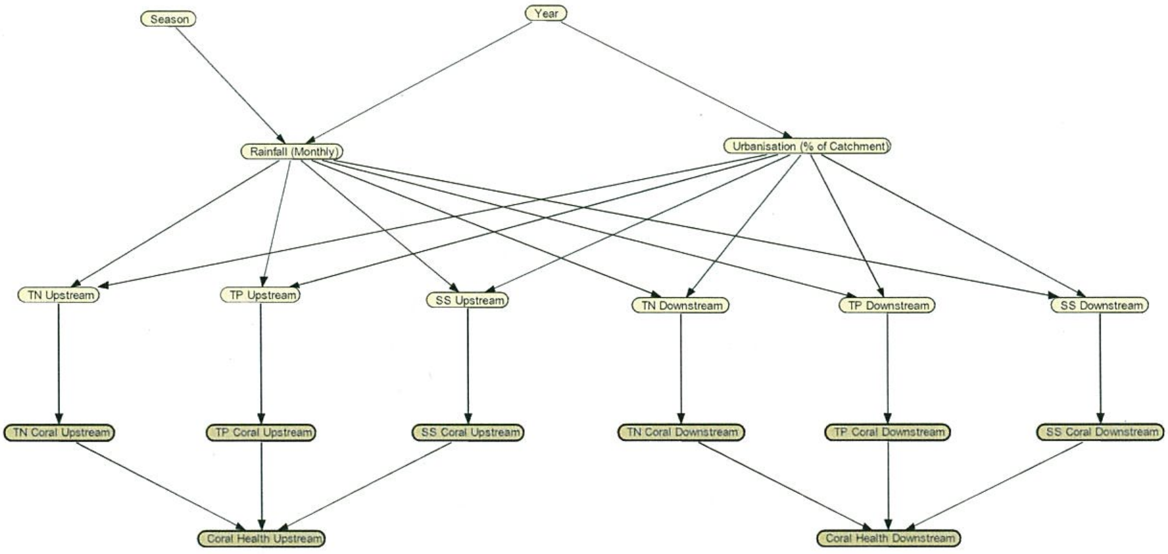


Figure 3: Conceptual model of the influence of urbanisation and water quality and inshore coral reef health.

6.2. Data analysis

The trend in percentage urbanisation of Eli Creek Catchment is shown in Figure 4. For 2003 and 2010 the urban area percentage was reported to be 17% and 26% respectively (Scheltinga & Moss 2010). In 1999 and 2009 the urban area was estimated to be 12% and 24.8% respectively. The growth in urban area between 1999 and 2011 has been approximately 1.3% per year. This trend line was used to interpolate urban percent for the other years.

When compared to total monthly rainfall and urban percentage in Eli Creek Catchment, TN, TP and SS displayed no clear trends (see Appendix D). For instance, Figures 5 and 6 show the trend in TN upstream of the Eli Creek wastewater treatment plant compared to total monthly rainfall (Figure 4) and urban area percentage. A line of best fit is shown on both graphs; however the goodness of fit (R^2) of these lines is very low, indicating a poor relationship between TN upstream and total monthly rainfall and urban area percentage.

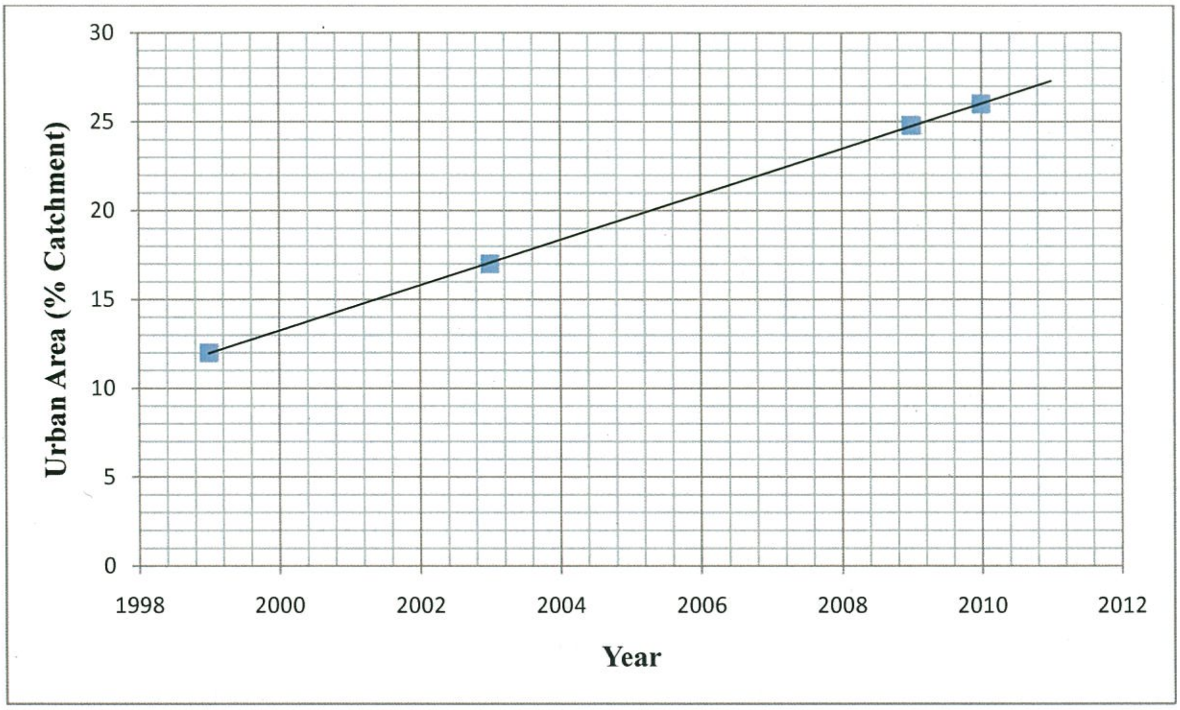


Figure 4: Eli Creek Catchment urbanisation trend from 1999 to 2011 (the graph shows the points where urban % is known for 1999, 2003, 2009 and 2010 and the trend line was used to interpolate urban % for the other years).

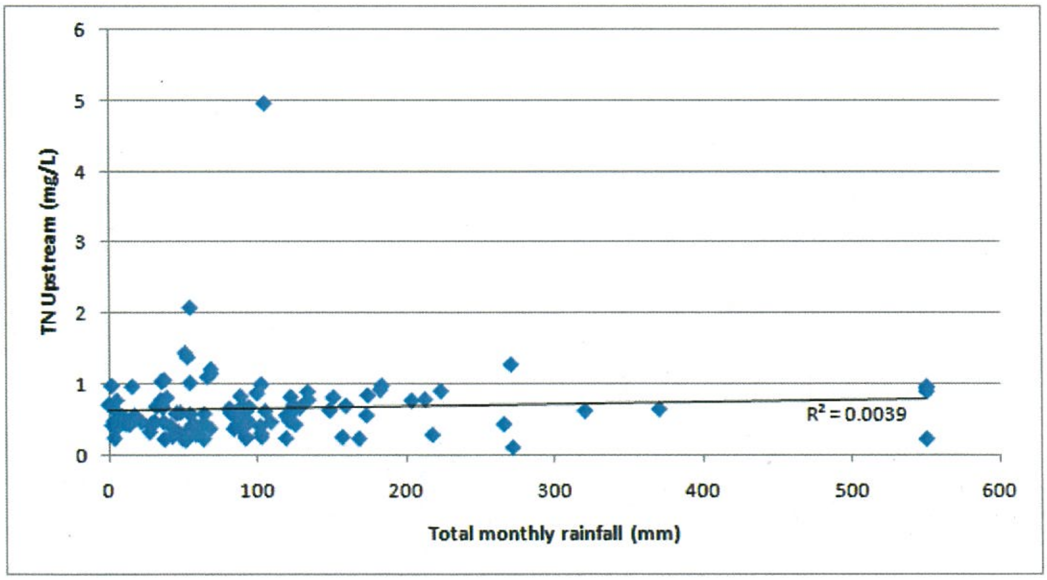


Figure 5: TN upstream of the Eli Creek wastewater treatment plant compared to total monthly rainfall (line of best fit is shown on the graph)

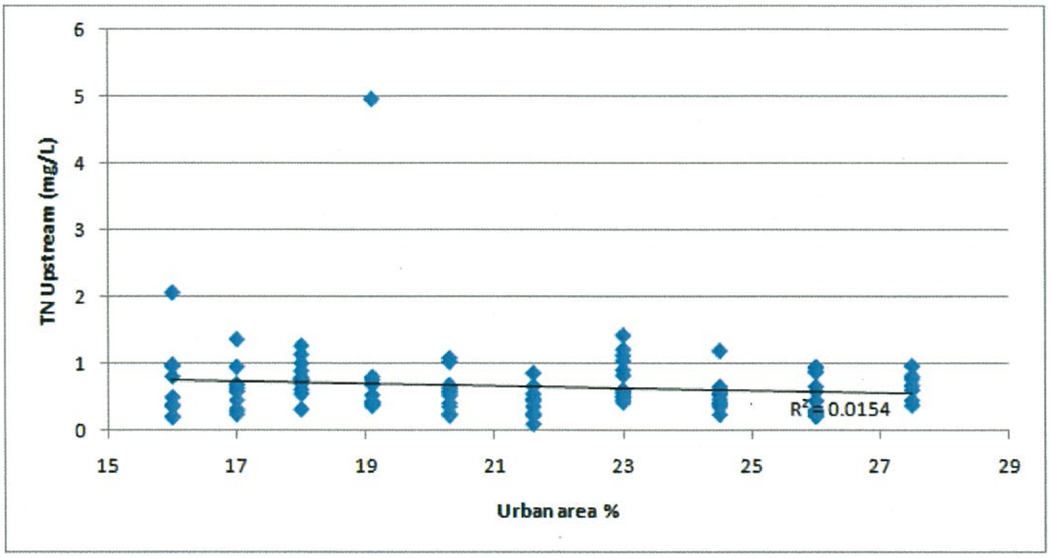


Figure 6: TN upstream of the Eli Creek wastewater treatment plant compared to urban area percentage (line of best fit is shown on the graph)

When plotted over time, TN, TP and SS in Eli Creek Catchment were highly variable and showed no clear trends with respect to increasing urban area over time or changes in monthly rainfall patterns (see Figures 7, 8 and 9).

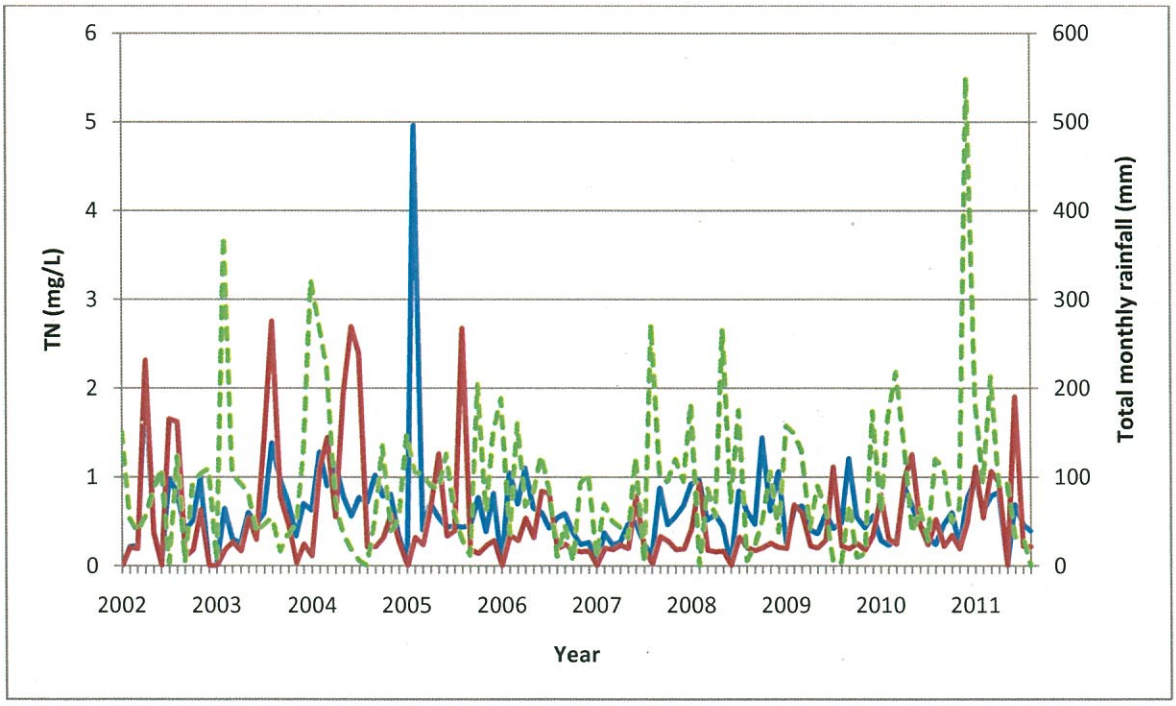


Figure 7: TN concentration (mg/l) measured in Eli Creek (blue line = upstream of wastewater treatment plant; red line = downstream of waste water treatment plant; dotted line = total monthly rainfall (mm))

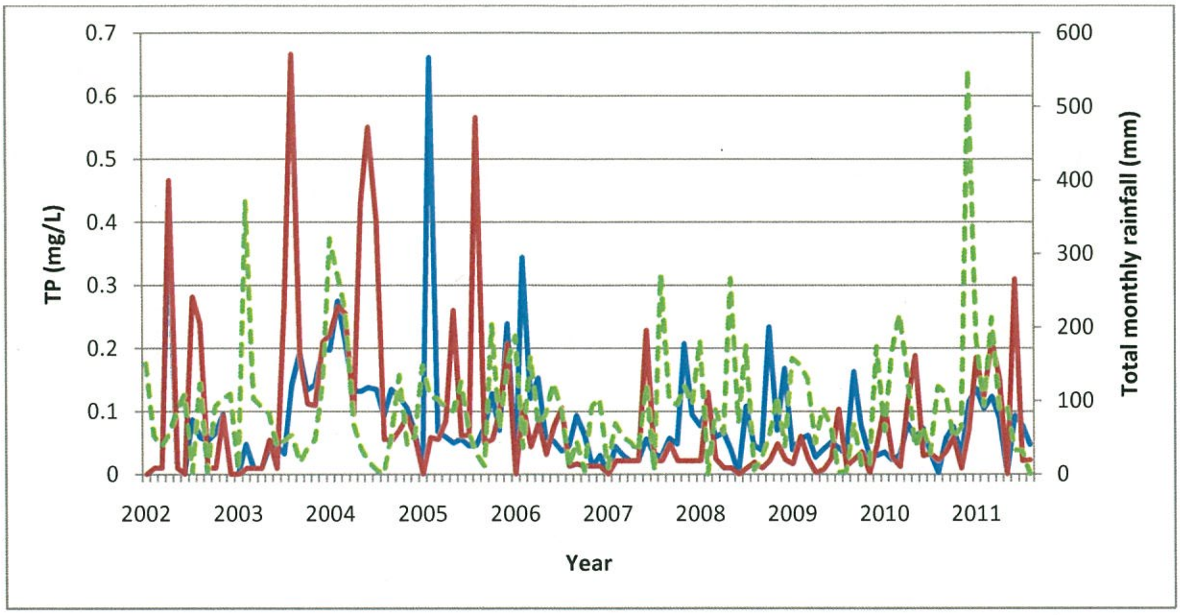


Figure 8: TP concentration (mg/l) measured in Eli Creek (blue line = upstream of wastewater treatment plant; red line = downstream of waste water treatment plant; dotted line = total monthly rainfall (mm))

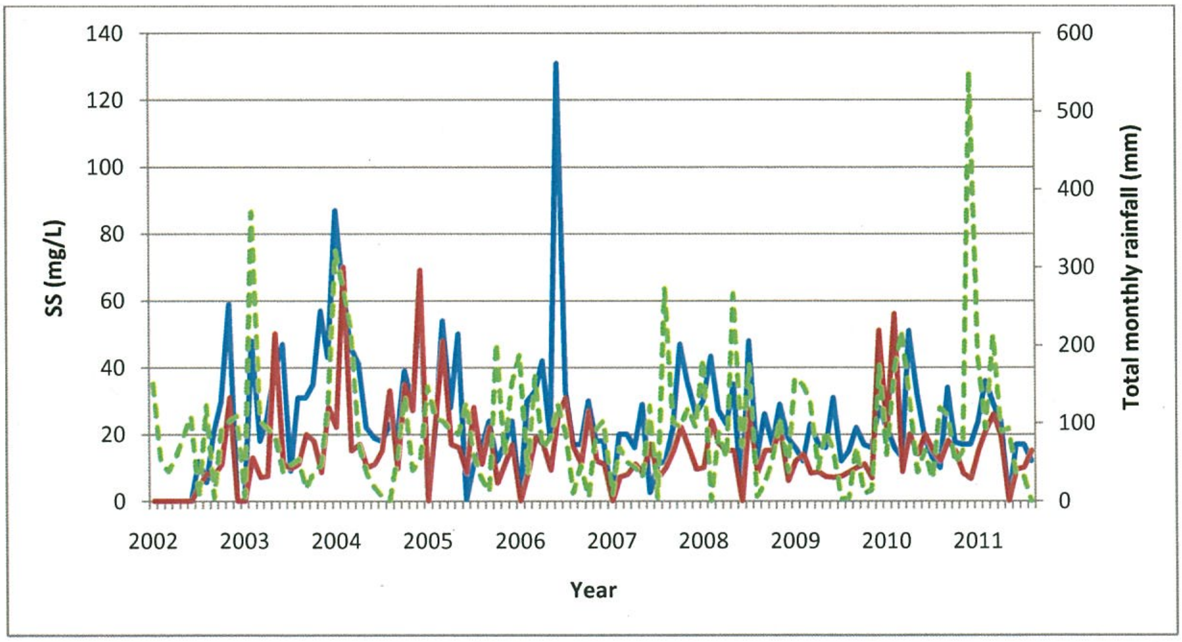


Figure 9: SS concentration (mg/l) measured in Eli Creek (blue line = upstream of wastewater treatment plant; red line = downstream of waste water treatment plant; dotted line = total monthly rainfall (mm))

6.3. Bayesian Network Model

6.3.1. The model

The complete Bayesian network model for the influence of urbanisation on Eli Creek water quality and subsequent coral health is show in Figure 10. The model has the same structure as the conceptual model show in Figure 3, however node states and probabilities are now shown. Conditional probability tables for each node in the model are given Appendix E. An example of one of the probability tables (for TN upstream) is shown in Table 6. The first row in this table indicates that, based on the available data, where monthly rainfall was less than the first quartile (0 to 38.35) and urbanisation was 14 to 16 %, there was a 66.67% chance that TN upstream was between the critical limit for coral and the median (0.014 to 0.4575) and a 33.33% chance it was greater than or equal to the median (>=0.4575).

There is no scenario selected in the model shown in Figure 10, hence the probability distributions for each node represent the probabilities for each variable in the model over the period 1999 to 2011. For instance, between 1999 and 2011, TN upstream of the Eli Creek wastewater treatment plant (TN Upstream) was most likely (62.1%) to exceed the median of 0.4575 mg/L, while TN downstream of the Eli Creek wastewater treatment plant (TN Downstream) was most likely (58.4%) to be between the critical limit for coral and the median of 0.014 and 0.4575 mg/L. A similar pattern occurred for TP and SS, with upstream levels more likely to exceed the median while downstream levels more likely to be below the median. The TN Coral, TP Coral and SS Coral nodes for both up and downstream indicate that Eli Creek water quality indicators were always above the critical levels for coral.

6.2.2. Scenario analysis

The results of scenario analysis using the Bayesian network are shown in Table 7. These results are graphed in Figures 11, 12 and 13 from TN, TP and SS respectively. For TN, upstream levels were consistently higher than downstream levels for both 2003 (low urban area %) and 2010 (high urban area %) (Figure 11). However there was a distinct difference in the seasonal trend in TN between 2003 and 2010. In 2003, TN levels moved in the opposite direction to rainfall, with lower TN levels occurring during higher rainfall periods and higher TN levels occurring during lower rainfall periods (Figure 11a). In 2010, TN levels moved in a similar direction to rainfall, with lower TN levels occurring during lower rainfall periods and higher TN levels occurring during higher rainfall periods (Figure 11b).

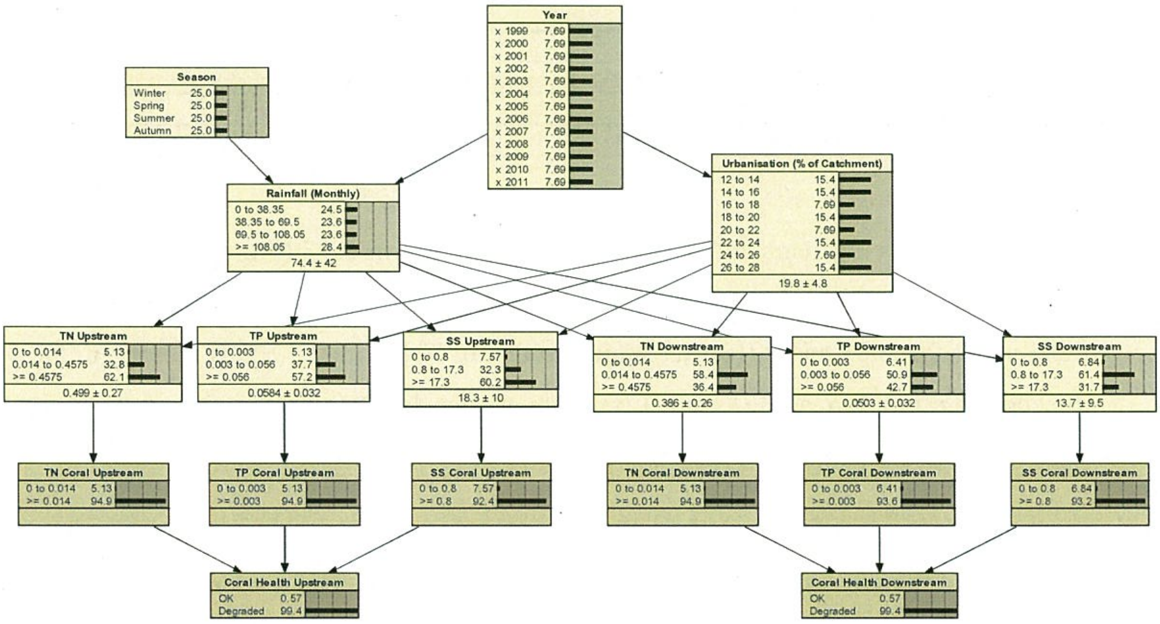


Figure 10: Complete Bayesian network

Table 6: Conditional probability table for TN Upstream

Rainfall (Monthly)	Urbanisation	0 to 0.014	0.014 to 0.4575	>=0.4575
0 to 38.35	12 to 14	33.33	33.33	33.33
0 to 38.35	14 to 16	0.00	66.67	33.33
0 to 38.35	16 to 18	0.00	0.00	100.00
0 to 38.35	18 to 20	0.00	33.33	66.67
0 to 38.35	20 to 22	0.00	33.33	66.67
0 to 38.35	22 to 24	0.00	20.00	80.00
0 to 38.35	24 to 26	0.00	50.00	50.00
0 to 38.35	26 to 28	0.00	25.00	75.00
38.35 to 69.5	12 to 14	33.33	33.33	33.33
38.35 to 69.5	14 to 16	0.00	50.00	50.00
38.35 to 69.5	16 to 18	0.00	33.33	66.67
38.35 to 69.5	18 to 20	0.00	60.00	40.00
38.35 to 69.5	20 to 22	0.00	0.00	100.00
38.35 to 69.5	22 to 24	0.00	60.00	40.00
38.35 to 69.5	24 to 26	0.00	33.33	66.67
38.35 to 69.5	26 to 28	0.00	75.00	25.00
69.5 to 108.05	12 to 14	33.33	33.33	33.33
69.5 to 108.05	14 to 16	0.00	33.33	66.67
69.5 to 108.05	16 to 18	0.00	66.67	33.33
69.5 to 108.05	18 to 20	0.00	20.00	80.00
69.5 to 108.05	20 to 22	0.00	75.00	25.00
69.5 to 108.05	22 to 24	0.00	0.00	100.00
69.5 to 108.05	24 to 26	0.00	100.00	0.00
69.5 to 108.05	26 to 28	0.00	0.00	100.00
>=108.05	12 to 14	33.33	33.33	33.33

>=108.05	14 to 16	0.00	0.00	100.00
>=108.05	16 to 18	0.00	0.00	100.00
>=108.05	18 to 20	0.00	14.29	85.71
>=108.05	20 to 22	0.00	0.00	100.00
>=108.05	22 to 24	0.00	33.33	66.67
>=108.05	24 to 26	0.00	25.00	75.00
>=108.05	26 to 28	0.00	36.36	63.64

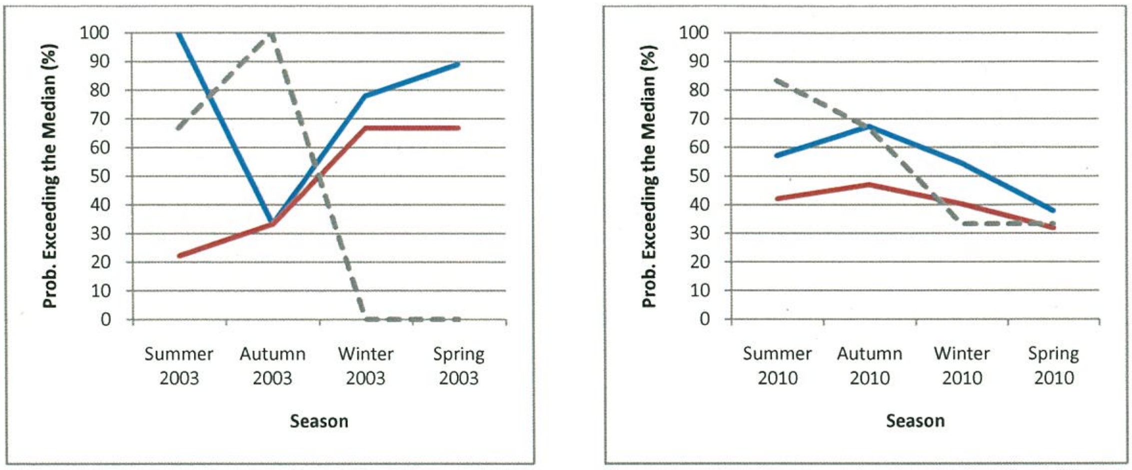
For TP, the levels upstream and downstream were similar in 2003 (Figure 12a), however, in 2010 upstream levels were consistently higher than downstream levels (Figure 12b). The seasonal trend in TP for 2003 and 2010 was similar to that of TN, with TP levels moving in the opposite direction to rainfall in 2003 (Figure 12a) and a similar direction to rainfall or remained relatively steady in 2010 (Figure 12b).

For SS, the upstream levels were consistently higher than downstream levels for both 2003 and 2010 (this difference was very clear in 2003) (Figure 13). The seasonal trend in SS was the opposite to that of TN and TP. In 2003, the trend in SS levels were similar to the trend in rainfall, with higher SS levels during higher rainfall periods and lower SS levels during lower rainfall periods (Figure 13a). In 2010, the trend in SS levels were opposite to the trend in rainfall, with lower SS levels during higher rainfall periods and higher SS levels during lower rainfall periods (Figure 13b).

In 2003, TN, TP and SS levels were generally more variable across the year compared to 2010.

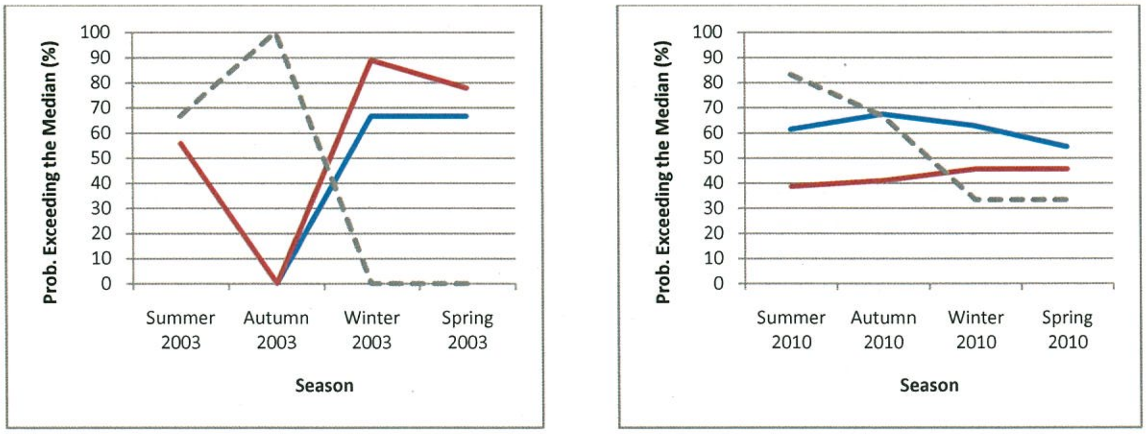
Table 7: Scenario analysis results for TN, TP and SS upstream and downstream of the wastewater treatment plant.

Scenario	Prob. Upstream TN exceeding the median	Prob. Downstream TN exceeding the median	Prob. Upstream TP exceeding the median	Prob. Downstream TP exceeding the median	Prob. Upstream SS exceeding the median	Prob. Downstream SS exceeding the median	Prob. Rainfall exceeding the median
1 – Summer 2003	100	22.2	55.6	55.6	100	55.6	66.7
2 – Summer 2010	57.2	42	61.4	38.6	54.2	50	83.3
3 – Autumn 2003	33.3	33.3	0	0	100	33.3	100
4 – Autumn 2010	67.4	47	67.4	40.9	41.7	33.3	66.7
5 – Winter 2003	77.8	66.7	66.7	88.9	77.8	22.9	0
6 – Winter 2010	54.5	40.2	62.9	45.5	50	33.3	33.3
7 – Spring 2003	88.9	66.7	66.7	77.8	88.9	44.4	0
8 – Spring 2010	37.9	31.8	54.5	45.5	66.7	50	33.3



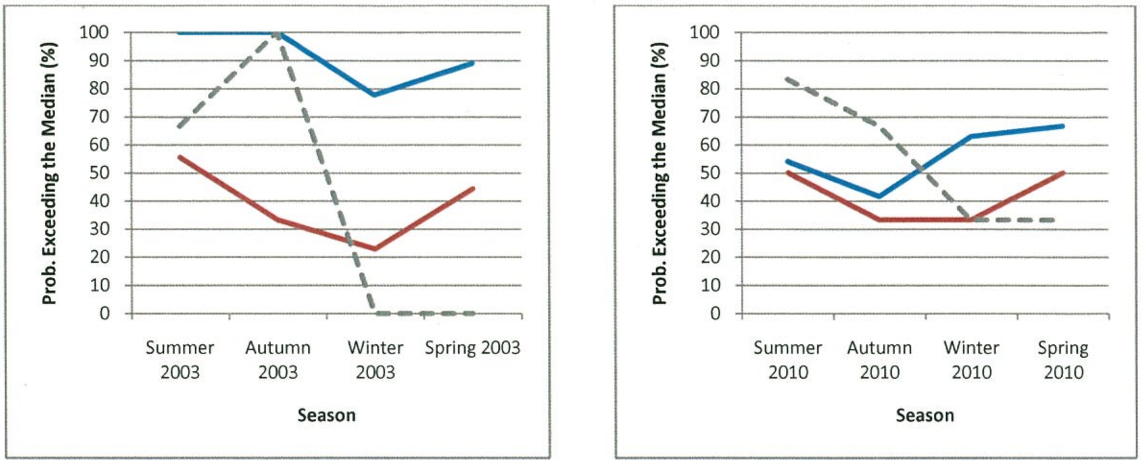
(a) (b)

Figure 11: Probability of TN and monthly rainfall exceeding the median in (a) 2003 and (b) 2010 (Blue line = upstream and Red line = downstream of the Eli Creek wastewater treatment plant; Dotted line = monthly rainfall).



(a) (b)

Figure 12: Probability of TP and monthly rainfall exceeding the median in (a) 2003 and (b) 2010 (Blue line = upstream and Red line = downstream of the Eli Creek wastewater treatment plant; Dotted line = monthly rainfall).



(a) (b)

Figure 13: Probability of SS and monthly rainfall exceeding the median in (a) 2003 and (b) 2010 (Blue line = upstream and Red line = downstream of the Eli Creek wastewater treatment plant; Dotted line = monthly rainfall).

6.2.3. Sensitivity analysis

The results of sensitivity analysis using the Bayesian network are shown in Table 8. These results excluded 1999 and 2000 because there was no water quality data available for these years. The results indicate that there was not a large difference in the influence of rainfall and urbanisation on upstream TN levels, while urbanisation had a much larger influence on downstream TN levels compared to rainfall. For TP, the influence of urbanisation was much larger than rainfall on both upstream and downstream levels. For SS, the influence of urbanisation and rainfall were relatively high but similar on both upstream and downstream levels, with rainfall slightly more influential than urbanisation. In other words, urbanisation seems to be particularly influential on downstream TN levels as well as upstream and downstream TP levels (particularly downstream TP levels). Both urbanisation and rainfall had a relatively high but similar influence on both upstream and downstream SS levels.

Table 8: Sensitivity analysis results (% variance reduction) for TN, TP and SS upstream and downstream of the wastewater treatment plant.

	TN Upstream	TN Downstream	TP Upstream	TP Downstream	SS Upstream	SS Downstream
Monthly Rainfall (mm)	4.32	0.22	1.68	1.47	10.2	6.92
Urbanisation (%)	3.05	11.8	12	24.2	8.77	6.77

7. Discussion

7.1. Main findings

7.1.1. What are the main stressors that impact on reef health in Hervey Bay?

From the results of previous studies the main stressors with the potential to impact coral reef health within Hervey Bay are sediments, nutrients, toxicants, freshwater, biota removal (fishing pressure) and habitat removal/ destruction (physical impacts to coral). Each of these has the potential to be influenced by a number of contributing issues, particularly point and non-point source pollution sources. In an urbanised catchment like Eli Creek, sewerage and industrial discharge are the most significant sources of point source pollution, however these also highly regulated and controllable. Both urban and rural non-point source pollution is much more difficult to regulate and manage. Stormwater is likely to be a significant contributor to non-point source pollution in Eli Creek and can deliver nutrients, toxicants and sediments to waterways. Soil erosion from construction areas and stream banks can also deliver nutrients and sediments to waterways within urban catchments.

7.1.2. How has urbanisation and water quality within Eli Creek changed over time?

It is clear that urban area percentage within Eli Creek catchment has increased rapidly over the last decade from around 12% in 1999 to 27.3% in 2011, and reports suggest that urban area could reach 60% (Scheltinga & Moss 2010). For water quality, there was no clear trend in TN, TP or SS with increasing urbanisation. Levels of these water quality parameters vary from season to season and year to year.

7.1.3. What influence has urbanisation had on water quality within Eli Creek over time?

Previous studies have indicated that increasing urban area within a catchment can significantly degrade water quality (Department of Environment and Resource Management 2010; Goonetilleke & Thomas 2004), however, this study found not definitive link between increasing urbanisation of Eli Creek Catchment and Eli Creek water quality. The results do point to some possible trends. For instance, in 2003 (low urbanisation), TN and TP were more likely to exceed the median during lower rainfall periods, while in 2010 (high urbanisation) TN and TP were more likely to exceed the median higher rainfall periods. This suggests that runoff in 2003 may have been relatively clean and diluted pollutant loads during higher rainfall periods, whereas runoff may have carried high pollutant loads in 2010 and degraded water quality during higher rainfall periods. For SS, levels were higher during higher rainfall periods in 2003, but lower during higher rainfall periods in 2010. Whether these differences in patterns between 2003 and 2010 are the result of urbanisation is not clear. Caruso (2001) found that TN and TP decreased during low flow periods because there was less runoff and transport of diffuse source pollutants during low flow periods, nutrient concentrations. This may explain the trend in 2010, where TN and TP concentrations were generally lower during low rainfall periods, however, it does not explain the 2003 trend. According to Scheltinga and Moss (2010), effluent from the Eli Creek wastewater treatment plant is mostly released to land as high quality recycled water. However during high rainfall events, excess treated effluent is discharged into Eli Creek. This may explain why TN levels tended to be higher during higher rainfall periods in 2010 compared to lower rainfall periods.

It is clear for both 2003 and 2010 that pollutant levels were more likely to exceed the median upstream of the wastewater treatment plant compared to downstream. This may be due to dilution from wastewater treatment plant discharges or better flushing of the creek water downstream purely because the downstream water quality monitoring point is closer to the creek mouth.

The results of sensitivity analysis used the Bayesian network indicated that TN levels downstream of the wastewater treatment plant and TP levels both up and downstream (particularly downstream) of the wastewater treatment plant were much more sensitive to urbanisation % than monthly rainfall. This indicates that urbanisation may have influenced water quality in Eli Creek, however, the mode of influence is not clear. One possible explanation is that the increase in urban area has lead to an increase in wastewater discharge, which in turn could cause fluctuations in downstream water quality levels. Another possible explanation is the increase in urban area has lead to an increase in hard surfaces, which can enlarge runoff volumes and velocities in urban waterways. This in turn can increase the amount of contaminants, carried by the flow. In addition, construction activities associated with urbanisation can be sources of nutrients and sediments due to water and wind erosion (Department of Environment and Resource Management 2010). During higher rainfall periods, soil erosion from building sites can lead to increased contaminant loads.

7.1.4. Does the quality of water within Eli Creek have the potential to degrade inshore coral reefs?

It is clear that the water within Eli Creek do have the potential to degrade inshore coral reefs. The results of this study show that TN, TP and SS levels in Eli Creek water are consistently above the critical levels for coral (Goreau & Thacker 1994; Fabricius 2009). The key questions are, 'are these pollutant concentrations diluted to below critical levels by the time they reach the inshore reefs of Hervey', and 'how tolerant of pollutant loads are the inshore corals of Hervey Bay'? Answers to these questions would provide a clearer picture of the risk to inshore coral reefs. M. Zann (pers. comm., 14 October 2011) indicated that the coral species in Hervey Bay area, especially inshore, are more tolerate of turbidity compared to typical offshore species. Therefore it may be possible that the inshore coral species within Hervey Bay are more tolerant of SS levels than the critical levels reported in the literature.

When compared to the Queensland water quality standard for constructed lakes and reservoirs and estuary (Bayley et al. 2007; John Wilson and Partners Pty Ltd 2003), median concentrations of TN, TP and SS recorded in Eli Creek are higher than the standard, particularly TP (Table 9). However, they were still lower than water quality standard for rivers and streams.

Table 9: Comparison of median concentrations of water quality parameters for Eli Creek with the Queensland Standards for constructed lakes and reservoirs, estuaries, and rivers and streams.

Indicators	Total Nitrogen (TN)		Total Phosphorous (TP)		Total Suspended Solids (SS)	
Location	Standard	Eli Creek	Standard	Eli Creek	Standard	Eli Creek
Lakes and Reservoirs	0.35 mg/L	0.4575 mg/L	0.01 mg/L	0.056 mg/L	15 mg/L	17.3 mg/L
Estuaries	0.3 mg/L		0.03 mg/L		15 mg/L	
Rivers and Streams	0.65 mg/L		0.07 mg/L		-	

7.2. Limitations of this study

There are several limitations of this study that should be considered when interpreting the results. The first limitation was the scope of the Bayesian network. There are several factors that could potentially influence water quality in Eli Creek besides urbanisation, such as weather conditions, creek flow, erosion and sediment transport, etc. However, data for these factors was not available so they were not included in the Bayesian network. The sensitivity analysis results for TN, TP and SS indicate that rainfall and urban area percentage only account for a portion of the variance in these water quality parameters.

The water quality data for Eli Creek was also limited. Only monthly records for two locations along Eli Creek were available, and creek flow and wastewater discharge data at the time of monitoring were not available. There can be a large difference between rainfall and creek flow (Department of Environment and Resource Management 2011). This study assumed that rainfall was indicative of Eli Creek flow due to the absence of flow data. The water quality data used in this study were also from points located in the Eli Creek Estuary, which may not be representative of upstream water quality or water quality within the manmade lakes constructed along Eli Creek.

8. Conclusions and Recommendations

This study could find no definitive link between urbanisation and water quality with Eli Creek Catchment, however, it is clear that median TN, TP and SS levels are higher than the recommended critical levels for coral and the Queensland water quality standard for estuary, constructed lakes and reservoirs. This can potentially be a risk to inshore coral reefs within Hervey Bay depending on the degree to which pollutants are diluted by the time they reach inshore coral reefs and the tolerance of these reefs to pollutant loads.

The sensitivity analysis performed in this study using the Bayesian network suggested that urbanisation has had an influence on Eli Creek water quality over the last decade and more influence than monthly rainfall. However the mode of influence is not clear.

The main recommendation from this study is that a precautionary approach to water quality management and urban development within the Eli Creek Catchment should be taken. This precautionary approach should include investment in further data collection and research to clarify the link between urbanisation and water quality within Eli Creek and the risk to inshore coral reefs within Hervey Bay. Water quality within the man-made lakes along Eli Creek should be monitored as well as at points upstream, particularly stormwater discharge points. Flow should also be recorded when water quality in measured and ideally flow and water quality should be measure during and after storm events, which is when runoff and pollutant loads would be greatest.

Pollutant loads at inshore reefs closest to the Eli Creek outlet should also be monitored so that the dilution of pollutants entering Hervey Bay can be understood. It is also recommended that research be conducted to understand the tolerance of inshore coral reefs within Harvey Bay to pollutant loads.

Besides simply monitoring physic-chemical indicators of water quality within Eli Creek, it is recommended that biological indicators also be monitored. Physic-chemical indicators such as TN and TP can be highly variable and can be depend on water depth and flow (which effects oxidation and reducing conditions) and weather conditions, which in turn can influence processes such as denitrification and phosphorous solubility. Biological indicators of water quality can be more stable over time and better reflection long-term trends in water quality. Physic-chemical water quality indicators represent the condition of water sampled at the particular point in time only. Added to this, important information may be missed due to the effects of periodic events if water is not sampled during storms or floods. Biological indicators "can provide a time-integrated measure (from time periods of days to years) of the effects of changes in water quality" (Cooper and Fabricius 2007). Biological indicators for coral recommend by Cooper and Fabricius (2007) include colony brightness, tissue thickness, density of macro-bioeroders, coral juvenile densities, species abundance and community structure. For freshwater watercourses biological indicators include aquatic macroinvertebrates and fish (Smith & Storey2001).

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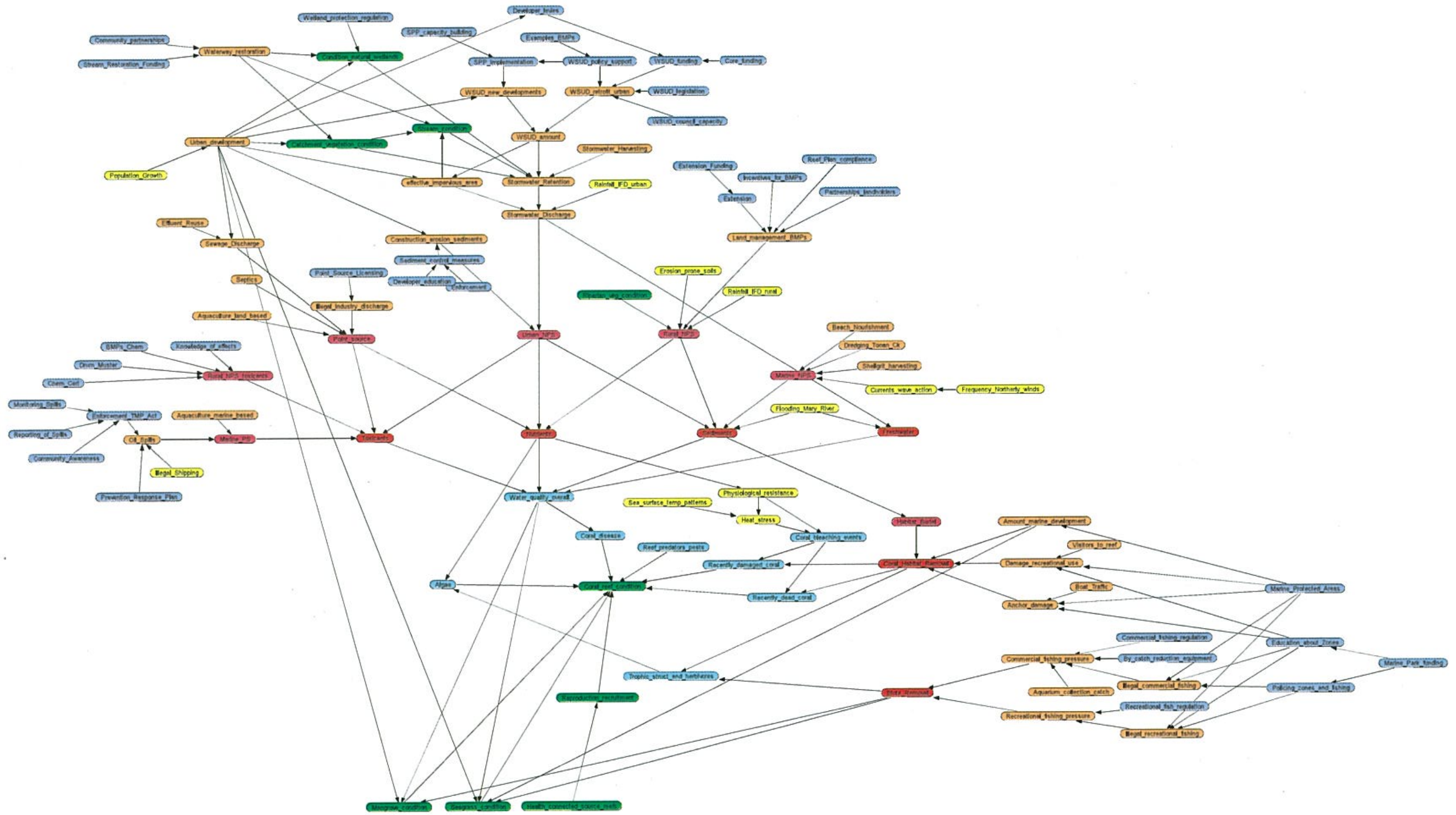
Appendices

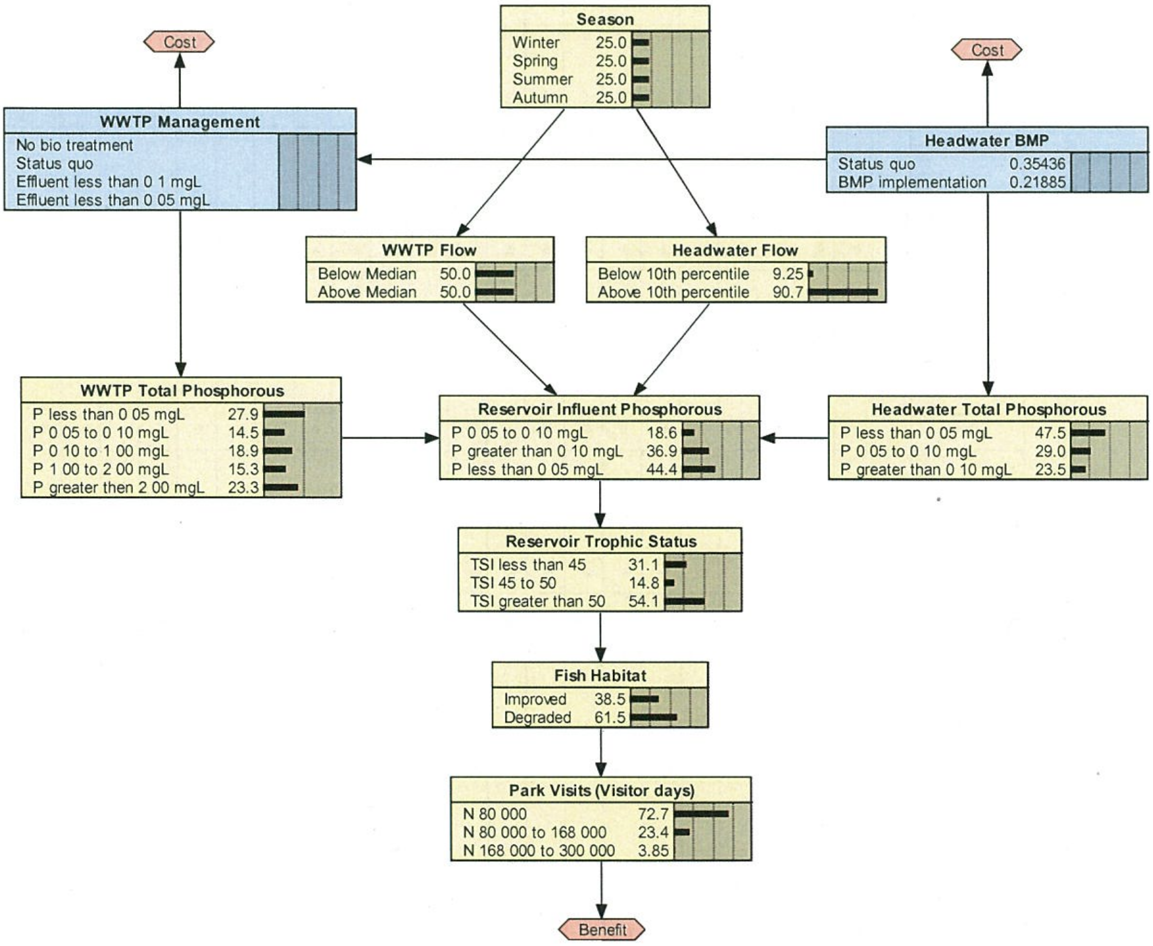
Appendix A – Influence diagram produced by participants of the Hervey Bay Reef Resilience workshop held on the 6-7 May 2010



LEGEND:

Purple	governance and implementing factors (e.g. enablers/barriers)
Orange	human activities in the catchment and coastal zone
Pink	contributing issues
Blue	indicators
Green	environmental assets
Yellow	controlling factors (i.e. variables outside our control at the scale of influence)

Appendix B – Bayesian Network used to model nutrient loads in East Canyon Creek, Northern Utah, USA, and their influence on fish habitat



Appendix C – The complete case file used to learn probabilities for the Eli Creek Bayesian Network (* = missing data).

ID	Year	Season	Rainfall	Urbanisation	TN Upstream	TN Downstream	TP Upstream	TP Downstream	SS Upstream	SS Downstream
1	x_1999	Autumn	54.4	12	*	*	*	*	*	*
2	x_1999	Autumn	50.2	12	*	*	*	*	*	*
3	x_1999	Autumn	295.8	12	*	*	*	*	*	*
4	x_1999	Winter	155.2	12	*	*	*	*	*	*
5	x_1999	Winter	127.6	12	*	*	*	*	*	*
6	x_1999	Winter	55.8	12	*	*	*	*	*	*
7	x_1999	Spring	48	12	*	*	*	*	*	*
8	x_1999	Spring	72.2	12	*	*	*	*	*	*
9	x_1999	Spring	42.2	12	*	*	*	*	*	*
10	x_1999	Summer	172	12	*	*	*	*	*	*
11	x_2000	Summer	43.6	13.2	*	*	*	*	*	*
12	x_2000	Summer	100	13.2	*	*	*	*	*	*
13	x_2000	Autumn	15.6	13.2	*	*	*	*	*	*
14	x_2000	Autumn	79.4	13.2	*	*	*	*	*	*
15	x_2000	Autumn	80.6	13.2	*	*	*	*	*	*
16	x_2000	Winter	90.6	13.2	*	*	*	*	*	*
17	x_2000	Winter	7.6	13.2	*	*	*	*	*	*
18	x_2000	Winter	33.4	13.2	*	*	*	*	*	*
19	x_2000	Spring	1.2	13.2	*	*	*	*	*	*
20	x_2000	Spring	100.4	13.2	*	*	*	*	*	*
21	x_2000	Spring	76	13.2	*	*	*	*	*	*
22	x_2001	Summer	98.6	14.48	*	*	*	*	*	*
23	x_2001	Autumn	73	14.48	*	*	*	*	*	*
24	x_2001	Autumn	42.4	14.48	*	*	*	*	*	*
25	x_2001	Winter	32.8	14.48	*	*	*	*	*	*

26	x_2001	Winter	50	14.48	*	*	*	*	*	*
27	x_2001	Winter	5.8	14.48	*	*	*	*	*	*
28	x_2001	Spring	53.4	14.48	*	*	*	*	*	*
29	x_2001	Spring	41.8	14.48	*	*	*	*	*	*
30	x_2001	Spring	115.4	14.48	*	*	*	*	*	*
31	x_2001	Summer	48.2	14.48	*	*	*	*	*	*
32	x_2002	Summer	150.8	15.76	*	*	*	*	*	*
33	x_2002	Summer	52.4	15.76	0.211	0.202	0.01	0.01	*	*
34	x_2002	Autumn	38	15.76	0.226	0.185	0.01	0.01	*	*
35	x_2002	Autumn	55.4	15.76	2.08	2.31	0.412	0.466	*	*
36	x_2002	Autumn	84.8	15.76	0.371	0.353	0.01	0.01	*	*
37	x_2002	Winter	108.8	15.76	*	*	*	*	*	*
38	x_2002	Winter	2.2	15.76	0.978	1.65	0.087	0.281	12	4.5
39	x_2002	Winter	122.8	15.76	0.822	1.62	0.059	0.238	5.6	8.2
40	x_2002	Spring	3.8	15.76	0.4	0.103	0.053	0.01	21	8
41	x_2002	Spring	93	15.76	0.509	0.179	0.065	0.01	30	11
42	x_2002	Spring	103.2	15.76	0.998	0.63	0.095	0.093	59	31
43	x_2002	Summer	109	15.76	*	*	*	*	*	*
44	x_2003	Summer	5.4	17.04	*	*	*	*	*	*
45	x_2003	Summer	370.8	17	0.648	0.176	0.048	0.009	48	13
46	x_2003	Autumn	103	17	0.304	0.266	0.009	0.009	18	7.1
47	x_2003	Autumn	92.6	17	0.256	0.16	0.009	0.009	25	7.4
48	x_2003	Autumn	82.6	17	0.6	0.536	0.043	0.054	40	50
49	x_2003	Winter	37.4	17	0.468	0.288	0.045	0.009	47	11
50	x_2003	Winter	46.6	17	0.593	1.43	0.033	0.269	9.1	9.8
51	x_2003	Winter	53.6	17	1.38	2.75	0.143	0.666	31	11
52	x_2003	Spring	16.2	17	0.966	0.769	0.194	0.185	31	20
53	x_2003	Spring	36	17	0.702	0.465	0.134	0.112	35	18
54	x_2003	Spring	47.2	17	0.333	0.022	0.142	0.109	57	8.5

55	x_2003	Summer	124.6	17	0.7	0.24	0.2	0.21	43	28
56	x_2004	Summer	321	18.31	0.625	0.107	0.197	0.223	87	22
57	x_2004	Summer	271	18.31	1.28	1.1	0.275	0.266	64	70
58	x_2004	Autumn	223.7	18.31	0.904	1.44	0.212	0.255	46	15
59	x_2004	Autumn	69.6	18.31	1.15	0.548	0.132	0.095	41	17
60	x_2004	Autumn	35.6	18.31	0.777	1.94	0.132	0.43	22	10
61	x_2004	Winter	17.6	18.31	0.56	2.69	0.138	0.55	19	11
62	x_2004	Winter	5.6	18.31	0.769	2.38	0.135	0.403	18	15
63	x_2004	Winter	0.4	18.31	0.711	0.209	0.092	0.055	23	33
64	x_2004	Spring	55.4	18.31	1.02	0.212	0.135	0.054	19	9.6
65	x_2004	Spring	134.8	18.31	0.784	0.314	0.122	0.071	39	35
66	x_2004	Spring	39.4	18.31	0.806	0.579	0.106	0.091	29	27
67	x_2004	Summer	52.4	18.31	0.329	0.264	0.066	0.057	64	69
68	x_2005	Summer	147.4	19.59	*	*	*	*	*	*
69	x_2005	Summer	105.8	19.59	4.96	0.316	0.661	0.058	23	25
70	x_2005	Autumn	102.4	19.59	0.404	0.232	0.068	0.055	54	48
71	x_2005	Autumn	90.6	19.59	0.697	0.666	0.06	0.085	28	17
72	x_2005	Autumn	86	19.59	0.543	1.26	0.05	0.26	50	16
73	x_2005	Winter	126	19.59	0.433	0.329	0.056	0.061	0.6	8.4
74	x_2005	Winter	57.6	19.59	0.441	0.39	0.045	0.062	11	28
75	x_2005	Winter	28.6	19.59	0.433	2.671	0.046	0.566	16	11
76	x_2005	Spring	11.4	19.59	0.442	0.177	0.075	0.05	24	22
77	x_2005	Spring	204	19.59	0.768	0.136	0.128	0.055	12	5.4
78	x_2005	Spring	60.6	19.59	0.383	0.227	0.07	0.1	17	11
79	x_2005	Summer	151.6	19.59	0.815	0.28	0.239	0.207	24	17
80	x_2006	Summer	188.2	20.87	*	*	*	*	*	*
81	x_2006	Summer	36	20.87	1.04	0.342	0.344	0.109	30	8.2
82	x_2006	Autumn	160	20.87	0.697	0.281	0.12	0.043	33	19
83	x_2006	Autumn	67	20.87	1.1	0.533	0.153	0.082	42	17

84	x_2006	Autumn	81.8	20.87	0.653	0.314	0.058	0.031	19	9.2
85	x_2006	Winter	124	20.87	0.604	0.836	0.053	0.076	131	26
86	x_2006	Winter	86.8	20.87	0.425	0.814	0.037	0.105	33	31
87	x_2006	Winter	10.2	20.87	0.536	0.193	0.045	0.013	17	16
88	x_2006	Spring	45.8	20.87	0.585	0.234	0.093	0.016	17	11
89	x_2006	Spring	5	20.87	0.368	0.168	0.063	0.013	30	27
90	x_2006	Spring	92.8	20.87	0.239	0.154	0.013	0.013	18	12
91	x_2006	Summer	103.2	20.87	0.261	0.16	0.03	0.013	18	11
92	x_2007	Summer	8.4	22.15	*	*	*	*	*	*
93	x_2007	Summer	69	22.15	0.371	0.194	0.044	0.021	20	7.2
94	x_2007	Autumn	50.2	22.15	0.236	0.178	0.03	0.021	20	8
95	x_2007	Autumn	43.2	22.15	0.267	0.228	0.021	0.021	16	11
96	x_2007	Autumn	30.8	22.15	0.467	0.196	0.022	0.021	29	8.3
97	x_2007	Winter	121.8	22.15	0.486	0.782	0.056	0.228	2.6	17
98	x_2007	Winter	4.2	22.15	0.24	0.177	0.033	0.021	11	6.9
99	x_2007	Winter	272.2	22.15	0.109	0.021	0.028	0.021	12	10
100	x_2007	Spring	100.2	22.15	0.874	0.325	0.057	0.048	22	15
101	x_2007	Spring	95	22.15	0.464	0.276	0.048	0.021	47	22
102	x_2007	Spring	119.8	22.15	0.559	0.177	0.207	0.021	35	16
103	x_2007	Summer	94.8	22.15	0.68	0.186	0.094	0.021	26	9.5
104	x_2008	Summer	183	23.43	0.921	0.418	0.077	0.021	30	10
105	x_2008	Summer	*	23.43	0.517	0.148	0.049	0.026	19	10
106	x_2008	Summer	*	23.43	1.14	1.38	0.142	0.202	52	36
107	x_2008	Summer	*	23.43	1.23	1.25	0.13	0.158	59	26
108	x_2008	Autumn	87.8	23.43	0.518	0.172	0.059	0.024	27	17
109	x_2008	Autumn	55.4	23.43	0.576	0.156	0.066	0.01	23	15
110	x_2008	Autumn	266.2	23.43	0.436	0.161	0.038	0.01	35	15
111	x_2008	Winter	70.2	23.43	*	*	*	*	*	*
112	x_2008	Winter	174.6	23.43	0.842	0.32	0.108	0.01	48	27

113	x_2008	Winter	5.6	23.43	0.612	0.202	0.046	0.019	13	8.5
114	x_2008	Spring	22.4	23.43	0.468	0.169	0.039	0.01	26	15
115	x_2008	Spring	52	23.43	1.44	0.203	0.234	0.022	17	15
116	x_2008	Spring	105.8	23.43	0.62	0.253	0.07	0.048	29	22
117	x_2008	Summer	37.8	23.43	1.06	0.205	0.168	0.023	19	6.1
118	x_2009	Summer	157.6	24.71	0.254	0.19	0.039	0.016	16	12
119	x_2009	Summer	149.2	24.71	0.632	0.683	0.056	0.06	12	14
120	x_2009	Autumn	129.2	24.71	0.672	0.593	0.062	0.023	23	8.2
121	x_2009	Autumn	41.8	24.71	0.409	0.222	0.027	0.002	17	8.7
122	x_2009	Autumn	89.6	24.71	0.365	0.2	0.04	0.007	16	7.2
123	x_2009	Winter	64.8	24.71	0.581	0.294	0.051	0.025	31	7
124	x_2009	Winter	2.8	24.71	0.422	1.11	0.043	0.103	12	7.4
125	x_2009	Winter	3.8	24.71	0.483	0.22	0.03	0.013	15	8.6
126	x_2009	Spring	69.4	24.71	1.21	0.193	0.163	0.024	22	10
127	x_2009	Spring	9.8	24.71	0.548	0.25	0.075	0.035	17	11
128	x_2009	Spring	14.2	24.71	0.428	0.173	0.03	0.002	16	6.8
129	x_2009	Summer	173.8	24.71	0.561	0.339	0.03	0.047	28	51
130	x_2010	Summer	59.2	26	0.287	0.793	0.035	0.109	22	21
131	x_2010	Summer	168.8	26	0.234	0.301	0.023	0.026	16	56
132	x_2010	Autumn	218	26	0.287	0.243	0.032	0.012	13	8.8
133	x_2010	Autumn	134.4	26	0.893	0.977	0.08	0.114	51	20
134	x_2010	Autumn	36.8	26	0.673	1.25	0.057	0.188	32	14
135	x_2010	Winter	64.8	26	0.451	0.449	0.073	0.029	19	20
136	x_2010	Winter	28	26	0.326	0.232	0.034	0.033	13	15
137	x_2010	Winter	119.8	26	0.238	0.519	0.003	0.022	10	12
138	x_2010	Spring	109.6	26	0.467	0.214	0.057	0.036	34	18
139	x_2010	Spring	48.8	26	0.6	0.345	0.076	0.058	17.6	14.9
140	x_2010	Spring	64.6	26	0.228	0.185	0.028	0.009	17	8.2
141	x_2010	Summer	550.6	26	0.23	0.138	0.003	0.013	17	6.6

142	x_2010	Summer	550.6	26	0.966	1.2	0.172	0.205	*	*
143	x_2010	Summer	550.6	26	0.952	0.365	0.152	0.044	*	*
144	x_2010	Summer	550.6	26	0.897	0.32	0.134	0.019	*	*
145	x_2011	Summer	184	27.26	0.981	1.11	0.136	0.185	24	15
146	x_2011	Summer	92.8	27.26	0.621	0.536	0.104	0.123	36	21
147	x_2011	Autumn	213	27.26	0.784	1.06	0.123	0.213	29	26
148	x_2011	Autumn	89.2	27.26	0.829	0.937	0.09	0.153	24	19
149	x_2011	Autumn	93.2	27.26	*	*	*	*	*	*
150	x_2011	Winter	32.4	27.26	0.686	1.9	0.093	0.309	17	9.5
151	x_2011	Winter	31.4	27.26	0.464	0.217	0.078	0.021	17	10
152	x_2011	Winter	*	27.26	0.391	0.213	0.047	0.022	12	15

Appendix D – Comparison of TN, TP and SS upstream and downstream of the Eli Creek wastewater treatment plant against total monthly rainfall and urbanisation percent.

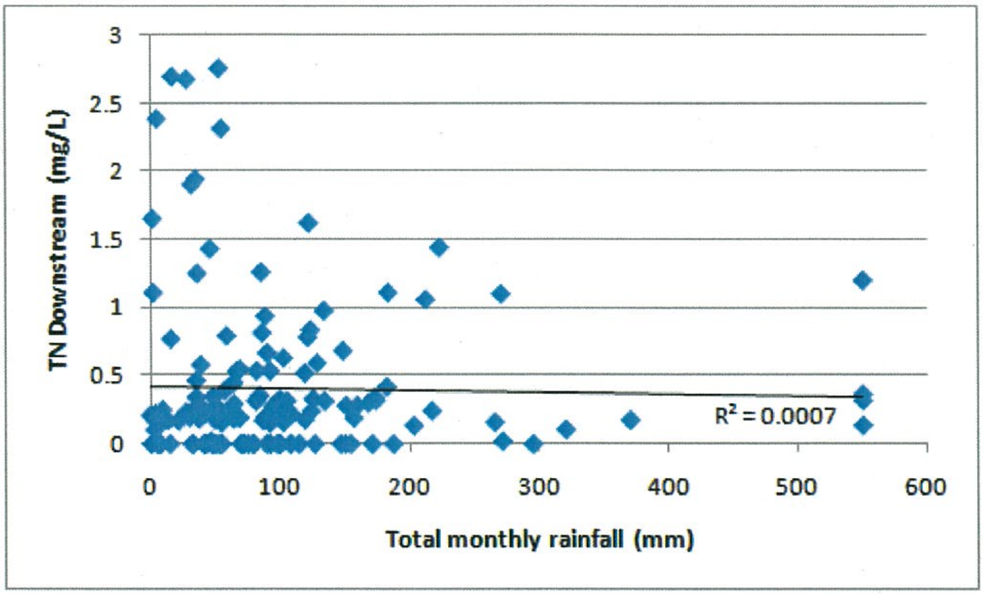


Figure a: TN downstream of the Eli Creek wastewater treatment plant compared to total monthly rainfall (line of best fit is shown on the graph)

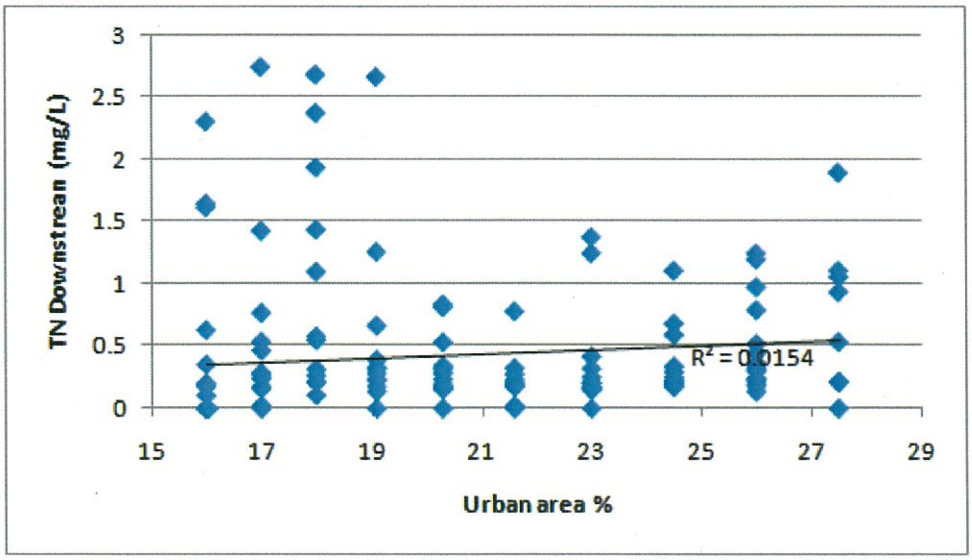


Figure b: TN downstream of the Eli Creek wastewater treatment plant compared to urban area percentage (line of best fit is shown on the graph)

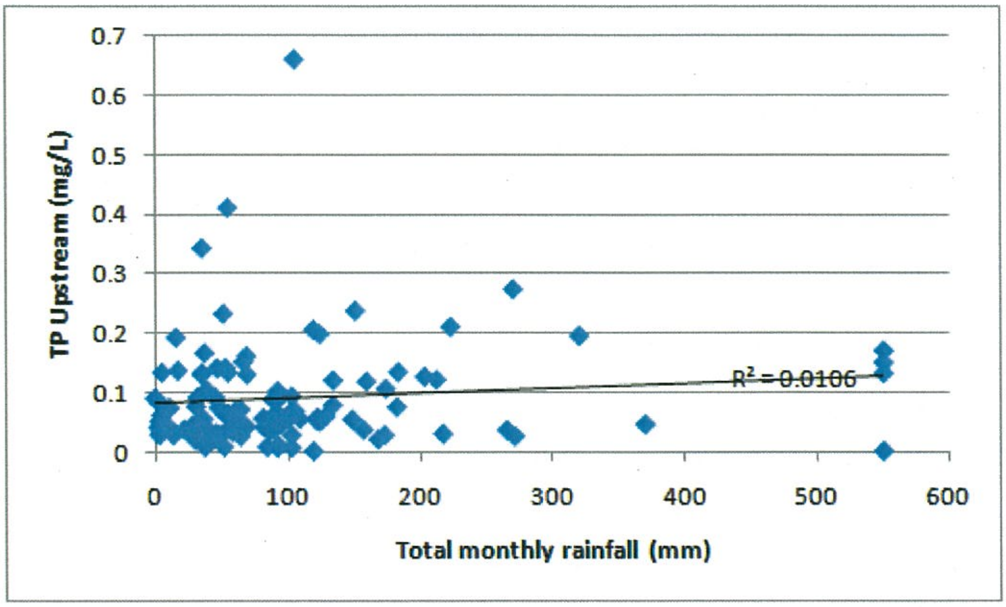


Figure c: TP upstream of the Eli Creek wastewater treatment plant compared to total monthly rainfall (line of best fit is shown on the graph)

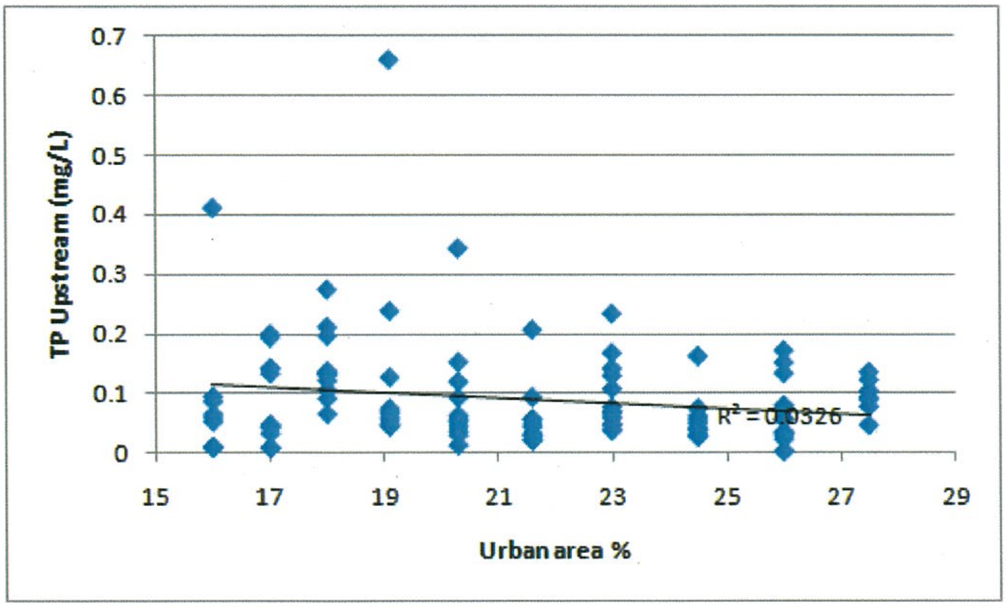


Figure d: TP upstream of the Eli Creek wastewater treatment plant compared to urban area percentage (line of best fit is shown on the graph)

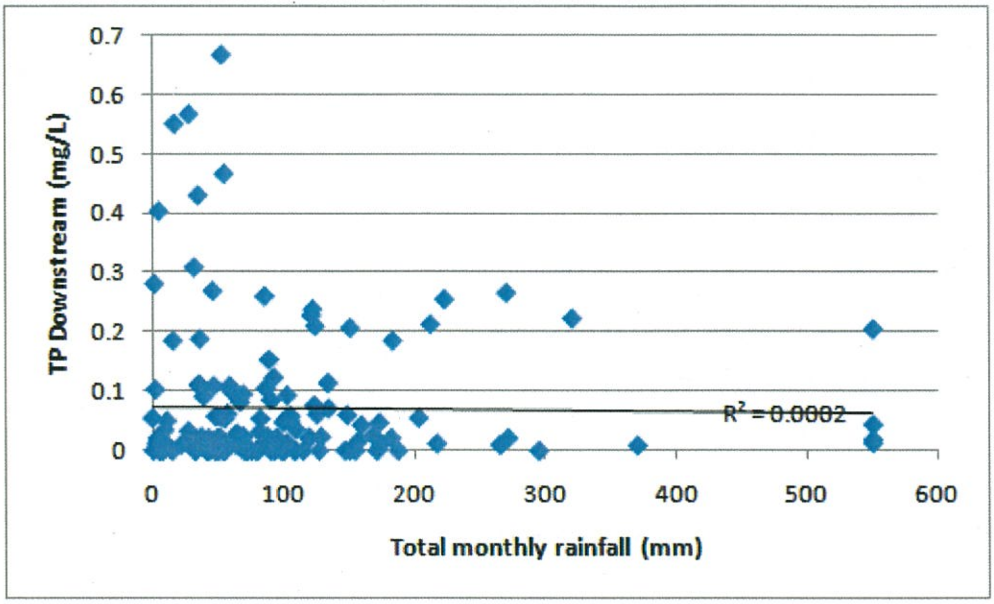


Figure e: TP downstream of the Eli Creek wastewater treatment plant compared to total monthly rainfall (line of best fit is shown on the graph)

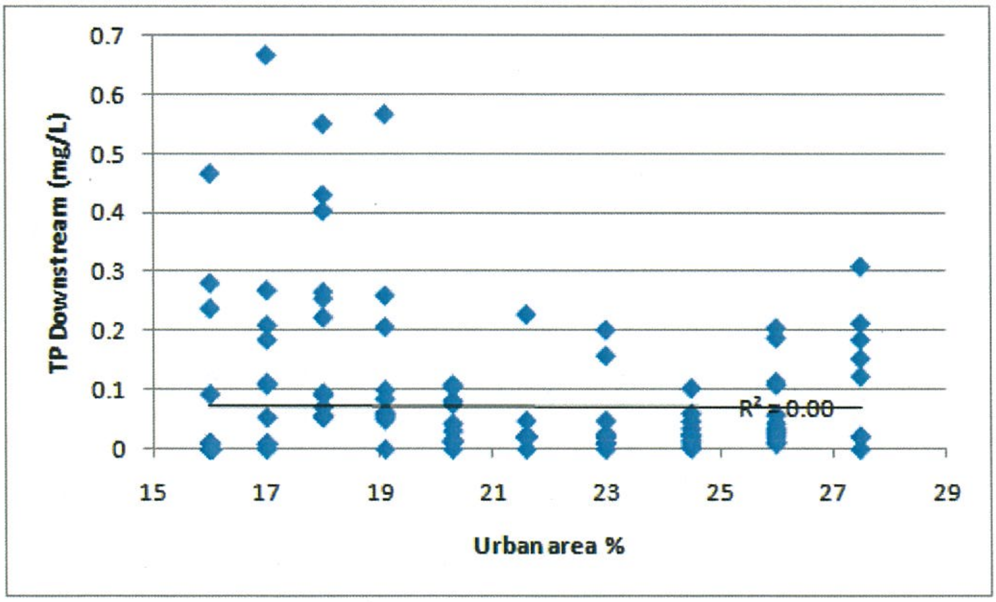


Figure f: TP downstream of the Eli Creek wastewater treatment plant compared to urban area percentage (line of best fit is shown on the graph)

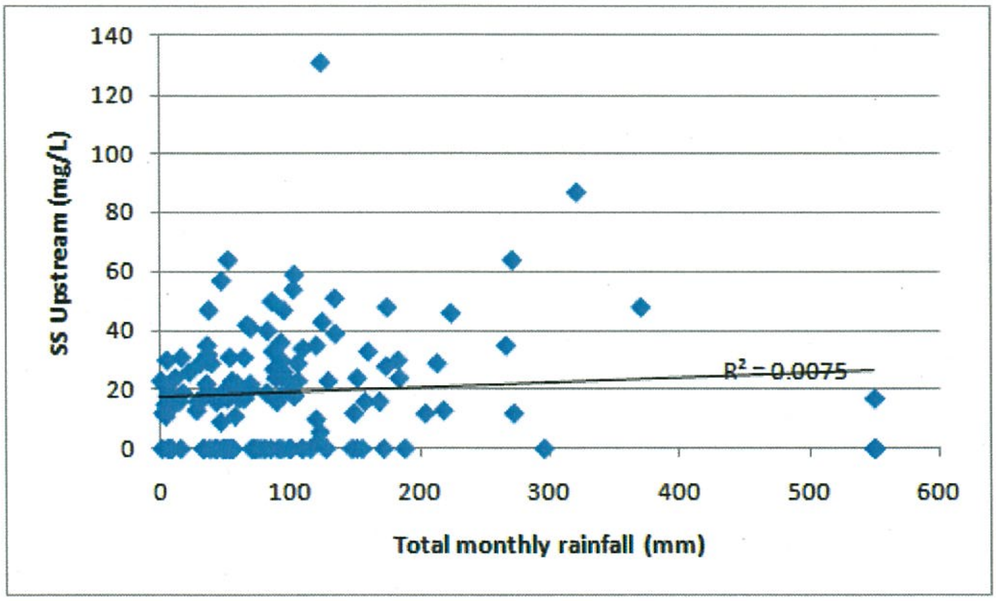


Figure e: SS upstream of the Eli Creek wastewater treatment plant compared to total monthly rainfall (line of best fit is shown on the graph)

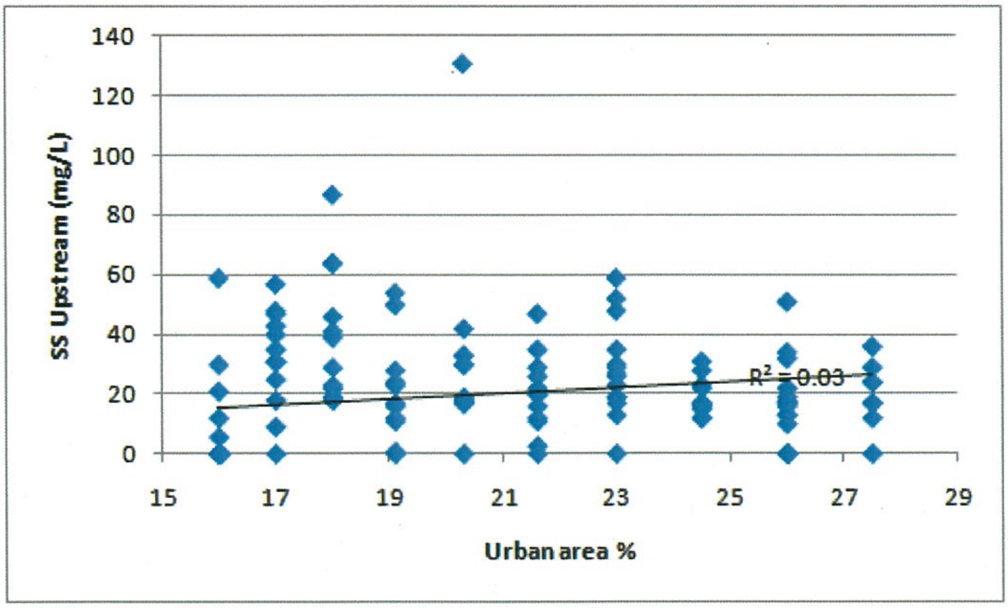


Figure b: SS upstream of the Eli Creek wastewater treatment plant compared to urban area percentage (line of best fit is shown on the graph)

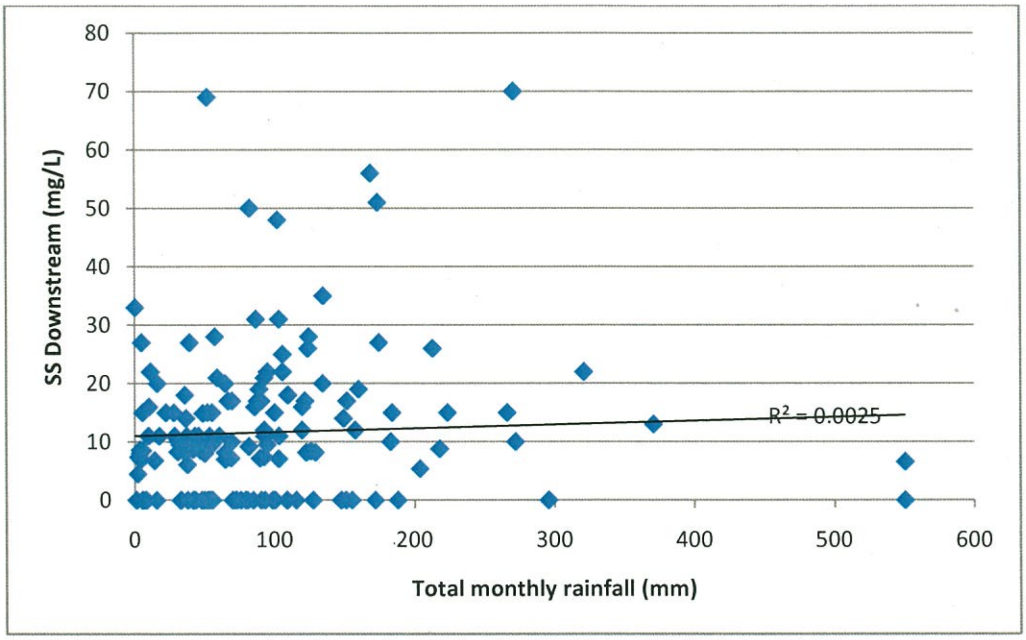


Figure a: SS downstream of the Eli Creek wastewater treatment plant compared to total monthly rainfall (line of best fit is shown on the graph)

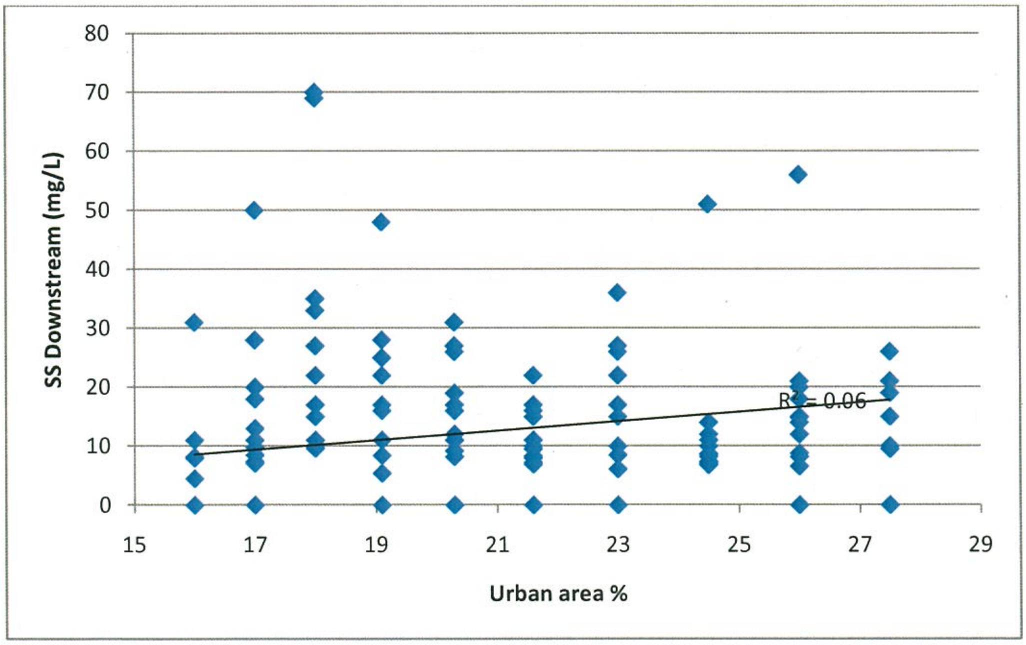


Figure b: SS downstream of the Eli Creek wastewater treatment plant compared to urban area percentage (line of best fit is shown on the graph)

Appendix E – Conditional probability tables for the Eli Creek Bayesian Network

Table a - Conditional probability table for Season

Season	% Probability
Winter	25
Spring	25
Summer	25
Autumn	25

Table b - Conditional probability table for Year

Year	% Probability
1999	7.692
2000	7.692
2001	7.692
2002	7.692
2003	7.692
2004	7.692
2005	7.692
2006	7.692
2007	7.692
2008	7.692
2009	7.692
2010	7.692
2011	7.692

Table c - Conditional probability table for monthly Rainfall

		Rainfall (Monthly)			
Year	Season	0 to 38.35	38.35 to 69.5	69.5 to 108.05	>=108.05
x_1999	Winter	0.00	33.33	0.00	66.67
x_1999	Spring	0.00	66.67	33.33	0.00
x_1999	Summer	0.00	0.00	0.00	100.00
x_1999	Autumn	0.00	66.67	0.00	33.33
X_2000	Winter	66.67	0.00	33.33	0.00
X_2000	Spring	33.33	0.00	66.67	0.00
X_2000	Summer	0.00	50.00	50.00	0.00
X_2000	Autumn	33.33	0.00	66.67	0.00
X_2001	Winter	66.67	33.33	0.00	0.00
X_2001	Spring	0.00	66.67	0.00	33.33

X_2001	Summer	0.00	50.00	50.00	0.00
X_2001	Autumn	0.00	50.00	50.00	0.00
X_2002	Winter	33.33	0.00	0.00	66.67
X_2002	Spring	33.33	0.00	66.67	0.00
X_2002	Summer	0.00	33.33	0.00	66.67
X_2002	Autumn	33.33	33.33	33.33	0.00
x_2003	Winter	33.33	66.67	0.00	0.00
x_2003	Spring	66.67	33.33	0.00	0.00
x_2003	Summer	33.33	0.00	0.00	66.67
x_2003	Autumn	0.00	0.00	100.00	0.00
x_2004	Winter	100.00	0.00	0.00	0.00
x_2004	Spring	0.00	66.67	0.00	33.33
x_2004	Summer	0.00	33.33	0.00	66.67
x_2004	Autumn	33.33	0.00	33.33	33.33
x_2005	Winter	33.33	33.33	0.00	33.33
x_2005	Spring	33.33	33.33	0.00	33.33
x_2005	Summer	0.00	0.00	33.33	66.67
x_2005	Autumn	0.00	0.00	100.00	0.00
x_2006	Winter	33.33	0.00	33.33	33.33
x_2006	Spring	33.33	33.33	33.33	0.00
x_2006	Summer	33.33	0.00	33.33	33.33
x_2006	Autumn	0.00	33.33	33.33	33.33
x_2007	Winter	33.33	0.00	0.00	66.67
x_2007	Spring	0.00	0.00	66.67	33.33
x_2007	Summer	33.33	33.33	33.33	0.00
x_2007	Autumn	33.33	66.67	0.00	0.00
x_2008	Winter	33.33	0.00	33.33	33.33
x_2008	Spring	33.33	33.33	33.33	0.00
x_2008	Summer	50.00	0.00	0.00	50.00
x_2008	Autumn	0.00	33.33	33.33	33.33
x_2009	Winter	66.67	33.33	0.00	0.00
x_2009	Spring	66.67	33.33	0.00	0.00
x_2009	Summer	0.00	0.00	0.00	100.00
x_2009	Autumn	0.00	33.33	33.33	33.33
x_2010	Winter	33.33	33.33	0.00	33.33
x_2010	Spring	0.00	66.67	0.00	33.33
x_2010	Summer	0.00	16.67	0.00	83.33
x_2011	Autumn	33.33	0.00	0.00	66.67
x_2010	Winter	100.00	0.00	0.00	0.00
x_2011	Spring	25.00	25.00	25.00	25.00
x_2011	Summer	0.00	0.00	50.00	50.00
x_2011	Autumn	0.00	0.00	66.67	33.33

Table d - Conditional probability table for Urbanisation (% of Catchment)

Urbanisation (% of Catchment)								
Year	12 to 14	14 to 16	16 to 18	18 to 20	20 to 22	22 to 24	24 to 26	26 to 28
x_1999	100	0	0	0	0	0	0	0
x_2000	100	0	0	0	0	0	0	0
x_2001	0	100	0	0	0	0	0	0
x_2002	0	100	0	0	0	0	0	0
x_2003	0	0	100	0	0	0	0	0
x_2004	0	0	0	100	0	0	0	0
x_2005	0	0	0	100	0	0	0	0
x_2006	0	0	0	0	100	0	0	0
x_2007	0	0	0	0	0	100	0	0
x_2008	0	0	0	0	0	100	0	0
x_2009	0	0	0	0	0	0	100	0
x_2010	0	0	0	0	0	0	0	100
x_2011	0	0	0	0	0	0	0	100

Table e - Conditional probability table for TN Downstream

TN Downstream				
Rainfall (Monthly)	Urbanisation	0 to 0.014	0.014 to 0.4575	>=0.4575
0 to 38.35	12 to 14	33.33	33.33	33.33
0 to 38.35	14 to 16	0.00	66.67	33.33
0 to 38.35	16 to 18	0.00	33.33	66.67
0 to 38.35	18 to 20	0.00	33.33	66.67
0 to 38.35	20 to 22	0.00	100.00	0.00
0 to 38.35	22 to 24	0.00	100.00	0.00
0 to 38.35	24 to 26	0.00	75.00	25.00
0 to 38.35	26 to 28	0.00	50.00	50.00
38.35 to 69.5	12 to 14	33.33	33.33	33.33
38.35 to 69.5	14 to 16	0.00	50.00	50.00
38.35 to 69.5	16 to 18	0.00	33.33	66.67
38.35 to 69.5	18 to 20	0.00	80.00	20.00
38.35 to 69.5	20 to 22	0.00	50.00	50.00
38.35 to 69.5	22 to 24	0.00	100.00	0.00
38.35 to 69.5	24 to 26	0.00	100.00	0.00
38.35 to 69.5	26 to 28	0.00	75.00	25.00
69.5 to 108.05	12 to 14	33.33	33.33	33.33
69.5 to 108.05	14 to 16	0.00	66.67	33.33
69.5 to 108.05	16 to 18	0.00	66.67	33.33
69.5 to 108.05	18 to 20	0.00	40.00	60.00
69.5 to 108.05	20 to 22	0.00	75.00	25.00

69.5 to 108.05	22 to 24	0.00	100.00	0.00
69.5 to 108.05	24 to 26	0.00	100.00	0.00
69.5 to 108.05	26 to 28	0.00	0.00	100.00
>=108.05	12 to 14	33.33	33.33	33.33
>=108.05	14 to 16	0.00	0.00	100.00
>=108.05	16 to 18	0.00	100.00	0.00
>=108.05	18 to 20	0.00	71.43	28.57
>=108.05	20 to 22	0.00	50.00	50.00
>=108.05	22 to 24	0.00	83.33	16.67
>=108.05	24 to 26	0.00	50.00	50.00
>=108.05	26 to 28	0.00	54.55	45.45

Table f- Conditional probability table for TP Upstream

TP Upstream				
Rainfall (Monthly)	Urbanisation	0 to 0.003	0.003 to 0.056	>=0.056
0 to 38.35	12 to 14	33.33	33.33	33.33
0 to 38.35	14 to 16	0.00	66.67	33.33
0 to 38.35	16 to 18	0.00	33.33	66.67
0 to 38.35	18 to 20	0.00	16.67	83.33
0 to 38.35	20 to 22	0.00	33.33	66.67
0 to 38.35	22 to 24	0.00	80.00	20.00
0 to 38.35	24 to 26	0.00	75.00	25.00
0 to 38.35	26 to 28	0.00	25.00	75.00
38.35 to 69.5	12 to 14	33.33	33.33	33.33
38.35 to 69.5	14 to 16	0.00	50.00	50.00
38.35 to 69.5	16 to 18	0.00	33.33	66.67
38.35 to 69.5	18 to 20	0.00	20.00	80.00
38.35 to 69.5	20 to 22	0.00	0.00	100.00
38.35 to 69.5	22 to 24	0.00	60.00	40.00
38.35 to 69.5	24 to 26	0.00	66.67	33.33
38.35 to 69.5	26 to 28	0.00	50.00	50.00
69.5 to 108.05	12 to 14	33.33	33.33	33.33
69.5 to 108.05	14 to 16	0.00	33.33	66.67
69.5 to 108.05	16 to 18	0.00	100.00	0.00
69.5 to 108.05	18 to 20	0.00	20.00	80.00
69.5 to 108.05	20 to 22	0.00	75.00	25.00
69.5 to 108.05	22 to 24	0.00	20.00	80.00
69.5 to 108.05	24 to 26	0.00	100.00	0.00
69.5 to 108.05	26 to 28	0.00	0.00	100.00
>=108.05	12 to 14	33.33	33.33	33.33
>=108.05	14 to 16	0.00	0.00	100.00
>=108.05	16 to 18	0.00	50.00	50.00
>=108.05	18 to 20	0.00	0.00	100.00
>=108.05	20 to 22	0.00	50.00	50.00

>=108.05	22 to 24	0.00	33.33	66.67
>=108.05	24 to 26	0.00	50.00	50.00
>=108.05	26 to 28	0.00	36.36	63.64

Table g - Conditional probability table for TP Downstream

TP Downstream				
Rainfall (Monthly)	Urbanisation	0 to 0.003	0.003 to 0.056	>=0.056
0 to 38.35	12 to 14	33.33	33.33	33.33
0 to 38.35	14 to 16	0.00	66.67	33.33
0 to 38.35	16 to 18	0.00	33.33	66.67
0 to 38.35	18 to 20	0.00	33.33	66.67
0 to 38.35	20 to 22	0.00	66.67	33.33
0 to 38.35	22 to 24	0.00	100.00	0.00
0 to 38.35	24 to 26	25.00	50.00	25.00
0 to 38.35	26 to 28	0.00	50.00	50.00
38.35 to 69.5	12 to 14	33.33	33.33	33.33
38.35 to 69.5	14 to 16	0.00	50.00	50.00
38.35 to 69.5	16 to 18	0.00	0.00	100.00
38.35 to 69.5	18 to 20	0.00	20.00	80.00
38.35 to 69.5	20 to 22	0.00	50.00	50.00
38.35 to 69.5	22 to 24	0.00	100.00	0.00
38.35 to 69.5	24 to 26	33.33	66.67	0.00
38.35 to 69.5	26 to 28	0.00	50.00	50.00
69.5 to 108.05	12 to 14	33.33	33.33	33.33
69.5 to 108.05	14 to 16	0.00	66.67	33.33
69.5 to 108.05	16 to 18	0.00	100.00	0.00
69.5 to 108.05	18 to 20	0.00	20.00	80.00
69.5 to 108.05	20 to 22	0.00	75.00	25.00
69.5 to 108.05	22 to 24	0.00	100.00	0.00
69.5 to 108.05	24 to 26	0.00	100.00	0.00
69.5 to 108.05	26 to 28	0.00	0.00	100.00
>=108.05	12 to 14	33.33	33.33	33.33
>=108.05	14 to 16	0.00	0.00	100.00
>=108.05	16 to 18	0.00	50.00	50.00
>=108.05	18 to 20	0.00	14.29	85.71
>=108.05	20 to 22	0.00	50.00	50.00
>=108.05	22 to 24	0.00	83.33	16.67
>=108.05	24 to 26	0.00	75.00	25.00
>=108.05	26 to 28	0.00	63.64	36.36

Table h - Conditional probability table for SS Upstream

SS Upstream				
Rainfall (Monthly)	Urbanisation	0 to 0.8	0.8 to 17.3	>=17.3
0 to 38.35	12 to 14	33.33	33.33	33.33
0 to 38.35	14 to 16	0.00	50.00	50.00
0 to 38.35	16 to 18	0.00	0.00	100.00
0 to 38.35	18 to 20	0.00	16.67	83.33
0 to 38.35	20 to 22	0.00	33.33	66.67
0 to 38.35	22 to 24	0.00	40.00	60.00
0 to 38.35	24 to 26	0.00	100.00	0.00
0 to 38.35	26 to 28	0.00	75.00	25.00
38.35 to 69.5	12 to 14	33.33	33.33	33.33
38.35 to 69.5	14 to 16	33.33	33.33	33.33
38.35 to 69.5	16 to 18	0.00	33.33	66.67
38.35 to 69.5	18 to 20	0.00	40.00	60.00
38.35 to 69.5	20 to 22	0.00	50.00	50.00
38.35 to 69.5	22 to 24	0.00	40.00	60.00
38.35 to 69.5	24 to 26	0.00	33.33	66.67
38.35 to 69.5	26 to 28	0.00	25.00	75.00
69.5 to 108.05	12 to 14	33.33	33.33	33.33
69.5 to 108.05	14 to 16	0.00	0.00	100.00
69.5 to 108.05	16 to 18	0.00	0.00	100.00
69.5 to 108.05	18 to 20	0.00	0.00	100.00
69.5 to 108.05	20 to 22	0.00	0.00	100.00
69.5 to 108.05	22 to 24	0.00	0.00	100.00
69.5 to 108.05	24 to 26	0.00	100.00	0.00
69.5 to 108.05	26 to 28	0.00	0.00	100.00
>=108.05	12 to 14	33.33	33.33	33.33
>=108.05	14 to 16	0.00	100.00	0.00
>=108.05	16 to 18	0.00	0.00	100.00
>=108.05	18 to 20	14.29	14.29	71.43
>=108.05	20 to 22	0.00	0.00	100.00
>=108.05	22 to 24	0.00	33.33	66.67
>=108.05	24 to 26	0.00	50.00	50.00
>=108.05	26 to 28	0.00	50.00	50.00

Table i - Conditional probability table for SS Downstream

SS Downstream				
Rainfall (Monthly)	Urbanisation	0 to 0.8	0.8 to 17.3	>=17.3
0 to 38.35	12 to 14	33.33	33.33	33.33
0 to 38.35	14 to 16	0.00	100.00	0.00
0 to 38.35	16 to 18	0.00	33.33	66.67
0 to 38.35	18 to 20	0.00	66.67	33.33
0 to 38.35	20 to 22	0.00	66.67	33.33

0 to 38.35	22 to 24	0.00	100.00	0.00
0 to 38.35	24 to 26	0.00	100.00	0.00
0 to 38.35	26 to 28	0.00	100.00	0.00
38.35 to 69.5	12 to 14	33.33	33.33	33.33
38.35 to 69.5	14 to 16	33.33	33.33	33.33
38.35 to 69.5	16 to 18	0.00	100.00	0.00
38.35 to 69.5	18 to 20	0.00	40.00	60.00
38.35 to 69.5	20 to 22	0.00	100.00	0.00
38.35 to 69.5	22 to 24	0.00	100.00	0.00
38.35 to 69.5	24 to 26	0.00	100.00	0.00
38.35 to 69.5	26 to 28	0.00	50.00	50.00
69.5 to 108.05	12 to 14	33.33	33.33	33.33
69.5 to 108.05	14 to 16	0.00	50.00	50.00
69.5 to 108.05	16 to 18	0.00	66.67	33.33
69.5 to 108.05	18 to 20	0.00	60.00	40.00
69.5 to 108.05	20 to 22	0.00	75.00	25.00
69.5 to 108.05	22 to 24	0.00	60.00	40.00
69.5 to 108.05	24 to 26	0.00	100.00	0.00
69.5 to 108.05	26 to 28	0.00	0.00	100.00
>=108.05	12 to 14	33.33	33.33	33.33
>=108.05	14 to 16	0.00	100.00	0.00
>=108.05	16 to 18	0.00	50.00	50.00
>=108.05	18 to 20	0.00	57.14	42.86
>=108.05	20 to 22	0.00	0.00	100.00
>=108.05	22 to 24	0.00	83.33	16.67
>=108.05	24 to 26	0.00	75.00	25.00
>=108.05	26 to 28	0.00	50.00	50.00

Table j - Conditional probability table for TN Coral Upstream

TN Coral Upstream	0 to 0.014	>=0.014
0 to 0.014	100	0
0.014 to 0.4575	0	100
>=0.4575	0	100

Table k - Conditional probability table for TN Coral Downstream

TN Coral Downstream	0 to 0.014	>=0.014
0 to 0.014	100	0
0.014 to 0.4575	0	100
>=0.4575	0	100

Table l - Conditional probability table for TP Coral Upstream

TP Coral Upstream	0 to 0.003	>=0.003
0 to 0.003	100	0
0.003 to 0.056	0	100
>=0.056	0	100

Table m - Conditional probability table for TP Coral Downstream

TP Coral Downstream	0 to 0.003	>=0.003
0 to 0.003	100	0
0.003 to 0.056	0	100
>=0.056	0	100

Table n- Conditional probability table for SS Coral Upstream

SS Coral Upstream	0 to 0.8	>=0.8
0 to 0.8	100	0
0.8 to 17.3	0	100
>=17.3	0	100

Table o - Conditional probability table for SS Coral Downstream

SS Coral Downstream	0 to 0.8	>=0.8
0 to 0.8	100	0
0.8 to 17.3	0	100
>=17.3	0	100

Table p - Conditional probability table for Coral Health Upstream

TN Coral Upstream	TP Coral Upstream	SS Coral Upstream	OK	Degraded
0 to 0.014	0 to 0.003	0 to 0.8	100	0
0 to 0.014	0 to 0.003	>=0.8	0	100
0 to 0.014	>=0.003	0 to 0.8	0	100
0 to 0.014	>=0.003	>=0.8	0	100
>=0.014	0 to 0.003	0 to 0.8	0	100
>=0.014	0 to 0.003	>=0.8	0	100
>=0.014	>=0.003	0 to 0.8	0	100
>=0.014	>=0.003	>=0.8	0	100

Table q - Conditional probability table for Coral Health Downstream

TN Coral Downstream	TP Coral Downstream	SS Coral Downstream	OK	Degraded
0 to 0.014	0 to 0.003	0 to 0.8	100	0
0 to 0.014	0 to 0.003	>=0.8	0	100
0 to 0.014	>=0.003	0 to 0.8	0	100
0 to 0.014	>=0.003	>=0.8	0	100
>=0.014	0 to 0.003	0 to 0.8	0	100
>=0.014	0 to 0.003	>=0.8	0	100
>=0.014	>=0.003	0 to 0.8	0	100
>=0.014	>=0.003	>=0.8	0	100