Identifying Groundwater Vulnerability from Nitrate Contamination: Comparison of the DRASTIC model and Environment Canterbury’s method

A dissertation

submitted in partial fulfilment

of the requirement for the Degree of

Master of Applied Science (Environmental Management)

at Lincoln University

by

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Lincoln University

2015

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Groundwater is a crucial natural resource in New Zealand, as it is used to support many environmental, economic, social and cultural aspects of the country. However, in recent years the quality of our groundwater resources has begun to degrade and is now of great concern, especially in the Canterbury region. The degradation of the groundwater has occurred over many years and is the result from a number of direct and indirect effects, but quite notably nitrogen, in the form of nitrates, used in intensive agricultural activities has been identified as one of the major contributors to this degradation. Nitrate contamination in groundwater can cause issues to the environment and to the people that rely on resource. These issues can range from increase in toxic algal blooms, to degradation of aquatic habitat, and it can cause biological effects to humans, such as blue baby syndrome. Local government agencies, such as Environment Canterbury (ECan), have now had to implement strategies and methods to monitor groundwater quality to address this situation. One of these methods that ECan has used is the development of risk maps for identifying groundwater vulnerability to nitrate contamination, which is based on water quality monitoring data. There are other methods used around the world for predicting vulnerability maps for groundwater contamination, with the most common method being the GIS-based DRASTIC model. This model produces vulnerability values that are reflected on a map, which represent the vulnerability of the groundwater from contamination, such as nitrate contamination. However, ECan has not implemented this model as a method for groundwater vulnerability. This research involves developing a DRASTIC model map for nitrate vulnerability in groundwater for the central and southern Canterbury region and comparing it with the vulnerability map produced by ECan. By doing this research, it will identify whether the DRASTIC map could be a reliable and therefore a viable monitoring tool for nitrate vulnerability in groundwater for the Canterbury region, in order to help manage Canterbury's crucial natural groundwater resource.

This dissertation presents results of a completed DRASTIC map, along with seven key areas that were identified on both the DRASTIC map and the ECan map, which were used for comparison. The comparison identified whether the vulnerability values produced on the DRASTIC map were able to predict reliable results in identifying areas of groundwater that are vulnerable to nitrate contamination based off of the nitrate concentrations represented on the ECan vulnerable map.

The results showed that five of the seven key areas used comparison showed reliable results for the DRASTIC mode for the Canterbury region. In these areas the DRASTIC model was able to show that it could be used to predict areas of groundwater that are vulnerable to nitrate contamination that may potentially receive further nitrate contamination in the future. The other two key areas used for comparison showed some unreliable results, as current nitrate concentrations shown on the ECan's maps were far greater than the vulnerability values provided by the DRASTIC model. From this it was gathered that the DRASTIC model has limitations, as the current nitrate concentrations on the ECan map were a result of current land use activities, which the DRASTIC model does not consider.

Overall, from the comparison of these seven key areas, the results suggest that the DRASTIC model could be a useful monitoring tool in the future, which can be used to identify nitrate contamination in groundwater. The DRASTIC model should be used alongside other current methods that are used for monitoring groundwater contamination. The model can also then be applied to the applications of the DRASTIC model that were identified by the EPA, which will be useful for future management of the groundwater resources in the Canterbury region. Therefore it is suggested that the DRASTIC model is a reliable and a viable method as a monitoring tool for identifying areas of groundwater that are vulnerable to nitrate contamination in the Canterbury region.

Keywords:

DRASTIC, Groundwater, Nitrate, Vulnerability, Contamination

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1. Introduction

Groundwater is a crucial natural resource in New Zealand, as it is used to support many environmental, economic, social and cultural aspects of the country. However, in recent years the quality of our groundwater resources has begun to degrade and is now of great concern, especially in the Canterbury region. The degradation of the groundwater has occurred over many years and is the result from a number of direct and indirect effects, but quite notably nitrogen, in the form of nitrates, used in intensive agricultural activities has been identified as one of the major contributors to this degradation (Howard-Williams, Davies-Colly, Rutherford, & Wilcock, 2013). Nitrogen fertilisers are seen as an essential tool to promote the growth of pasture and crop production for agricultural activities, and has been applied to the land for many years to aid in production. This can then create the issue of there being more nitrogen in the soil than the plants can absorb, which is then leached through the soil into the groundwater as nitrates, causing contamination (Environment Canterbury, 2010). The levels of nitrates found in groundwater aquifers have become of concern as they have increased significantly and are starting to cause major water quality and health problems to the environment and the people who rely on groundwater. An environmental problem from too many nitrates in groundwater is that when the water recharges the surface water environments it promotes the growth of aquatic plants, which can then cause toxic algal blooms. Elevated levels of nitrates in surface water can also be toxic to aquatic life (Stevenston, Wilks, & Hayward, 2010). Nitrates in groundwater can also cause problems to the people as it can contaminate drinking water, which can cause major biological affects to humans, especially infants also known as blue baby syndrome (World Health Organization, 2011). Local governmental agencies have now had to implement strategies and methods to monitor the groundwater quality in an attempt to address the situation. Monitoring the groundwater quality is important as the resource is used to support the many agricultural activities, drinking water for the region, maintaining healthy river flows and it has cultural significance to local iwi.

Environment Canterbury (ECan) is one of these local government agencies that has been monitoring groundwater aquifers throughout the Canterbury through water quality sampling, which is then used to identify trends and areas of concern. With these data, ECan has developed vulnerability maps for identifying areas of groundwater that are vulnerable to nitrates based on water quality monitoring and maps showing nitrate levels in groundwater. This method can be very time consuming and expensive, as each site needs to have its own data collected and analysed. There are other vulnerability assessments that can be used to generate digital maps that can highlight areas of groundwater that are vulnerable to nitrate contamination using spatial data. One of these methods is the DRASTIC model, which utilises a geographic information system (GIS). DRASTIC was developed by the United States Environmental Protection Agency (EPA) in the 1980s and is known as an index model that is used to produce vulnerability scores for different locations by combining several data layers (Nor Said, Jamil, & Reba, 2013). This method has been widely adopted by many countries around the world, as it identifies vulnerable areas based on a specific set of spatial criteria. It is also considered to be the most widely used tool for vulnerability mapping (Saatsaz, Sulaiman, Eslamian, & Mohammadi, 2011). However, this method is not commonly used in New Zealand, with very few studies using the DRASTIC method being conducted, even though it has potential to be a viable method for assessing groundwater vulnerability to nitrate contamination.

The purpose of this research is to development maps for identifying groundwater vulnerability to nitrate contamination for a portion of the Canterbury Region by using the DRASTIC model. The results of this vulnerability map will be compared with groundwater vulnerability maps of nitrate concentrations produced by ECan. The DRASTIC model is common practice around the world, but not in New Zealand, so if the comparison of the map produced by the DRASTIC model and the vulnerability map produced by ECan proves to be reliable, then the DRASTIC model could be considered as an additional monitoring tool that can be used for the Canterbury region in the future. The dissertation will begin by providing a literature review on the current information on this topic, which will also outline the importance of this research. It will include the importance of groundwater for the Canterbury region, the use of nitrates in the Canterbury region, how nitrates have impacted groundwater quality, how ECan has been attempting to monitor this issue, and how the DRASTIC model can be applied to this issue. The research aims and objectives will then be stated, followed by a description of the methods that will be used for this research. The results of this research will then be displayed with a discussion that will review these results. The limitations and recommendations of this research will then be outlined. Finally the concluding remarks of this research will be presented.

2. Literature Review

2.1 Importance of groundwater in Canterbury

Groundwater is an invaluable and vital natural resource that has become very important in recent years due to the increasing demand and availability of such resources (Nor Said et al., 2013). It is an important resource all over the world, with approximately one-fifth of the total fresh water being located within these groundwater environments (Saatsaz et al., 2011). In some places groundwater is the only source of fresh water. The water within these groundwater environments is used to meet the demands for many types of economic provisions, such as agricultural, commercial and industrial, as well as to meet the demands of the many people by acting as a source of drinking water (Aljazzar, 2010). Groundwater is also considered to be one of the most extracted natural resources, for these many reasons mentioned above, causing increased pressure on the quantity and quality of this resource (Aljazzar, 2010). This is what is broadly seen in many parts of the world and the Canterbury region in the South Island of New Zealand is no different.

The Canterbury region has many unique characteristics, which is what also makes the demand for this groundwater resource so high. The region has a land area of 4.53M ha, which accounts for 17% of New Zealand’s total land area and is bounded by the Southern Alps and the Pacific Ocean (Leckie, 1994; Moot, Mills, & Pollock, 2010). The spatial aspect of this region consists of 63% being classified as mountain and hill country, 13% for inland basins, 3% for Banks Peninsula, and alluvial plains account for the remaining 21%. The Canterbury Plains are approximately 185 km long and 70 km wide (Moot et al., 2010). There are also four major gravel-bed rivers; Waimakariri River, Rakaia River, Rangitata River and the Waitaki River, which run through the region (Leckie, 1994). Under these alluvial plains, are a number of groundwater aquifers, which are mainly river-recharged, but some aquifers are limited to being recharged by local precipitation (Taylor et al., 1989). There are many types of groundwater aquifers, but Canterbury’s mainly consist of unconfined gravel aquifers that are fairly accessible, though around Christchurch City the aquifers mainly confined (Taylor et al., 1989). Another characteristic of the region is that it has relatively low rainfall compared to other regions in New Zealand. The average rainfall in New Zealand ranges from 600 mm to around 1600 mm, Canterbury is on the lower end with an average rainfall of approximately

650 mm (Moot et al., 2010; National Institute of Water and Atmospheric Research, 2001). All three of these characteristics, large areas of flat land, make the Canterbury region an ideal place for intensive agricultural activities with the help of irrigation methods. However, the groundwater resources are not just limited to agricultural activities; the Canterbury region has a population of approximately 540,000 people (12.7% of New Zealand's total population (Statistics New Zealand, 2013)). The people in this region rely on very high quality fresh water, extracted from groundwater aquifers, as their main source of drinking water.

To supply both the needs for these agricultural activities and domestic use as fresh drinking water, a large amount of water is extracted from these groundwater aquifers. In the Canterbury region approximately 1,986M m^3 of groundwater is allocated to be extracted for each year, which is used for both agricultural and domestic needs (Tricker, Young, Ettema, & Earl-Goulet, 2012). A total of 86.5M m^3 from the allocated groundwater is extracted and used to meet the needs, as high quality drinking water, of Christchurch city alone, which is two-thirds of the total public water supply (Christchurch City Council, 2009). So it is important that the water stays safe from contamination as it affects a large number of people. The Ministry of Health (2008) stated in the Drinking-water Standards for New Zealand that the Maximum Acceptable Value (MAV) for nitrate in water is at 50 mg/L, which relates to a nitrate nitrogen concentration of 11.3 mg/L. If the amount of nitrates in the water is higher than the MAV, then it will be contaminated and unsafe to drink. The rest of the allocated water is for other uses, but significantly for the use of irrigation in the agricultural sector. It has been estimated that roughly 400,000 ha of land in Canterbury is currently being irrigated (Pangborn & Woodford, 2011; Trevis, 2012). It is important to know where the vulnerable areas are of nitrate contamination, so that extracting drinking water from these areas can be avoided. It is also important for agricultural purposes to know where nitrate contamination is, so that farmers do not put excess nitrates on their land for plant growth.

2.2 The use of nitrates in the Canterbury Region

The Canterbury region is an integral part of the agricultural industry in New Zealand and is one of the major areas in New Zealand for agricultural activities (Trevis, 2012). The conditions in this region are perfect for a range of these activities, with vast areas of flat land and easily accessible water, though the region has very low rainfall. This is a reflection of the use of rural land in the region, with 97% of this land being used for agricultural activities, which includes 84% for pastoral land activities and 6% for dairy production (Hill, 2008). Agriculture is of significant economic importance to the region and New Zealand as a whole, but for these activities to stay productive and economically viable, nitrogen fertilisers are added onto the land.

For successful and profitable operation of a dairy farm, the use of extra nitrogen fertilisers is essential for pastoral lands as it provides many benefits that do not naturally occur (Castillo, 1999). Nitrogen is the second most important factor that promotes plant growth, closely following water, to ensure that the needs of society for meat, produce and dairy products are met while maintaining profit. Farmers have utilised nitrogen fertilisers as a cheap supplement to promote growth in grasses to maintain a high livestock carrying capacity on pasture based systems and to aid in the growth of plants for produce (Ledgard, Penno, & Sprosen, 1997). Nitrogen is important as it is a component of DNA molecules, giving it a very important role in cell division and reproduction. It helps to increase the photosynthesis of grasses through its light receptors that turns light energy into chemical energy in the plant that is essential for life. This means that the extra nitrogen added to the land promotes plant growth of produce and grass on pastoral land, which is essential for cows (Trevis, 2012). The application of nitrogen fertilisers can increase pasture production through most of the year. When large amounts of nitrogen fertilisers are applied to grass pasture, the annual production is estimated to be 25-40% higher compared to when no nitrogen fertilisers are used (Ledgard & Thorrold, n.d.).

In New Zealand, dairy farmers use nitrogen fertilisers to produce extra grass growth for cows during spring to overcome temporary feed shortages. Farmers also add a total estimated amount of 200 kg of nitrogen per hectare throughout the year to continue to promote extra grass growth (Ledgard & Thorrold, n.d.). Nitrogen helps to mitigate the deficit of nitrogen in the soils from continued production on the land.

The use of nitrogen fertilisers has changed dramatically in the Canterbury region, which correlates with the dramatic change in land use over the past 30 years, due to the technological advances in agriculture. These land use changes are continuing and are anticipated to carry on for the next 20 years. With changes in land use comes changes in the use of nitrates on the land. Many farms have recently converted to dairy operations, as these products are in demand and have a high rate of return, making a conversion economically viable (Trevis, 2012). The use of nitrogen fertilisers on dairy farms is much higher than any other land use type, which means that with more farms converting to dairy, more nitrogen is being applied. Dairy requires more nitrogen as it involves intensive grazing in order to produce milk at optimum levels. Therefore, good pasture growth that is rich in nutrients is necessary in this increasingly competitive and demanding industry (Statistics New Zealand, 2006). An example of the land use changing, is that dairy farming increased from 20,000 ha in 1980 to nearly 190,000 ha in 2009. At the same time, production has also increased, with total production increasing by 1500% (Pangborn & Woodford, 2011). Also between 1994 and 2009 the number of dairy cattle increased by 6 times (Dynes, Burggraaf, Goulter, & Dalley, 2010). The land use changes also correlates with the amount of fertilisers being used in the Canterbury region, which has increased by tenfold since 1985 and has doubled since the mid 1990's. This shows that nitrogen fertilisers are seen as an important element when it comes to farming (Ministry for the Environment, 2007). This higher production from the change in land use has significant consequences, which result in detrimental impacts for the environmental health of the land and water environments.

2.3 Impact of nitrates for groundwater quality

Groundwater quality is undeniably an important issue in the Canterbury region, as there is great reliance on this resource to meet domestic and economic needs. It is also clear that the use of nitrogen fertilisers is abundant in the region for intensive agricultural purposes, especially for the growing dairy industry, which is of concern for the current and future quality of the groundwater environments. The Ministry for the Environment (2007) has stated that the intensification of the agricultural industry in the Canterbury region is the main cause for many environment issues, which has led to the degradation of both surface water and groundwater environments. There are many reasons why the agricultural industry is the cause of these issues, but the use of nitrogen fertilisers is seen as being one of the biggest contributors that is causing degradation (Castillo, 1999).

The main issue with using nitrogen fertilisers on the land is that when the fertilisers are added to the land for the growth of plants, there is often far too much nitrogen for the plants to absorb. The excess nitrogen leaches into the receiving waters which then can cause environmental issues and can impact on human health. Currently there is already natural nitrogen in the soil, but with agricultural advancements, artificial nitrogen is added onto the land, which can often cause excess nitrogen (Trevis, 2012). The nitrogen that is absorbed by the plants is usually recycled back into the soil by the breakdown of organic material. However, the excess nitrogen that is not absorbed by the plants goes through a transformation process and becomes either a gaseous nitrogen that goes back into the atmosphere or it becomes nitrate, which is a soluble form that leaches through the soil. Due to the solubility of the nitrates, it leaches through the soil profile and then can build up in surface water and groundwater environments (Trevis, 2012). Rainfall is a major factor in the contribution of the nitrates entering the groundwater environments, as some of the aquifers in the Canterbury region rely on their recharge from rainwater, which also carries the nitrates with it. When it builds up in the surface and groundwater environments, it can cause detrimental problems to the aquatic ecology due to the promotion of aquatic plant growth and can have a negative effect on drinking water quality (Paul & Meyer, 2001).

The issue of promoted aquatic plant growth in surface water systems is a process known as eutrophication and has been of concern in the waterways in the Canterbury region. Many of the groundwater aquifers in the region are used as a natural source for the environment to help with surface water flows, so the contamination in the groundwater also has a severe impact on the surface water environment. Eutrophication can occur in rivers, lakes and coastal areas, which can happen naturally or as a result of cultural activities, such as agriculture (Statistics New Zealand, 2006). Cultural activities that influence eutrophication can make the process much more intense when compared to when it naturally occurs (Perry & Vanderklein, 2009). Eutrophication is a result of nutrient loading that then increases the production of aquatic plants in the waterways, which is why nitrogen is a major issue (Paul & Meyer, 2001). The algae in the waterways can even become a harmful algal bloom, which impacts the habitat quality further. The loss of habitat quality is a mixture of a reduction in dissolved oxygen in the water, warmer water temperatures, and an increase in toxins in the water (Perry & Vanderklein, 2009). This then becomes an issue for the aquatic life, such as invertebrates and fish, as they may no longer be able to survive in these conditions.

The damage to the environment from excess nitrogen in the waterways is only a part of the problem, as it always has a massive impact on the people who rely on the water as a fresh water drinking source. Nitrate levels in drinking water that exceed the MAV of 11.3 mg/L can be toxic to humans, especially in infants that are less than six months of age and when in the womb (Austin, 2014; Payment, Waite, & Dufour, n.d.). It has a severe biological effect on humans, where it prevents oxidation occurring in our bodies, which then prevents oxygen from getting to the bodies tissues. In infants and babies in the womb, it causes blueness around the mouth, hands and feet, that is serious and can be fatal (Austin, 2014). This is a condition known as methamogloinaemia (also known as blue baby syndrome), which then causes cyanosis and, at higher concentrations of nitrate in water, asphyxia (World Health Organization, 2011).These can causes major complications in humans, which can be fatal, especially at a young age. Knowing how much nitrate is in the groundwater is important for these reasons, as it causes issues to both the environment and the people that rely on it as a resource.

2.4 How ECan has been monitoring this issue

ECan is the Regional Council of the Canterbury region and is part of New Zealand’s local government structure, which requires all regions to have a governing authority over natural resources. One of their roles as a Regional Council is to monitor water quality as it is an important resource for both domestic and agricultural needs, as well as the natural environment for our native flora and fauna. ECan monitor water in many different environments, covering both surface water and groundwater. ECan has also monitored specific contaminants in these environments, which pose threats to human and animal health (Scott & Hanson, 2013). With a focus on nitrates, ECan have developed a number of maps to show nitrate levels in groundwater across the Canterbury region.

The first lot of maps that were produced by ECan in 2002, which represent the nitrate nitrogen concentrations in wells across the Canterbury region (Hanson, 2002). There are a total of four maps that were produced, which are for four key areas within the Canterbury region (Figure 1-4). The information for these maps were obtained by collecting analytical data from 14,014 groundwater samples, from a total of 2,350 wells in the region. These maps were produced to identify spatial patterns of nitrate nitrogen concentrations in Canterbury region. ECan calculated a median nitrate nitrogen concentration for each well, which are represented six categories on the maps as colour-coded dots (Hanson, 2002).

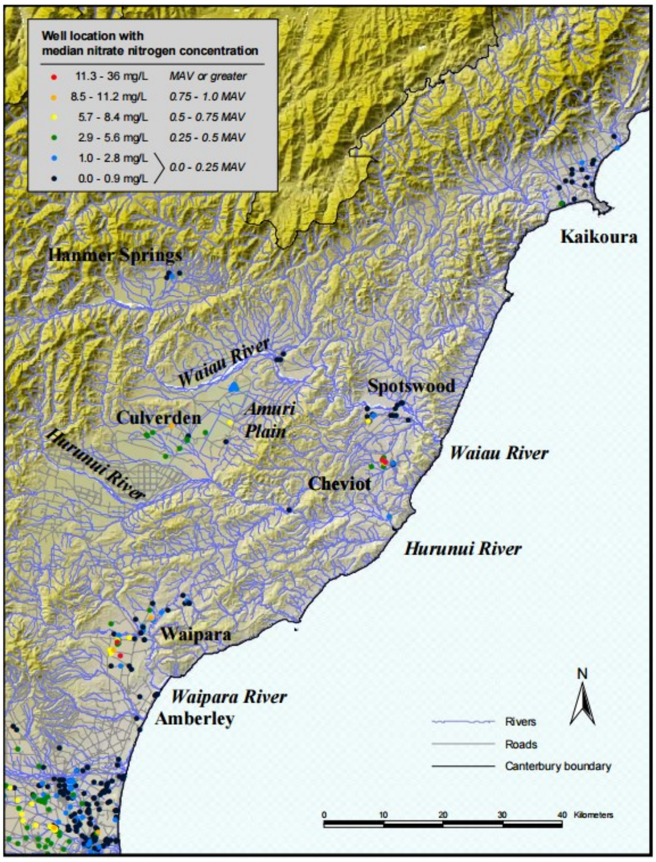


Figure 1. ECan's map for median nitrate nitrogen concentrations in northern Canterbury Plains.

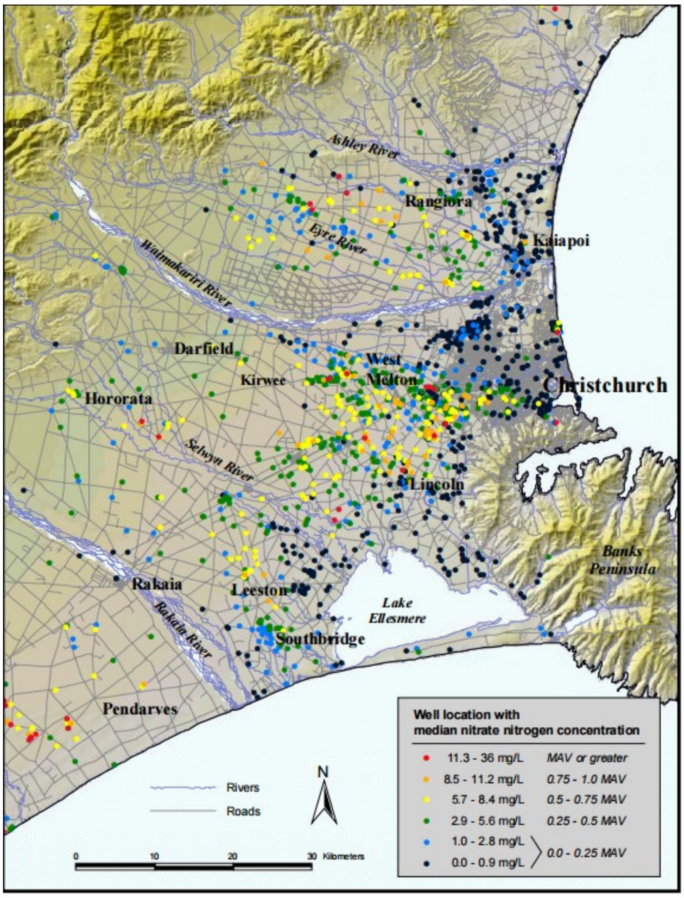


Figure 2. ECan's map for median nitrate nitrogen concentrations in northern and central Canterbury Plains.

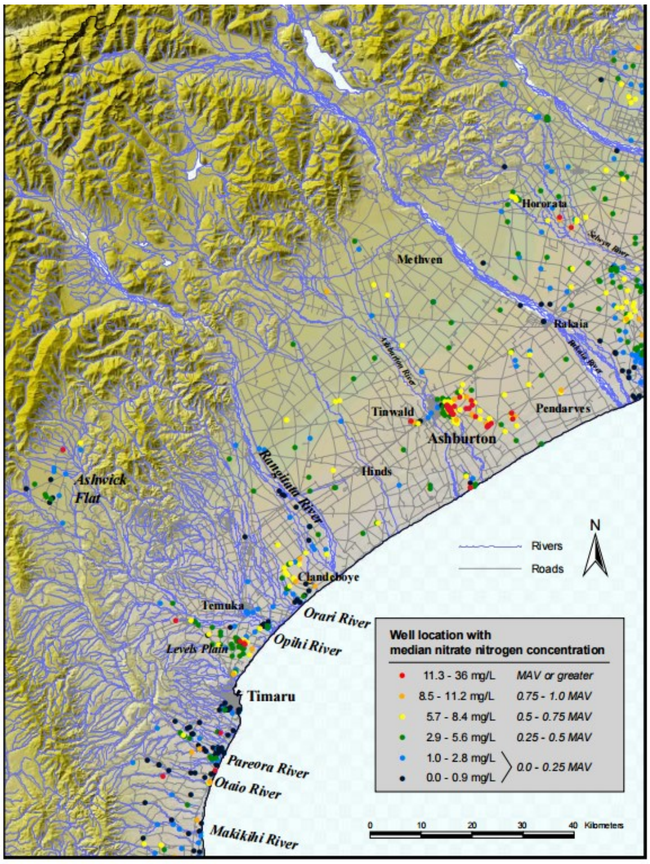


Figure 3ECan's map for median nitrate nitrogen concentrations in southern Canterbury Plains.

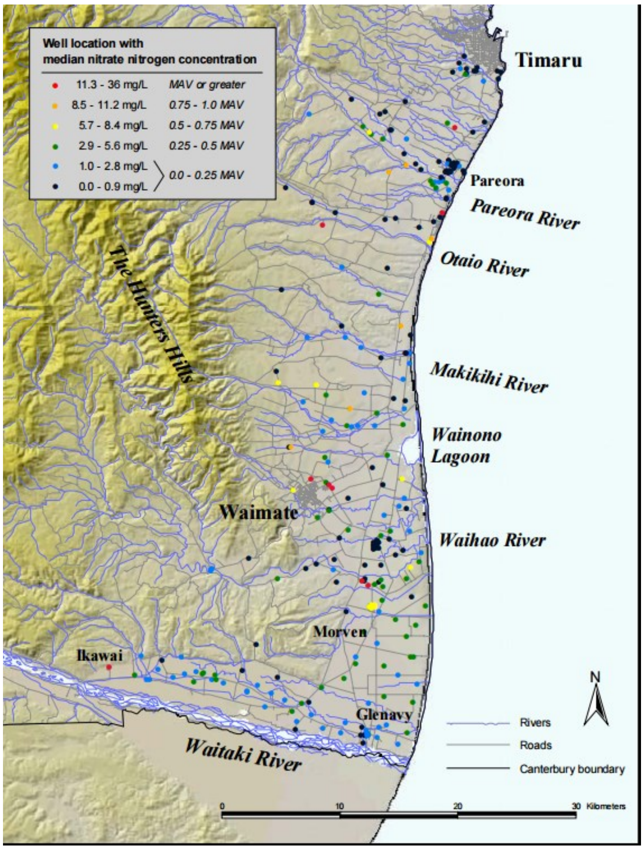


Figure 4. ECan's map for median nitrate nitrogen concentrations between Timaru and Waitaki River.

The next map that ECan produced in 2012, which also represents nitrate nitrogen concentrations in wells in the Canterbury region, is the result of an annual survey for groundwater quality in 2012 (Figure 5). The annual survey covered only nine out of the ten Canterbury Water Management Strategy (CWMS) zones, leaving out the Banks Peninsula area. This map was produced with only 128 wells being sampled in this survey, which is far fewer than the amounts of wells in the maps above that were produced in 2002. Only four categories of colour-coded dots are represented on this map (Environment Canterbury, 2012).

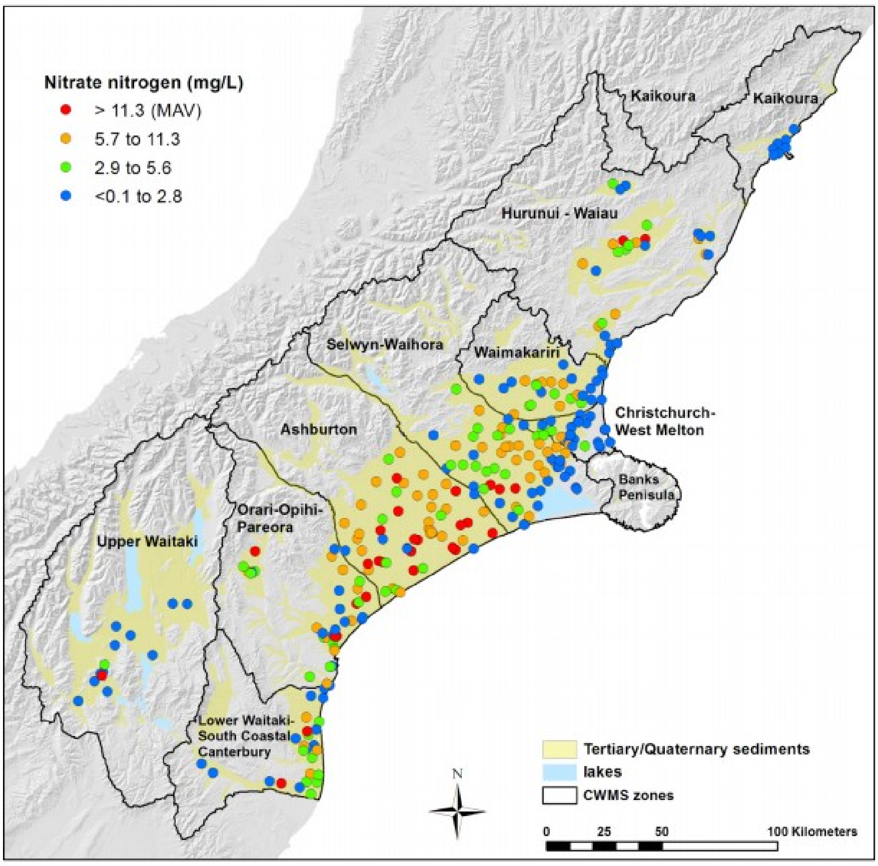


Figure 5. ECan's map of Nitrate nitrogen concentrations in the 2012 annual groundwater survey.

Another map was produced by ECan in 2013, which is a representation of the vulnerability of nitrates in groundwater across the Canterbury region (figure 6). This map was developed differently to the previous maps, as it is a representation of the nitrate nitrogen concentrations in groundwater as a spatial form, which is in the form of risk zones, rather than being represented as well points showing this same data.

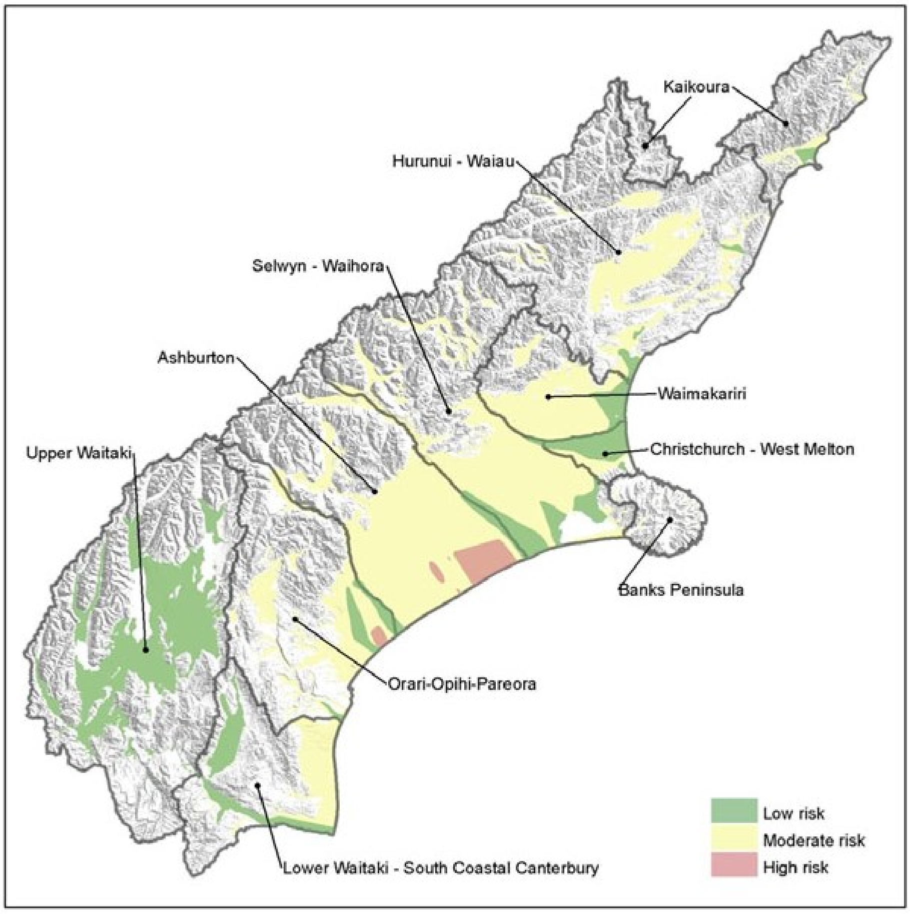


Figure 6. ECan's nitrate vulnerability in groundwater map for the Canterbury region.

The map (figure 6) includes each of the ten zone boundaries in the CWMS (Scott & Hanson, 2013). The map is a reflection of the groundwater environments that are at risk of nitrate concentrations that exceed the MAV of 11.3 mg/L based on water quality sampling. For ECan to develop a map such as this, they require a large amount of information and data from wells that had access to this groundwater resource all across the Canterbury region, such as data from the maps seen in figure 1 to 5. Only areas with known aquifers were included in this assessment and also mountainous areas and large larges were excluded (Scott & Hanson, 2013). Nitrate level data for this risk assessment was based on reports and currently available data. In the ECan database for water quality there are data collected from 3,498 sampling wells, with a total of 24,030 samples taken and analysed, which is also the same data that was used to development the previous ECan maps (figure 1-5) (Scott & Hanson, 2013; Trevis, 2012). This is some of the data that were used for this vulnerability assessment. From these data, only information for groundwater that was up to 40 metres deep from the water table were included, as anything below 40 metres have nitrate concentrations below the MAV. The data allowed ECan to identify the amount of nitrates that was present in each of the groundwater aquifers (Scott & Hanson, 2013). This method to gather data for this vulnerability map is a labour and cost intensive method.

Once all the data were collected and analysed, they presented their results on the map shown in figure 1. They divided the groundwater vulnerability into three ratings to show the level of risk; these are low, medium and high risk, which are coloured green, yellow and red respectively. The Green areas represent the areas that the groundwater is unlikely to have nitrate levels that exceed the MAV of 11.3 mg/L, so it is considered low risk. The yellow areas represent areas that may be above or below the MAV, which is why they are considered medium risk. Finally the red areas on the map represent the areas in the Canterbury region that are likely to exceed the nitrate MAV, so therefore are considered to be of high risk (Scott & Hanson, 2013).

From these nitrate vulnerability maps, ECan identified that the Ashburton zone was at the highest risk of nitrate contamination (figure 7). Many of the groundwater areas are of moderate risk and it also has the highest number of groundwater areas at high risk. Four high risk areas were identified and it was reported that they were most likely impacted by meatworks wastewater discharges and also by arable farming practices. Also one area in the Ashburton zone that has been highlighted a high risk area, had elevated levels of nitrate concentrations that were above the MAV, which was associated with discharges of effluent from a feedlot (Scott & Hanson, 2013).

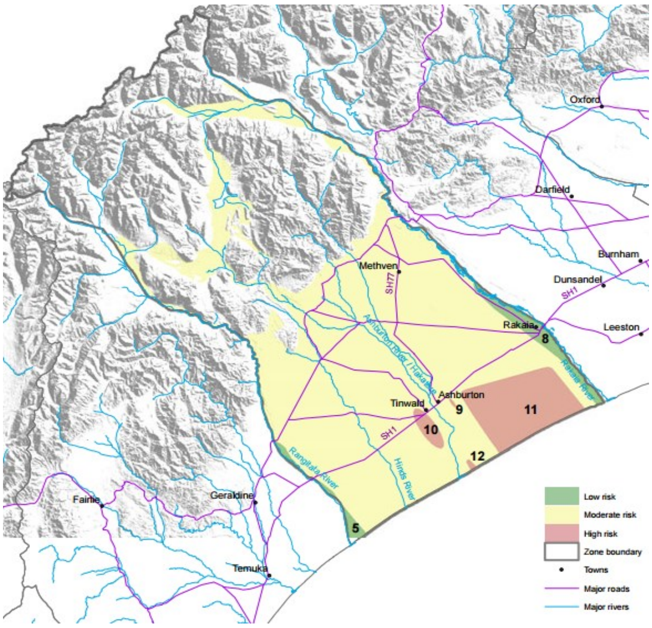


Figure 7. Map of the Ashburton zone showing nitrate vulnerability in groundwater.

The purpose of these maps are for ECan to monitor the groundwater so that they can identify trends or any significant changes in nitrates levels in the groundwater. This information is important for the people that use groundwater aquifers as a source of drinking water and for farms that rely on groundwater for irrigation. ECan annually collect groundwater data, so in the future these maps may change, which is vital for the region. With additional data the boundaries could of low-risk areas could be refined and they believe that some moderate risk areas may become high risk areas, as land use intensifies (Scott & Hanson, 2013).

2.5 How the DRASTIC model can be applied to this issue

The model that ECan has developed is very useful for identifying existing vulnerable areas. However, the DRASTIC model may also be a reliable method that requires fewer resources. This model was developed in the 1980s by the United States Environmental Protection Agency (EPA), with the purpose of evaluating groundwater pollution potential for the United States (Saatsaz et al., 2011). It has been recognised by many countries as an important tool for groundwater vulnerability and has since become the most widely used tool around the world for this purpose (Nor Said et al., 2013). New Zealand is an exception this though, as there are only a few independent studies that incorporate the DRASTIC method in their research, which have only been conducted in the North Island of New Zealand. There is no evidence of governing authorities in New Zealand utilising the DRASTIC model, even though it has potential to identify vulnerable areas of groundwater contamination. ECan's method for identifying vulnerable areas of groundwater from nitrate contamination requires a lot of time and resources, so this is where the DRASTIC model may be of some importance to the Canterbury region and New Zealand as a whole.

The DRASTIC model was originally designed by the US Environmental Protection Agency (EPA) for use in the United States as the quality of groundwater became of concern due to the intensification of the agricultural industry. The model has gone through a set of changes since its initial development, which has been achieved by adapting the methodology of the model to generate the required outcome for specific studies. The first change was that model initially only incorporated pollution potential from unconfined aquifers, but was later changed during development, as it became desirable to adapt the methodology of the model to also be used for confined aquifers systems (Aller, Bennet, Lehr, Petty, & Hackett, 1987). Another change was that the methodology was also able to be adapted to other countries around the world, allowing it to become compatible for any country wishing to use it. One of the major changes to the DRASTIC model was that it was able to be adapted to specific contaminants, such as nitrates or phosphorus, which only required some of the values to change in the methodology depending on the specific contaminants characteristics (Aller et al., 1987). No matter how the model has been adapted for the specific study, the final outcome would generate reliable results.

The final outcome of the DRASTIC model is to produce vulnerability scores for different locations by combining a number of parameters, which are in the form of spatial data layers (Babiker, Mohamed, Hiyama, & Kato, 2005). These parameters are digitised information of physical characteristics that can affect the quality of the groundwater aquifers (Aller et al., 1987). The EPA evaluated a number of parameters that could be used, such as water depth, net water recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity. These seven parameters were seen to be most important mappable factors that control the groundwater vulnerability to contamination. Other factors that were consid0ered were aquifer chemistry, temperature, transmissivity, tortuosity, and gaseous phase transport, but these were later deemed by the EPA to be too difficult to map and did not have a significant impact to groundwater contamination (Aller et al., 1987). The seven parameters are then given values and a weight, which are then added together to produce the final vulnerability scores. A description of each of the seven data layers follows:

Depth to water – This was an important layer chosen by the EPA to be included into the DRASTIC model as it is what primarily determines the depth of that a material, such as nitrates, much travel through before it can reach the aquifer. It may also help to determine the contact time with the media surrounding the aquifer. Deeper the aquifer is also means that there is a greater chance for attenuation to occur, which is beneficial for reducing contamination in groundwater aquifers. The deeper the aquifer, the less of the contaminant gets into the aquifer.

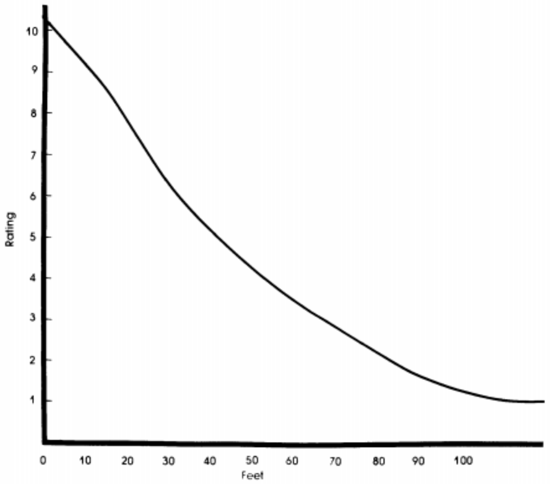


Figure 8. Graph of ranges and ratings for depth to water.

The only downfall of depth to water for the DRASTIC model is that it does not include saturated zones, as they have insufficient permeability to yield significant quantities of water to be considered an aquifer. The methodology for depth to water allows the user to evaluate either confined or unconfined aquifers. With a focus on unconfined aquifers, the user chooses depth to water as the depth from the ground surface to the water table. The water table is the expression of the surface water that is below the ground level where all the pore spaces in the surrounding media are filled with water. The values then given to the different depths are based on how much they will affect the aquifer below the surface, which is shown in figure 8 (Aller et al., 1987).

Net recharge – This is an important layer as the primary source for groundwater recharge is typically from precipitation which penetrates through the surface of the ground and enters down to the water table. The amount of water for net recharge from precipitation is based on the amount of water per unit area of land. This recharge water then allows contaminants to be transported vertically down to the water table and horizontally within the aquifer. Another important aspect of net recharge is that the quantity of water available for dispersion and dilution of any contaminants is controlled by this parameter. In general, the recharge water is the principal vehicle for leaching and transporting of solid or liquid contaminants into the aquifers. The greater the recharge, the greater the potential for groundwater pollution, until it gets to the point where significant dilution occurs. The DRASTIC model does acknowledge the dilution affect, however it does not include this in the ranges and ratings associated for the net recharge parameter. In addition to precipitation there are a number of factors that should be included, which are irrigation, artificial recharge and wastewater application. These factors may have a significant effect on the amount of water available to carry a pollutant into the aquifer. The methodology for net recharge is defined as the total quantity of water from the aforementioned sources that is applied to the ground surface and infiltrates to reach the aquifer. Also for unconfined aquifers, the recharge to the aquifer occurs more freely and

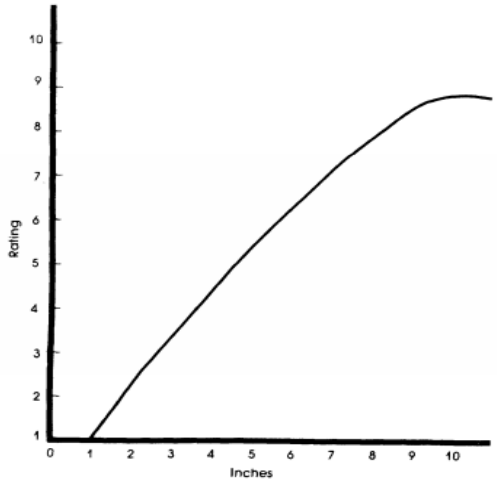


Figure 9. Graph of ranges and ratings for net recharge.

the pollution potential is generally greater than that of confined aquifers. The values given to the ranges for net recharge are based on the greater the recharge the higher the value, which is show in figure 9 (Aller et al., 1987).

Aquifer media – This parameter refers to the consolidated and unconsolidated rock which serves as an aquifer, such as sand, gravel or limestone. The water is contained in these aquifers within the pore spaces of the media. The flow system within the aquifer is based on the media, which affects the route and path length that a contaminant must follow. The path length is an important control in determining the time available for the attenuation processes to occur, which include sorption, reactivity and dispersion. The route that the contaminant goes through in the media is strongly influenced by fracturing or interconnected series of solution openings which may provide pathways for easier flows. The aquifer media also has an impact on the amount of effective surface area of materials with which the contaminant may come in contact within the aquifer. In general, the larger the grain size of the media and the more factures or openings within the aquifer media, the higher the impact the contaminant has on the water within the aquifer. The different types of aquifer media can be placed into categories, which are as follows; massive shale, metamorphic/igneous, weathered metamorphic/igneous, glacial till, bedded sandstone/limestone/shake, massive sandstone, massive limestone, sand and gravel, basalt, and karst limestone. The values are assigned to these categories and the values are given in the methodology, which are based on potential the contaminant has on making its way to the groundwater (Aller et al., 1987).

Soil media – This parameter refers to the uppermost portion of the vadose zone characterised by significant biological activity. For the purpose of the DRASTIC model, the soil is commonly considered the upper weathered zone of the earth which averages a depth of six feet or less from the ground surface. This is an important parameter for the model, as it has a significant impact on the amount of recharge which can infiltrate into the ground, therefore having an impact on the ability of a contaminant to move into the vadose zone. The ability that the soil has on the contaminant moving through the soil is based on the texture of the soil. For example, fine textured soils such as silts and clays can decrease relative soil permeability's and restrict contaminant migration, thus reducing the impact on the groundwater. Figure 10 can be used to identify the characteristics of the soil, which then can be used to identify its potential impact on the groundwater. Also in areas where the soil zone is fairly thick, the attenuation processes of filtration, biodegradation, sorption and volatilization may be quite significant. The different types of soil media can be placed into categories, which are as follows; non-shrinking and non-aggregated clay, clay loam, silt loam, loam, sandy loam, aggregated clay, peat, sand, and gravel. For certain land practices the soil may have the main influence of potential. Furthermore, the pollution potential of the soil media is largely affected by the type of clay present, the swell potential and the grain size of the media. The quantity of organic material present in the soil may also be an important factor for the attenuation of pesticides. In the methodology for soil media, the values are given to the soil categories based on their ability of a contaminant to make its way through the media (Aller et al., 1987).

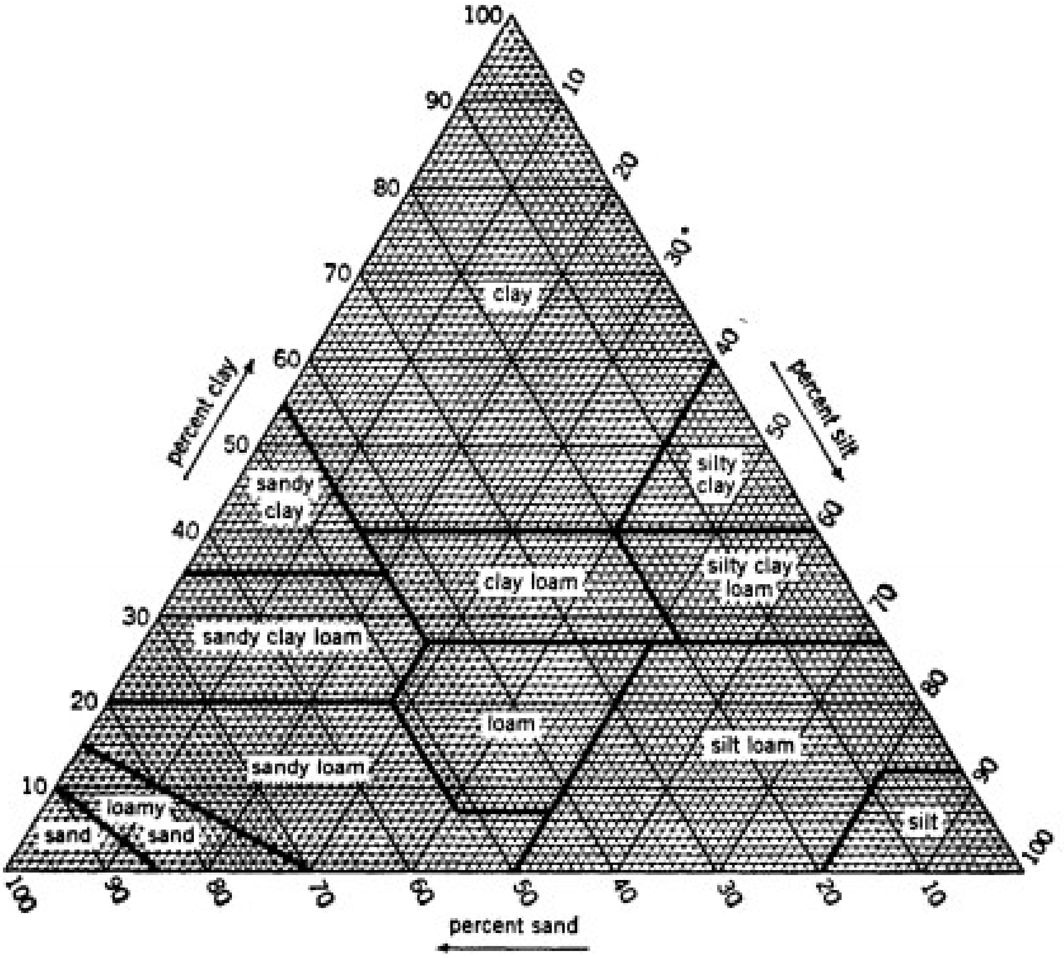


Figure 10. Soil textural classification chart.

Topography – This parameter refers to the slope and slope variability of the land surface in the given area. Topography is important for DRASTIC as it helps control the likelihood that a contaminant will run off or remain on the surface in an area long enough for it to enter the groundwater aquifer. Slopes provide a greater opportunity for contaminants to infiltrate the groundwater, which will then have a more significant impact on the groundwater and have a higher groundwater pollution potential. For example, the more gradual the slope is the greater opportunity it has to infiltrate into the groundwater. Topography has the ability to influence the soil development, which then has an effect on contaminant attenuation. This parameter is also significant for DRASTIC, as the gradient and direction of flow often can be inferred for water table conditions from general slope of the land. In most circumstances, the steeper slopes signify higher groundwater velocity. The values for topography in the methodology are based on the graph seen in figure 11 (Aller et al., 1987).

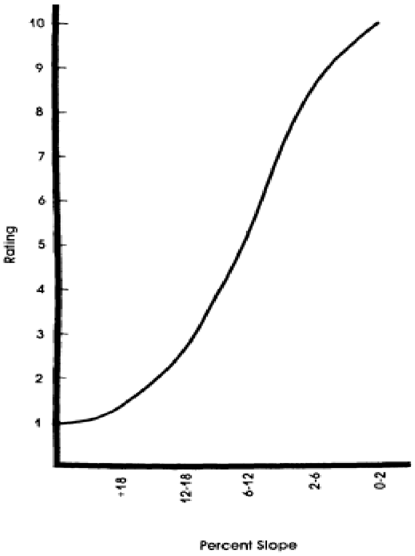


Figure 11. Graph of ranges and ratings for topography.

Impact of vadose zone – This parameter is defined as the zone above the water table which is unsaturated or discontinuously saturated. The type of vadose zone media is what determines the attenuation characteristics of the material below the soil horizon and above the water table. A number of processes can occur within the vadose zone, which can have an impact on the pollution potential. These processes include biodegradation, neutralisation, mechanical filtration, chemical reaction, volatilisation and dispersion. The vadose media also controls the path length and routing of the water that is trying to penetrate into the groundwater aquifers, which affects the time available for attenuation. For the DRASTIC methodology, the selection of the vadose zone media depends on the most significant media which influences pollution potential. For example, if the vadose zone media has a mixture of limestone and sand, then the media that will have the biggest impact for allowing a contaminant to enter the groundwater aquifer will be chosen. The vadose media can be split into categories, which are as follows; silt/clay, shale, limestone, metamorphic/igneous, sandstone, bedded limestone/sandstone/shale, sand and gravel, and basalt. The value then given to the vadose media category, which is based on the contaminants ability to make it through that media into the groundwater (Aller et al., 1987).

Hydraulic conductivity – This parameter refers to the ability of the aquifer materials to transmit water, which then controls the rate at which the groundwater will flow under a given hydraulic gradient. The flow rate of the groundwater also controls the rate that a contaminant moves away from the point at which it enters the aquifer. Hydraulic conductivity is controlled by the amount and interconnection of void spaces within the groundwater aquifer, which can often occur as a consequence of intergranular porosity, fracturing and bedding planes. For the purpose of the DRASTIC model, hydraulic conductivity it divided into ranges where the higher the hydraulic conductivity the greater the pollution potential. Figure 12 represents the ranges of hydraulic conductivity and the value given to each range (Aller et al., 1987).

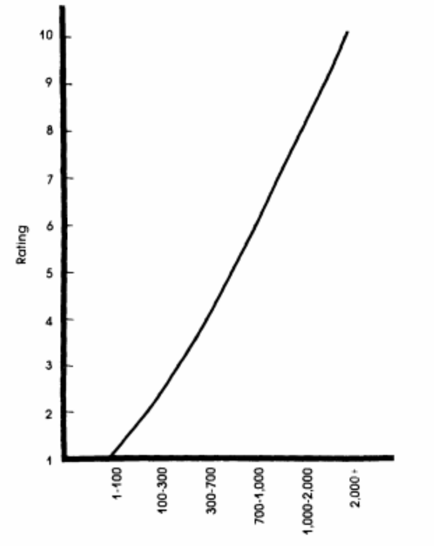


Figure 12. Graph of ranges and ratings for hydraulic conductivity.

The seven parameters identified by the EPA are what is required to generate the DRASTIC model, but the EPA developed this model to use four major assumptions, which work with the methodology. These assumptions are: 1) the contaminant is introduced at the ground surface; 2) the contaminant is flushed into the groundwater by precipitation; 3) the contaminant has the mobility of water; and 4) the area evaluated using the DRASTIC model is 100 acres or larger (Aller et al., 1987). For example, the methodology with these assumptions assumes that the contaminant will start at the surface, entering the soil and then travel through the vadose zone before entering the aquifer much like how water flows (Aller et al., 1987). When it comes to a specific contaminant, its characteristics may make it denser than water, so the methodology will change by changing the weights of the parameters, as some parameters may a higher impact on groundwater contamination depending on the characteristics of the specific contaminant (Aller et al., 1987). These assumptions are one of the major limitations of the DRASTIC model, which can be seen in both a positive and a negative way. However, these assumptions still generate valuable information for groundwater vulnerability and have many useful applications.

One of these independent studies in New Zealand involving the DRASTIC model has been identified. This study is the ‘Assessment of a groundwater quality monitoring network using vulnerability mapping and geostatistics: A case study from the Heretaunga Plains, New Zealand’ by Baalousha (2010). This study uses an approach that combines a hydrogeological modelling approach of groundwater systems along with geostatistics to design and optimise a groundwater quality monitoring network. The hydrological modelling approach was the use DRASTIC model for creating a vulnerability map, and the geostatistical method was the use of the kriging variance map. The DRASTIC map was developed using the aforementioned seven DRASTIC data layers, which was able to identify the groundwater vulnerability for contamination in the Heretaunga Plains. With this map, they identified that the least vulnerable area is located in the east where the groundwater aquifer systems are confined, and the most vulnerable areas were identified to be in the west where the aquifers are unconfined and the net recharge is high. A geostatistical analysis was then done to develop a kriging variance map, which was used to determine the nitrate values in groundwater, along with the lag effect of nitrates that occurs from groundwater flow. They found that the nitrate concentrations were greater in the east than the west, due to the groundwater flow being west to east. With both the DRASTIC map and the kriging variance map, they combined these together to create a final vulnerability map (figure 13.). The map shows that the higher the value, the greater the need for these areas to be monitored than areas with lower values. Baalousha (2010) determined that with the proposed and tested methodology of this study, that it can be used for the design of a new monitoring network, or to assess already established networks for the Heretaunga Plains (Baalousha, 2010).

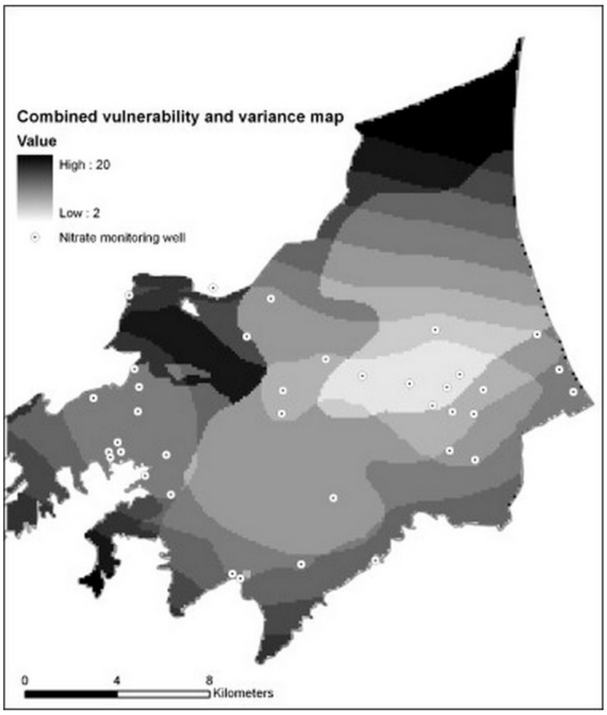


Figure 13. Combined DRASTIC and kriging variance map for the Heretaunga Plains, Hastings (Baalousha, 2010).

The DRASTIC model has many beneficial applications, which have been recognised by the EPA. One of the applications is that the model may be used for preventative purposes through the prioritisation of areas where groundwater protection is critical (Aller et al., 1987). This can be done with the model as it can identify the most vulnerable zones based on the vulnerability scores and with this information it can identify the areas that have the highest need for protection. Another application is that the model can be used as part of a strategy to identify vulnerable areas for monitoring purposes (Aller et al., 1987). This would also utilise monitoring programmes that have been designed by the appropriate authorities that look after the specific site. The EPA have also identified that the DRASTIC model may be used as part of a strategy to identify areas where either additional or less stringent protection measures in the localised legislation may be required (Aller et al., 1987). There are also specific applications for the DRASTIC model in the Canterbury region for nitrate contamination in groundwater. Groundwater is an important resource for Canterbury and identifying vulnerable areas to nitrates using the DRASTIC model is another way to protect this resource. Based on the aforementioned applications, the DRASTIC model can be used in the Canterbury region to assist ECan in identifying groundwater areas that may require monitoring for the purpose of ensuring that drinking water from these aquifers are still below the MAV level. ECan may also be able to use the DRASTIC model as a cheaper and less time consuming tool compared to other methods that they use. There are many applications for this model for the Canterbury region, which do not have to be restricted to nitrates, but the DRASTIC model does have potential to be used in conjunction with ECan’s current methods, especially since groundwater contamination is a major issue that Canterbury is facing.

3. Research aims and objectives

3.1 Research aim

To find out if the DRASTIC model, created through GIS, can be a reliable method as a monitoring tool for identifying areas of groundwater that are vulnerable to nitrate contamination in the Canterbury region, when it is compared with the vulnerability map produced by ECan.

The DRASTIC model is a widely adopted approach around the world for government agencies to use for identifying vulnerable areas of groundwater to nitrate contamination, as this is a major issue that is happening all over the world. New Zealand is also facing this issue, especially for areas such as Canterbury, as nitrogen fertilisers are used in this region for intensive agricultural activities. ECan have been attempting to monitor this issue by collecting data from groundwater wells located all over the Canterbury region and creating maps showing this data, however this is a costly exercise to run and to continue. The maps also only show the current data and how monitoring can be planned from that. The DRASTIC model could be applied to this region, which may be able to produce maps to show where future contamination may occur so that monitoring programmes and mitigation methods can be put in place before nitrate contamination occurs. The DRASTIC map can be produced in an efficient amount of time and is a cost effective approach. So if these DRASTIC maps are proven to be reliable for the Canterbury region, then they could potentially be used by ECan and other interested parties for monitoring groundwater contamination along with the use of current methods.

3.2 Research objectives

Three objectives have been identified for this research, which will be used to achieve the aim of the research. The research objectives are:

1. To develop a DRASTIC map that shows vulnerability results for nitrate contamination in groundwater for the Canterbury region.
2. To determine if the DRASTIC map can produce reliable results to determine potential future vulnerable areas by comparing them with the ECan vulnerability map.
3. To determine if the DRASTIC model can be a useful monitoring tool for predicting groundwater contamination in the Canterbury region.

4. Study area

The study area for this research will be located in the Canterbury region in the South Island of New Zealand. For the purpose of this study, only Christchurch City and the areas south of this location will be used for this research, so any areas in the Canterbury region north of Christchurch City will be excluded (figure 14). This section of the Canterbury region was chosen as the vulnerability maps developed by ECan only show areas of high importance to be in the southern region, and it also identifies are a good number of low and intermediate areas of importance for nitrate vulnerability. No areas north of Christchurch City had areas of high importance. By doing this it will be able to produce results that can be easily comparable to the most significant areas in the ECan vulnerability map.

Figure 14. Study area within the Canterbury region.

5. Methods

The aim of this research is to identify whether the DRASTIC model is a reliable method for nitrate vulnerability in groundwater by comparing it with the both the nitrate vulnerability map (figure 6) and the other nitrogen nitrate level maps (figure 1-5) produced by ECan. The ECan maps will give a good indication of whether the DRASTIC model can be used as a reliable tool for nitrate vulnerability identification in the Canterbury region, which can then potentially be considered as a useful tool for any further research on nitrate vulnerability in groundwater or be a tool for monitoring purposes. The DRASTIC model is widely used around the world, but has rarely been used in New Zealand and has not been seen in the Canterbury region, so the results from comparing these maps in the Canterbury region will be of importance and this model could potentially be applied to other regions in New Zealand. DRASTIC uses fewer resources and is more time efficient compared to current methods. In order to achieve the aim of this research, the objectives that were identified will need to be answered.

The process required to answer these objectives will be split into a three sections. These sections are the following: Obtaining the seven DRASTIC data layers, developing the final DRASTIC map, and comparing the DRASTIC map with ECan's vulnerability map (Figure 6).

5.1 Obtaining the DRASTIC data layers

As stated earlier the DRASTIC model is a digital model that necessitates specific data to reach a required outcome, which in this case in a map of the Canterbury region for nitrate vulnerability in groundwater. It requires the use of a Geographic Information System (GIS) in order to process these data to reach the outcome, which will be in the raster format. The type of data that is required for the DRASTIC model for this research will be specific to identify nitrates in groundwater, as this model also has the ability to model other types of contaminants, and it must be specific to the Canterbury region. There are a total of seven data layers that are required for this model, which will be used in the GIS programme, ArcGIS. These data layers are as follows: Depth to water (D), Net recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of vadose zone (I), and Hydraulic conductivity (C). The data layers are then broken down into several classes that have ranges, which are then given individual values and weights. The values and weights are given to the data layers are based on the groundwater systems being unconfined aquifers and that we are identifying pesticide contamination (in form of nitrates).

In order to obtain these seven DRASTIC data layers, they have to be developed from other data layers that are found in various databases containing GIS data. These data layers will then be used in GIS software (ArcGIS) to go through analysis to create the seven DRASTIC data layers. A description for how each of the seven DRASTIC data layers were obtained and how they were given values follows:

Depth to Water (D)

The depth to water data layer was developed through information found on Canterbury well data, which was found on ECan's database of GIS data. The well data was presented in the form of points around the Canterbury region. These points had data on well depth to the water level, which was used as the basis for the depth to water data layer. An interpolation process, known as Inverse Distance Weighted (IDW), was done using GIS to predict the water depth over the entire Canterbury region based on the well data points. It does this by creating a surface layer based on the water depth data. Once this layer was created, it was then reclassified giving it values that ranged from 1 to 10, based on the depth from the surface to the water table depth (Table 1.). The data layer was also given a weight of 5, as it is considered to be one of the most significant factors for nitrate vulnerability in groundwater. This created the finished Depth to Water data layer. The typical ratings for depth to water for this study vary between 5 and 50.

Net Recharge (R)

The net recharge data layer was developed using average annual rainfall data in the Canterbury Region, which was sourced from Lincoln University's GIS database. To obtain the net recharge, the rainfall layer was reclassified by giving it values that ranged from 1 to 9 (Table 1.), based on the amount of water (mm) that can potentially transfer nitrates into the groundwater aquifers. The layer was also given a weighting of 4, as it has significant impact on nitrate contamination in groundwater. Other factors such as irrigation, artificial recharge and wastewater application were not included in this data layer, as this information was not available. Evapotranspiration was also not included for this layer, in order to compensate for not including the previously mentioned factors. The typical ratings for depth to water for this study vary between 4 and 36.

Aquifer Media (A)

The aquifer media data layer was developed using Canterbury geological data, which was sourced from the 1:250,000 geological maps produced by Geological & Nuclear Sciences (GNS). The geological maps were in the vector format and were split into three areas of the Canterbury region (excluding northern Canterbury); the Christchurch, Aoraki and Waitaki areas. These three areas were then merged together using the merge tool in data management in ArcGIS, combining them into a single geological data layer. This layer contained data on the different types of groundwater aquifer media, which were then placed into categories based on the media characteristics (Appendix A). These categories then allow a value to be assigned to that aquifer media type. A field was added into the attribute table of this layer, which is where values were entered, based on the contaminants ability to make its way through the fractures or openings within the aquifer media. These values ranged from 3 to 9 (Table 1.). Once the values were assigned, the layer was then converted into the raster format, using the polygon to raster tool, based on these given values, which results in the final aquifer media layer being developed. The layer was given a weight of 3, making the typical ratings for aquifer media for this study to vary between 9 and 27.

Soil Media (S)

The soil media data layer was developed using New Zealand soils data, which was sourced from the New Zealand Land Resource Inventory (NZLRI) database. The soils layer were in the vector format, which contained information on different soil types from all over New Zealand. The soil types were then sorted into the categories based on the soil characteristics, which were identified in the New Zealand soils classification guide (Appendix A). Much like the aquifer media, the categories allow a value to be assigned to the soil type. A field was added into the attribute table of this layer, which is where values were entered, based on the contaminants leeching ability through the soil type. These values ranged from 1 to 10 and is given a weight of 5 (Table 1.), as it is considered one of the most significant factors for nitrate vulnerability in groundwater. The layer was then converted into a raster format, much like the aquifer media layer, which created the finished soil media data layer. The typical ratings for soil media for this study vary between 5 and 50.

Topography (T)

The topography data layer was developed using New Zealand Digital Elevation Model (DEM) data, which was sourced from Lincoln University's GIS database. To obtain the topography, the DEM layer was converted using the slope tool under Spatial Analyst in ArcGIS, which produced a layer showing the slope percentage for the Canterbury region. This layer was then reclassified to give it values from 1 to 10, with a weighting of 3 (Table 1.), which created the finished topography data layer. The typical ratings for topography for this study vary between 3 and 30.

Impact of Vadose Zone (I)

The impact of vadose zone data layer was developed using NZLRI geological data, which was sourced from the NZLRI database. This geological data was in vector format, which contained information on the main rock (in the vadose zone) that covers the Canterbury region. The rock types were then placed into categories based on their characteristics (Appendix A). Much like the aquifer and soil media layers, the categories allow a value to be assigned to that rock type. If there were multiple types of rock in the same vadose zone, then the one that had the greatest impact on groundwater vulnerability was selected as the main rock type. A field was then added to the attributes table of this data layer, where the values were given. These values ranged from 4 to 8 and were given a weighting of 4 (Table 1.). The layer was then converted into the raster format using the polygon to raster tool, which then created the finished impact of vadose zone data layer. The typical ratings for this layer for this study vary between 16 and 32.

Hydraulic Conductivity (C)

The hydraulic conductivity data layer was developed from the same data used to make the aquifer media data layer. From the available geological data, the hydraulic conductivity for each of the geological media was calculated using a chart provided by Aller et al. (1987) (figure 15). Once the hydraulic conductivity for each geological media was calculated, they were placed into ranges, so that values could be assigned based on the chart seen in figure 12, which were adjust to metres per day from gallons per day per square foot. To assign the values, a field was added into the attribute table where the values were assigned to the geological media type. These values ranged from 1 to 10, with a weight of 2 (Table 1.). The layer was then converted into raster format, using the polygon to raster tool, which results in the final hydraulic conductivity data layer being developed. The typical ratings for hydraulic conductivity for this study vary between 2 to 20.

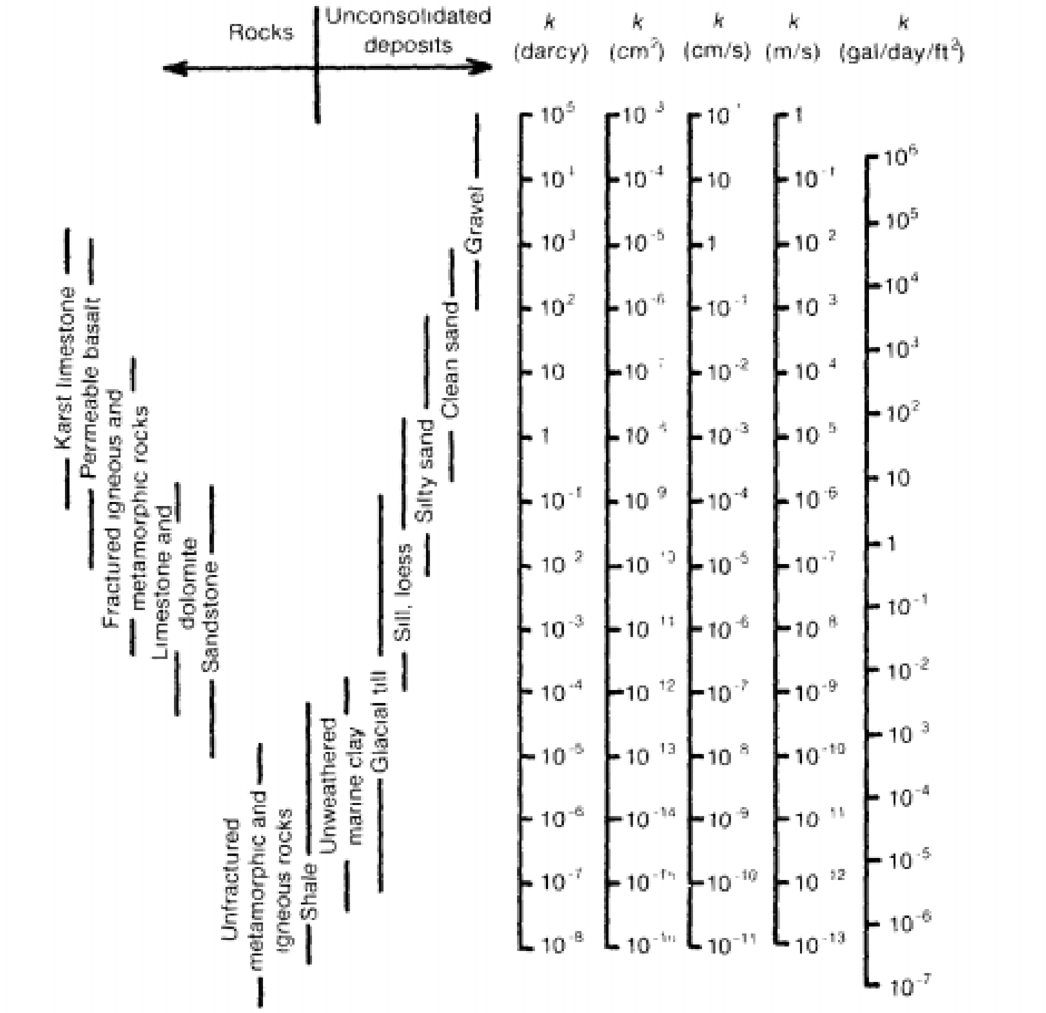


Figure 15. Range of values of hydraulic conductivity.

Data Layer	Range	Value	Weight
Depth to Water (m)	0 – 0.4	10	5
	0.4 - 12	9	
	12 - 18	8	
	18 - 26	7	
	26 – 34	6	
	34 - 44	5	
	44 - 52	4	
	52 - 68	3	
	68 - 88	2	
	88+	1	
Net Recharge (mm)	0 – 25.4	1	4
	25.4 – 50.8	2	
	50.8 – 76.2	3	
	76.2 – 101.6	4	
	101.6 - 127	5	
	127 – 152.4	6	
	152.4 – 177.8	7	
	177.8 – 203.2	8	
	203.2+	9	
Aquifer Media	Metamorphic/Igneous	3	3
	Weathered Metamorphic/Igneous	4	
	Glacial Till	5	
	Bedded Sandstone/Limestone /Shale	6	
	Massive Sandstone	6	
	Massive Limestone	6	
	Sand and Gravel	8	
	Basalt	9	

Data Layer	Range	Value	Weight
Soil Media	Non-shrinking and Non-aggregated Clay	1	5
	Clay Loam	3	
	Silt Loam	4	
	Loam	5	
	Sandy Loam	6	
	Aggregated Clay	7	
	Peat	8	
	Sand	9	
	Gravel	10	
Topography (slope %)	0 – 2	10	3
	2 – 6	9	
	6 – 12	5	
	12 – 18	3	
	>18	1	
Impact of Vadose Zone	Shale	4	4
	Limestone	5	
	Metamorphic/Igneous	5	
	Sandstone	6	
	Bedded Limestone/Sandstone /Shale	7	
	Sand and Gravel	8	
Hydraulic Conductivity (m/day)	0.01 – 4	1	2
	4 – 12	2	
	12 – 28	4	
	28 – 40	6	
	40 – 80	8	
	>80	10	

Table 1. Values and weights for each of the seven DRASTIC data layers.

5.2 Developing the final DRASTIC map

Once all of the seven DRASTIC data layers are obtained, they are to be combined together to create a single layer, which will be used to produce the final DRASTIC map. This section involves combining the values from the DRASTIC data layers so that it represents the accumulated values in a single layer, which is represented as d. The first step of this section is to change all the data layers to a maximum cell size of 500m by 500m using the ‘Resample Tool’ under Data Management in ArcGIS. This will allow the values from each layer to be more representable in the final DRASTIC map. Now to make the final DRASTIC map, the data layers will go through the Map Algebra function under the Spatial Analyst tools in ArcGIS. The formula for doing this calculation is:

$$d = (DvDw) + (RvRw) + (AvAw) + (SvSw) + (TvTW) + (IvIw) + (CvCw)$$

When all these layers are added together, it represent the vulnerability of nitrate contamination in groundwater in the Canterbury region, with the higher values showing the greatest vulnerability for contamination. The values range from 57 to 227. In order to make the final DRASTIC map, this single layer (d), needs to be further reclassified into four ratings. This will allow the map to visually show the areas of groundwater that are more vulnerable to nitrate contamination. These ratings are; low vulnerability, moderate vulnerability, high vulnerability, and very high vulnerability. The ratings will then be assigned a colour; green, yellow, orange, and red, respectively. These colours makes the map visually appealing and easier to distinguish between the different ratings. The process from turning the initial data layers into the DRASTIC data layers, then into the final DRASTIC map is seen below (figure 16).

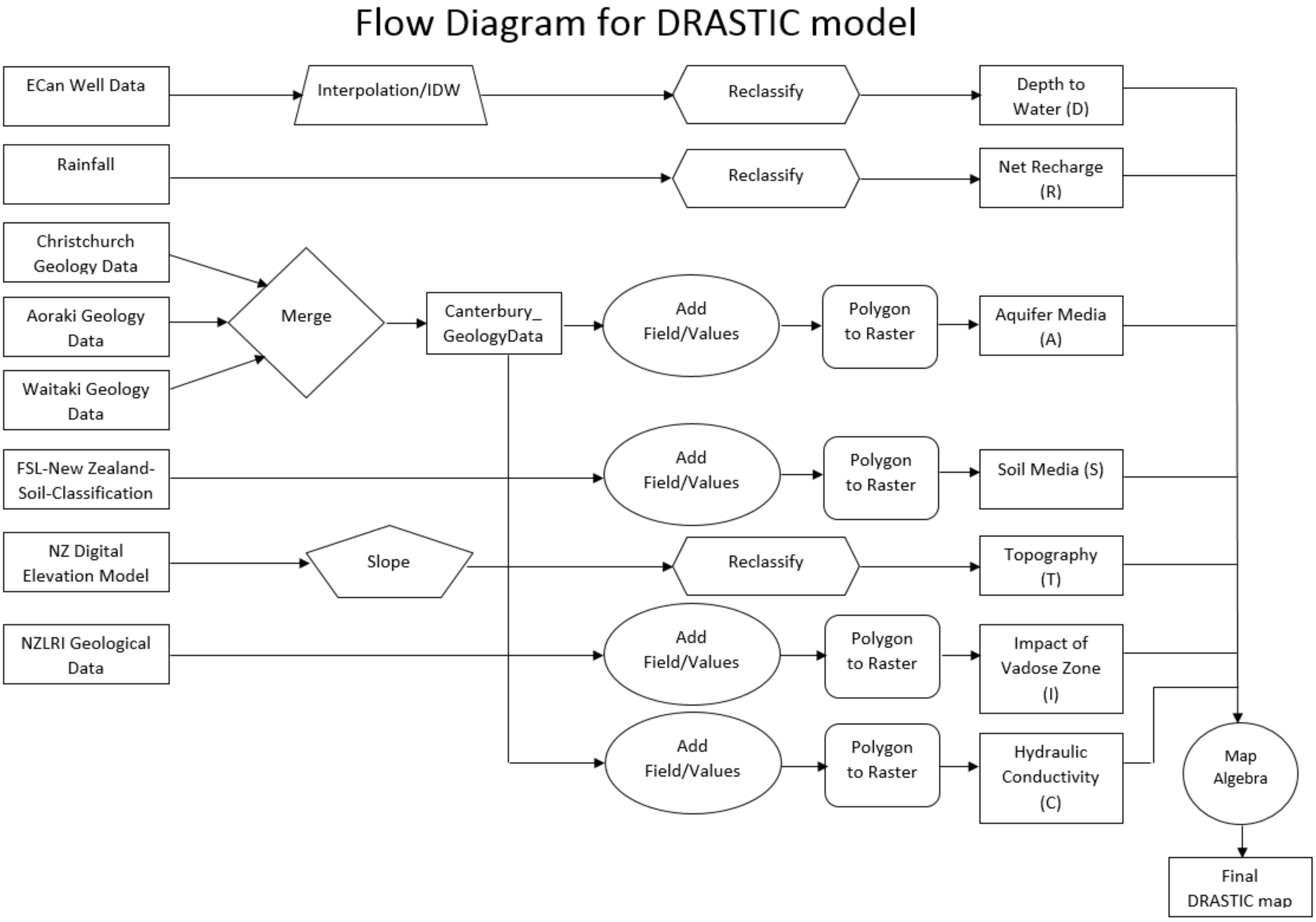


Figure 16. Flow diagram of the DRASTIC model process.

5.3 Comparison of the DRASTIC and the ECan vulnerability map

Using both the final DRASTIC map that will be produced and the groundwater vulnerability map produced by ECan (figure 6), a comparison will be carried out. The comparison will be using visual techniques and will be based off of key areas from both the DRASTIC and ECan maps. These key areas will be identified as areas that have similarities or differences between the two maps. An example of a similarity, which will be used to identify a key area, will be if an area on the DRASTIC map is shown as a very high vulnerability area and this same area on the ECan vulnerability map is also shown as high risk. An example of a difference, which will also identify a key area, will be if the DRASTIC map shows a high vulnerability in an area, but this area on the ECan vulnerability map is considered low risk.

A total of seven key areas for comparison were identified between the DRASTIC and the ECan vulnerability maps. Zoomed in versions of these key comparison areas will be extracted from the original maps and placed side by side for visual comparisons to be made. Based on these key areas, if there are many areas that are considered a higher vulnerability in the DRASTIC map, than the risk ratings of the ECan map, then it will show that the DRASTIC model could be a useful tool for monitoring groundwater vulnerability. If the DRASTIC map shows that the vulnerability rating is lower than the risk ratings in the ECan map, then it will show that the DRASTIC map will not be a useful monitoring tool for groundwater vulnerability.

6. Results

6.1 DRASTIC map results

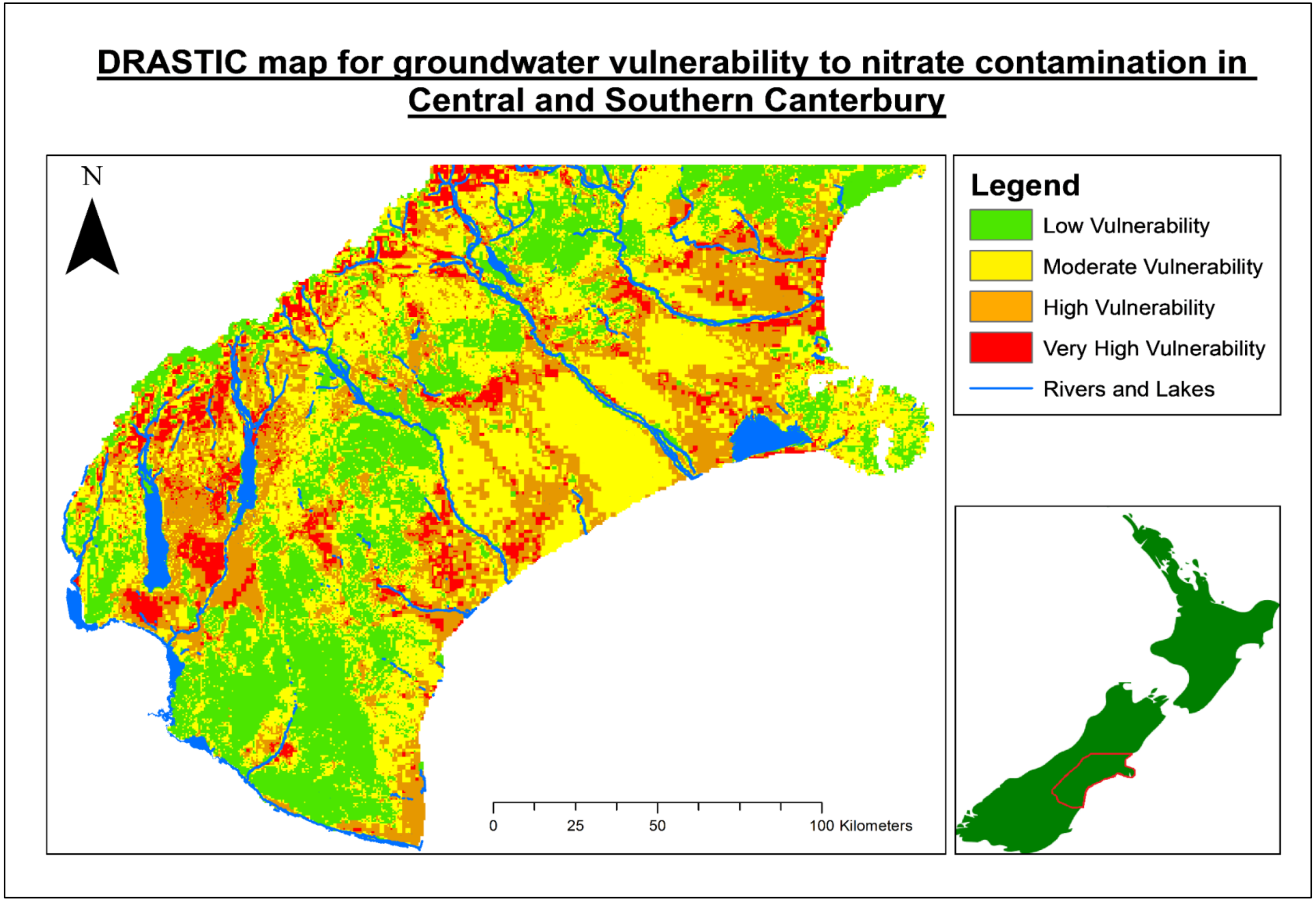


Figure 17. DRASTIC map produced for the Canterbury region, showing the four ratings of groundwater vulnerability to nitrate contamination.

The final DRASTIC map (figure 17) shows the vulnerability scores for the selected study area for the Canterbury region. The map is a prediction of the vulnerable groundwater areas that may become contaminated in the future. The map shows a mixture of vulnerability ratings throughout the Canterbury region, with significant areas of each vulnerability rating. The low vulnerability rating is seen mainly around the northern and southern parts of the study area, and in areas around the foothills of the Southern Alps in the Aoraki area. The moderate vulnerability rating is scattered throughout the region, but there are significant areas of moderate vulnerability in the Canterbury Plains and in areas within the Southern Alps. The high vulnerability rating also shows some significant areas in the region, mainly around Christchurch City, Lake Ellesmere, around the Rangitata River, and between Lake Pukaki and Lake Tekapo. There is far less areas that have a very high vulnerability rating, but these are mainly found the coastal area of Christchurch, areas within the Southern Alps, between the Ashburton area and Opihi River, and to the south and east of Lake Pukaki.

Rating	Count	Percentage area
Low Vulnerability	34,431	29.2%
Moderate Vulnerability	45,208	38.4%
High vulnerability	29,034	24.6%
Very High Vulnerability	9,213	7.8%

Table 2. Number of cells on the DRASTIC map for each of the four vulnerability ratings.

The DRASTIC map (figure 17) represents the study area with a total of 117,886 grid cells, which is the total number of cells from each of the four ratings (table 2.) Each cell has an area measurement of 500 by 500 metres. For the low vulnerability rating there are a total of 34,431 cells, which is 29.2% of the study area. The moderate vulnerability rating has a total of 45,208 cells, which is 38.4% of the study area. The high vulnerability has a total of 29,034 cells, which is 24.6% of the study area. Finally the very high vulnerability has a total of 9,213 cells, which is 7.8% of the study area.

6.2 Significant areas for comparison

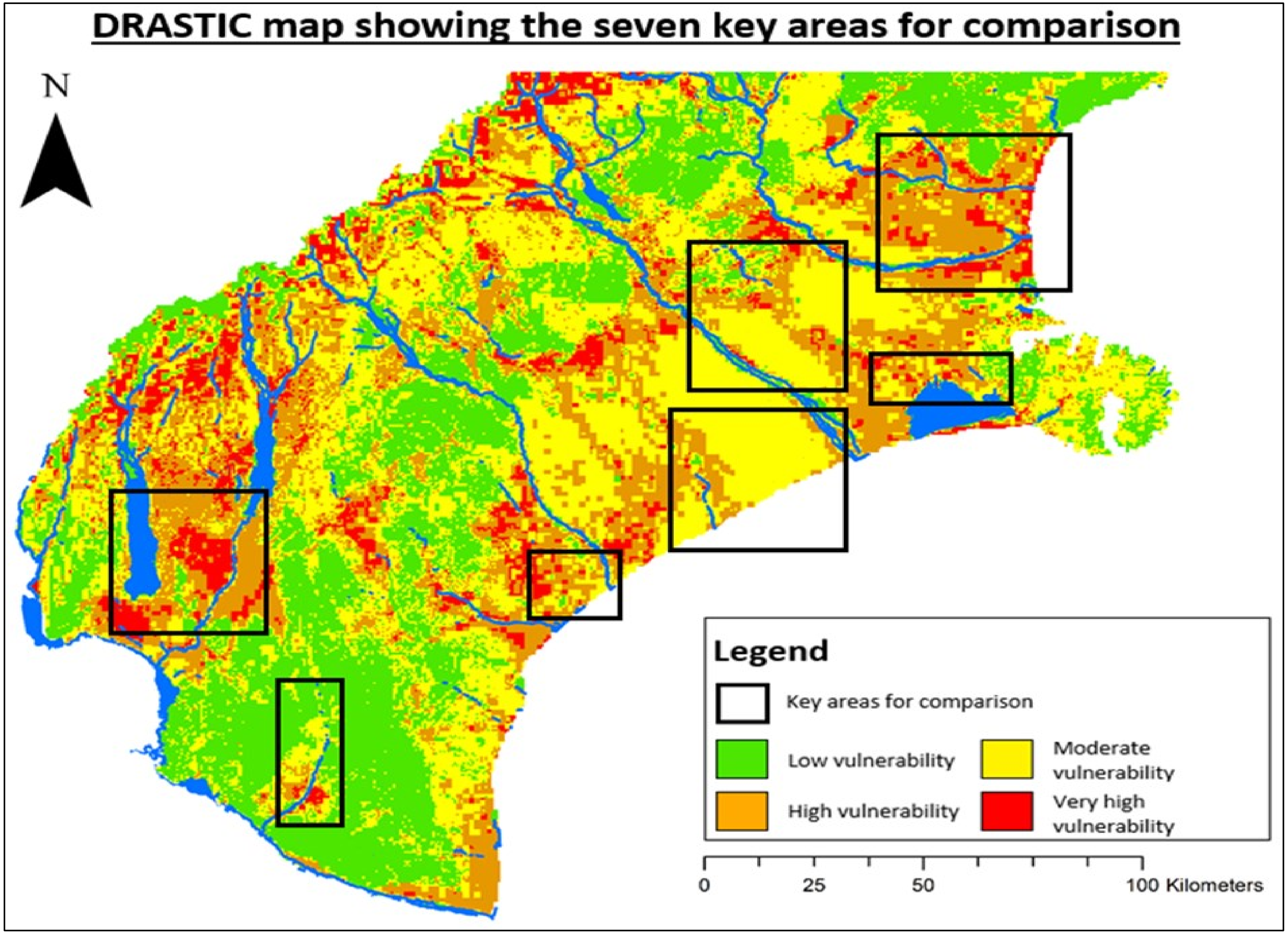
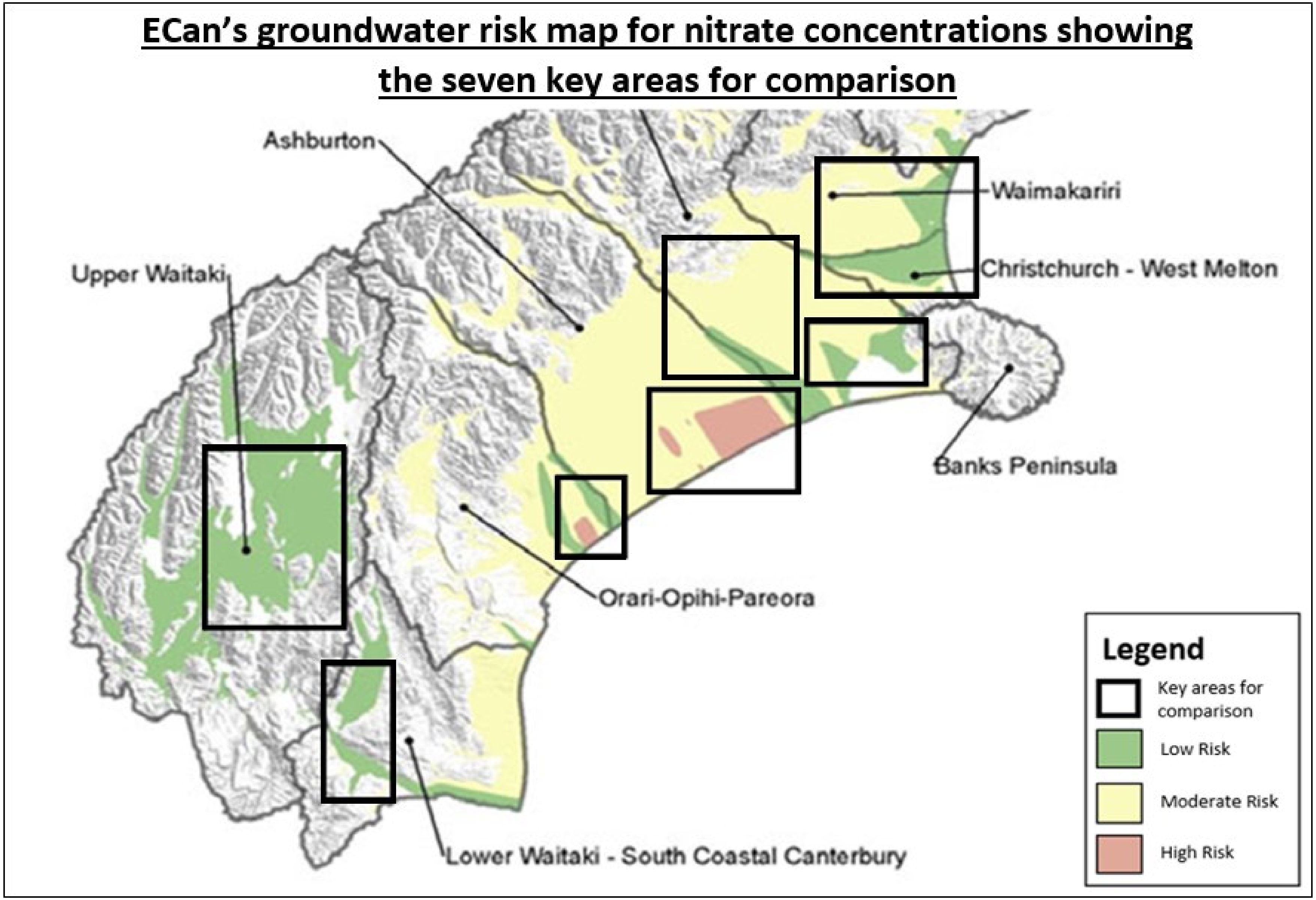


Figure 18. The DRASTIC map showing the four ratings of groundwater vulnerability and the seven key areas for comparison.



ECan's groundwater risk map for nitrate concentrations showing the seven key areas for comparison

Figure 19. The ECan vulnerability map showing the three groundwater risk ratings for nitrate concentrations and the seven key areas for comparison.

Both the DRASTIC map (figure 18) and the ECan map (figure 19) show the location of the seven key areas that will be used for comparison. These areas were chosen due to the either the significant similarities or differences between the two maps. All of the seven key areas that were identified from both maps can be found side by side below.

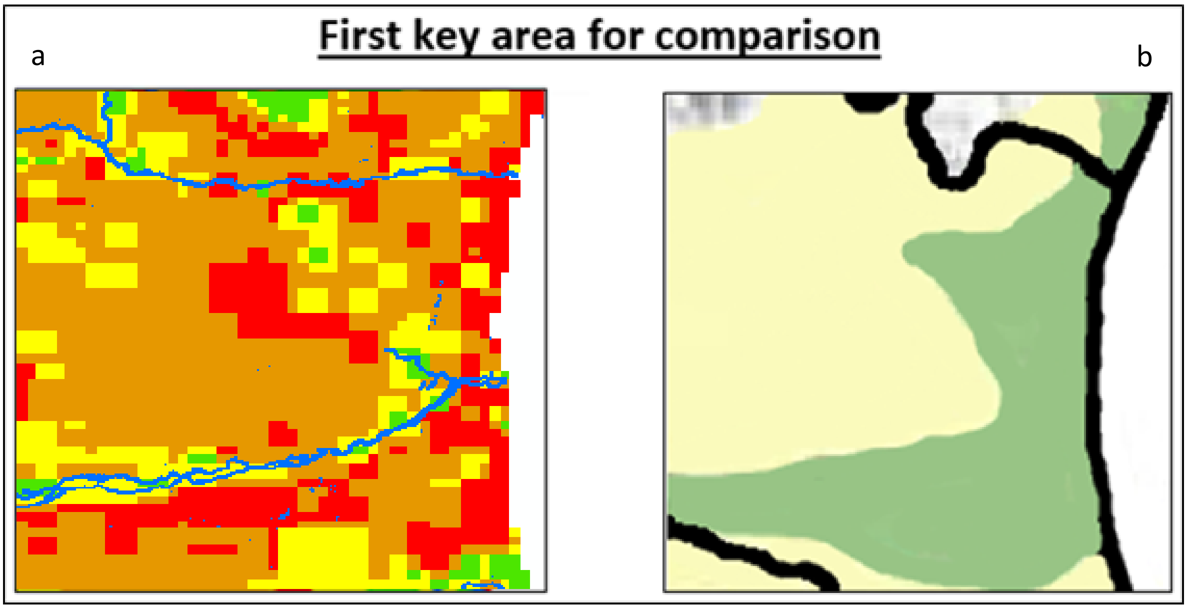


Figure 20 (a and b). First key area identified for comparison of the DRASTIC and ECan maps.

This key area is located north of Christchurch City in Central Canterbury, containing the Waimakariri River. The DRASTIC map for this area (Figure 20a), mainly consists of areas that have a high vulnerability rating, with a few areas on the coast and around the rivers that have a very high vulnerability rating. There are also patches of moderate vulnerability throughout this area. The DRASTIC map shows very few areas of low vulnerability. The ECan map (figure 20b) consists of areas that are either low risk or moderate risk. The low risk areas around located around the coastal area and in the bottom part of the map, and the moderate risk areas are located further inland from the low risk areas.

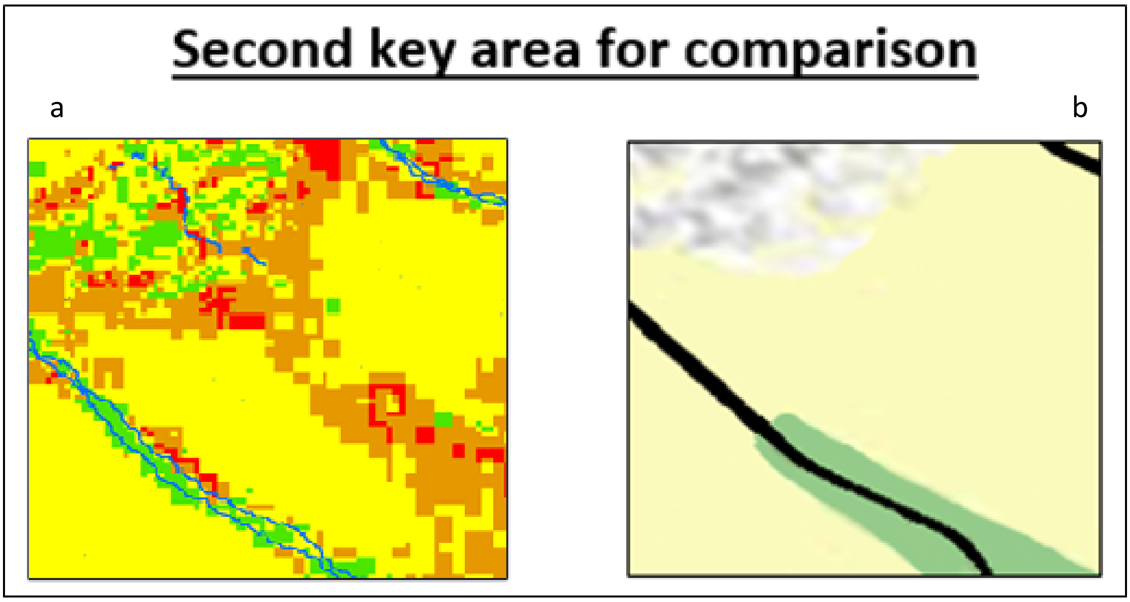


Figure 21 (a and b). Second key area identified for comparison of the DRASTIC and ECan maps.

This key area is located around Methven, which is west of Christchurch and north of Ashburton, located on the Canterbury Plains and it has the Rakaia River flowing through this area. On the DRASTIC map (figure 21a), the area consists of mainly moderate vulnerability and high vulnerability. There are also areas that have a very high vulnerability rating near the foothills, next to the Rakaia River and in the eastern part of this key area. The ECan map (figure 21b), mainly consists of moderate risk and there is an area that is low risk round the Rakaia River.

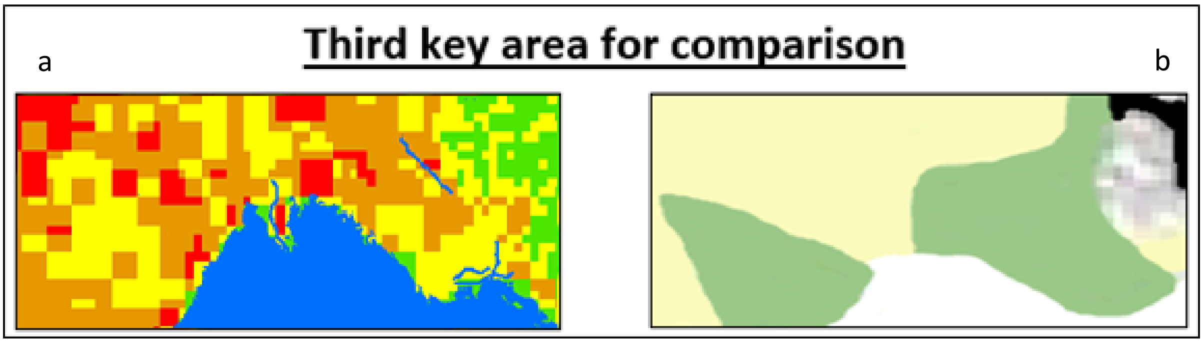


Figure 22 (a and b). Third key area identified for comparison of the DRASTIC and ECan maps.

This key area is located around Lake Ellesmere in the Selwyn District of the Canterbury region. On the DRASTIC map (figure 22a), the area consists of a mixture of moderate, high and very high vulnerability ratings. There is also an area of low vulnerability, however this is located on the Port Hills of Banks Peninsula. The ECan map (figure 22b), mainly consist of areas that are low risk around Lake Ellesmere and around Banks Peninsula. The other areas, that are further inland, have a moderate risk rating.

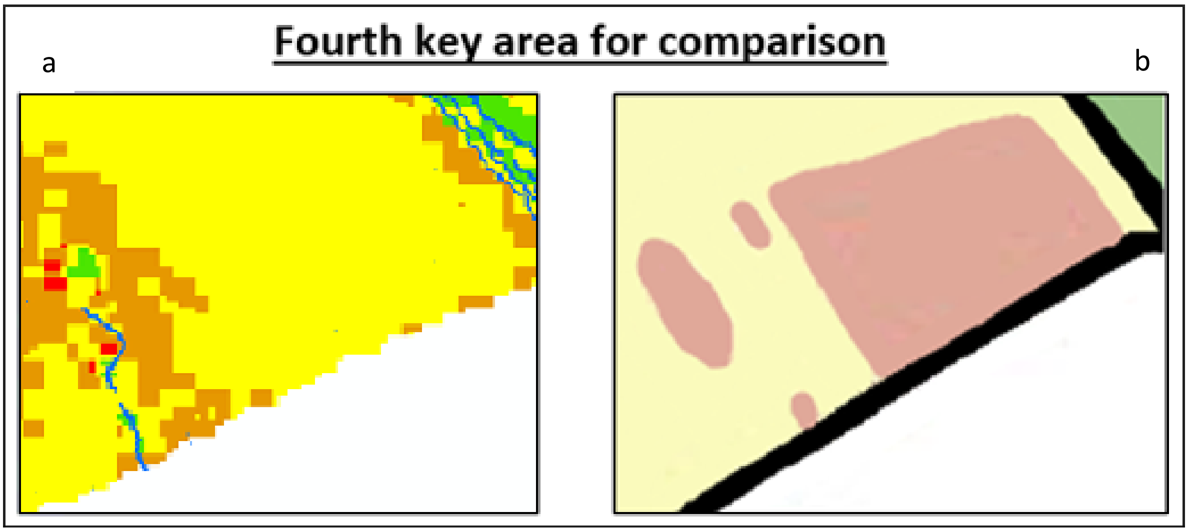


Figure 23 (a and b). Fourth key area identified for comparison of the DRASTIC and ECan maps.

This key area is located in the eastern parts of the Ashburton zone in the Canterbury region. The DRASTIC map (figure 23a), shows the area consists of mainly moderate and high vulnerability. Minimal areas of very high vulnerability are seen on this map, which are located around the Ashburton River. The ECan map (figure 23b), shows a large area that is of high risk and a few smaller areas that are also high risk. The other parts of this area show a moderate risk.

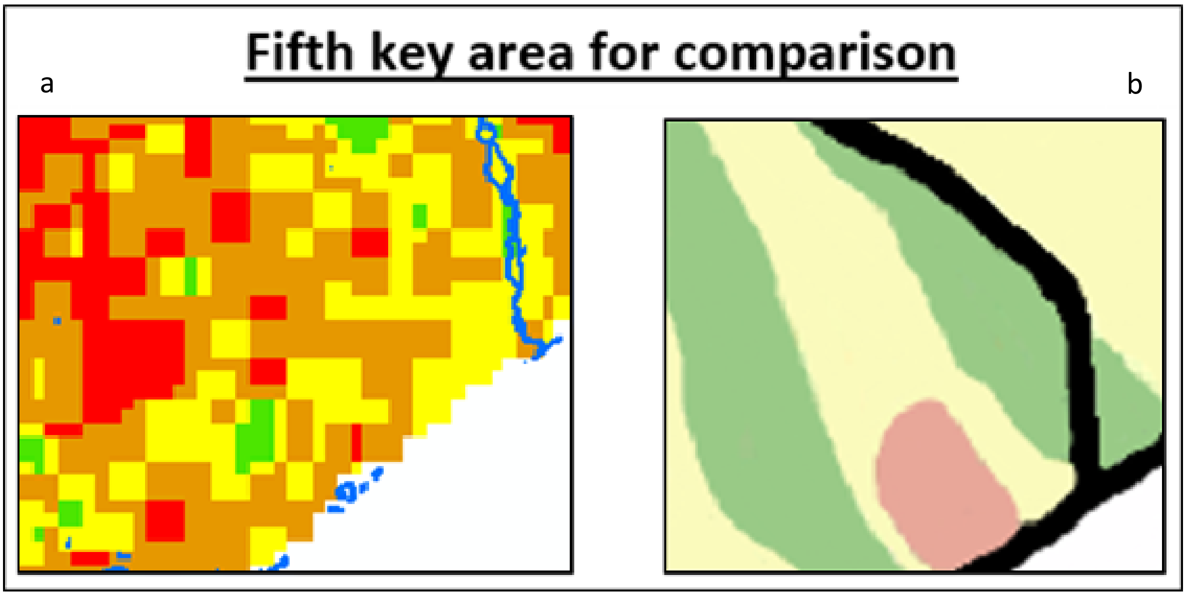


Figure 24 (a and b). Fifth key area identified for comparison of the DRASTIC and ECan maps.

This key area is located between the Rangitata River and Opihi River, north of Timaru in Southern Canterbury. The DRASTIC map (figure 24a), shows a mixture of moderate, high and very high vulnerability ratings. There is a significant area of very high vulnerability in the western part of this key area, with areas of high vulnerability mixed in. The vulnerability ratings drop on the eastern side, with areas of moderate rating with areas of high vulnerability mixed in. The ECan map (figure 24b), shows areas of low risk stretching along the Rangitata River and on the western part of this area. There is almost areas of moderate risk in between these areas of low risk and also to the north of the Rangitata River. Finally there is an area of high risk next to the coast.

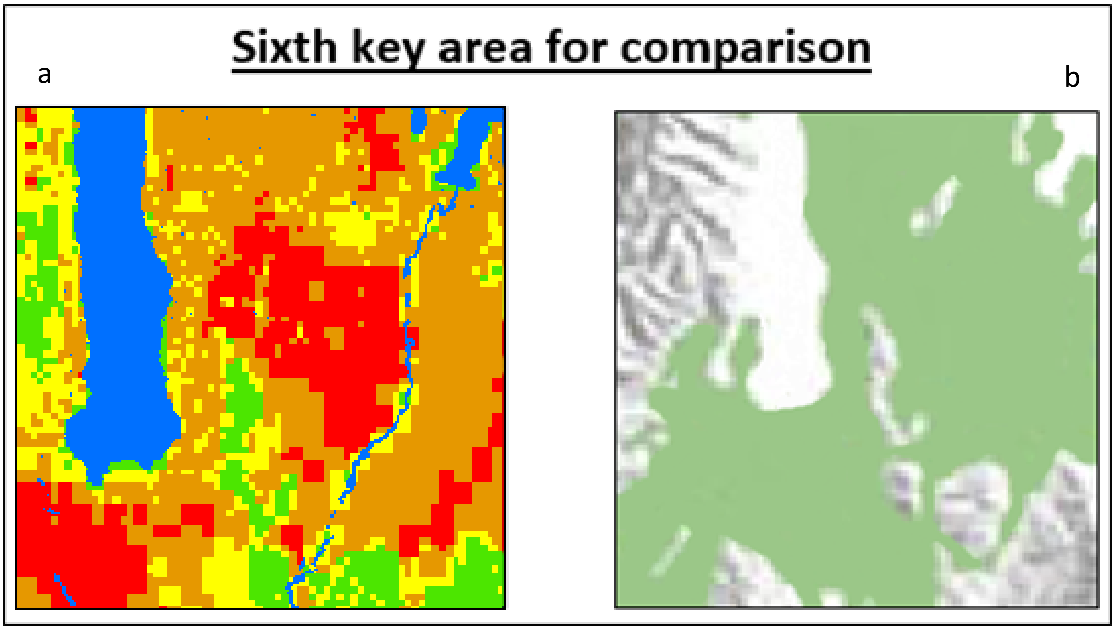


Figure 25 (a and b). Sixth key area identified for comparison of the DRASTIC and ECan maps.

This key area is located inland around the foothills in the Southern Canterbury region. The area contains Lake Pukaki, Lake Tekapo, and the Tekapo River. The DRASTIC map (figure 25a), shows four significant areas of high vulnerability, with the most significant being in the central and south-west parts of this key area. There is also a significant areas of high vulnerability throughout the map, with few areas of moderate vulnerability. The ECan map (figure 25b), shows that this area is considered low risk for nitrate concentrations.

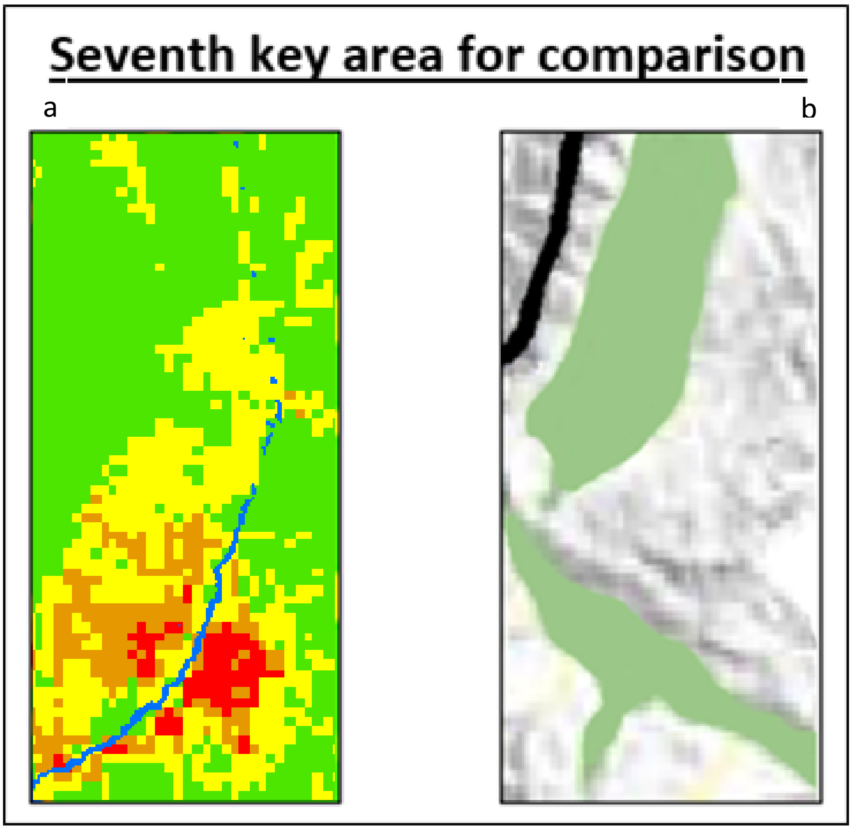


Figure 26 (a and b). Seventh key area identified for comparison of the DRASTIC and ECan maps.

This key area is located around the Hakataramea Valley, which includes the Hakataramea River, in Waitaki area of Southern Canterbury. The DRASTIC map (figure 26a), shows that the outer parts of this area have a low vulnerability rating. The vulnerability ratings then increase as they get closer to the Hakataramea River, with a significant area of very high vulnerability on the eastern side of the river. The ECan map only (figure 26b), shows that there is only low risk for this area.

7. Discussion

7.1 Review of results

The DRASTIC map was created in ArcGIS using the seven DRASTIC data layers for the study area within the Canterbury region, which assumes that the groundwater aquifers are unconfined and has been adapted for specifically nitrate contamination. The DRASTIC map (figure 17) shows the four vulnerability ratings, which are low, moderate, high and very high. These ratings represent the groundwater vulnerability to nitrate contamination. The map is not a reflection of quantitative data, which is what the ECan vulnerability map (figure 6) shows, instead it represents a prediction of where potential future nitrate contamination may occur depending on the land use in those areas. For example, on the DRASTIC map just north of the Rangitata River there is a very high vulnerability area but on the ECan map it is only a moderate risk area, so if an intensive dairy farm was to be located in this area, then with the nitrogen fertilisers used on the farm to make it economically viable, the groundwater in this area will most likely see an increase in nitrate levels as it is considered to be very vulnerable to nitrate contamination. So the DRASTIC map is a way of predicting areas of groundwater that may see an increase in nitrate contamination based on the land characteristics used to develop the map.

The DRASTIC map is a collection of the values and weights that were assigned to the ranges of each of the seven DRASTIC data layers. As mentioned in the methods section, the values were assigned to the ranges based off of their impact or ability for letting nitrates leach its way into the groundwater. As an example, certain aquifer media types that have large pores, such as gravels or sands, allow for a very high leaching capability of nitrates to make their way through and entering the groundwater. Therefore these types would receive a higher rating compared to a media type that has smaller pores, such as metamorphic types of media, which would receive a lower rating as they limit nitrates ability to leach through and getting into the groundwater. Some values were much more difficult to give to certain DRASTIC data layers, especially hydraulic conductivity. This data layer was especially difficult, as the ranges for calculating the conductivity of certain media are quite broad. In figure 15 it shows how broad these ranges can be. It is difficult to calculate exactly what the hydraulic conductivity is of a certain area without physically going to that area and testing. These values were basically worked out on the worst case scenario basis, by calculating the highest hydraulic conductivity, based on figure 15, of each of the media types. By doing this, it definitely has an impact on the reliability of the results of the DRASTIC map (figure 17), but working out the values was kept consistent to reduce any further limitations. The other data layers were much easier to assign values as they were kept consistent with the methodology provided by the EPA.

Based off the DRASTIC map the moderate vulnerability for groundwater contamination is the most significant rating across the study area, followed by low vulnerability, then high vulnerability and finally the very high vulnerability is the least significant, based off of the percentage area cover (table 2). The low vulnerability rating covers 29.2% of the study area, with the most significant areas being in the northern parts of the Canterbury region, just north of Christchurch City, and in the southern parts of the Canterbury Region in the Waitaki area and Aoraki. The low vulnerability has a large concentration in the Waitaki area, which is due to the land characteristics. The moderate vulnerability rating covers 38.4% of the study area, with the most significant areas of this vulnerability being located in the Canterbury Plains and in areas within the Southern Alps. It is also scattered throughout the region amongst the other vulnerability ratings. The high vulnerability rating covers 24.6% of the study area, which is lower than the previous two ratings. This vulnerability rating also does not cover areas as large as the two lower vulnerability ratings, but there are still some clear significant areas of high vulnerability within the study area. These significant areas being around Christchurch City, Lake Ellesmere, around the Rangitata River, and between Lake Pukaki and Lake Tekapo. Finally the very high vulnerability rating covers only 7.8% of the study area. There is far less areas of very high vulnerability than the other vulnerability ratings, as the land characteristics from the seven DRASTIC parameters have to mainly consist of the most detrimental conditions for groundwater contamination, or it can be said the 'best' conditions for nitrate leaching. The very high vulnerability rating is seen mainly around the coastal area of Christchurch, within areas of the Southern Alps, between the Ashburton area and Opihi River, and to the south and east of Lake Pukaki. Overall, most of the groundwater aquifers in the Canterbury region are not at great risk, as the low vulnerability and high vulnerability ratings make up 67.6% of the area, which is roughly two-thirds of the study area. The most vulnerable, which are the high vulnerability and very high vulnerability, make up the remaining 32.4% and these areas. These are the most important areas to be identified as these are the groundwater areas that at greater risk of nitrate contamination. Developing this DRASTIC map shows the vulnerability of nitrate contamination in groundwater for the Canterbury region, which answers objective 1 of this research.

After developing the final DRASTIC map (figure 17), it was compared with the ECan vulnerability map (figure 6) in order to identify key areas for comparison, which will be used to identify if the DRASTIC map can produce reliable results to determine future potential groundwater vulnerability from nitrate contamination. A total of seven key areas were identified on both of the maps, which are shown within the marked areas on a modified DRASTIC map (figure 18) and on a modified ECan map (figure 19). Each of the seven key areas for comparison will be discussed below.

First key area for comparison:

The first key area for comparison (figure 20) is found north of Christchurch city. This was chosen as a key area to be compared, as the vulnerability ratings of the DRASTIC map for this key area (figure 20a) are generally greater than the risk ratings of the ECan map for this key area (figure 20b). A noticeable difference in vulnerability/risk ratings between the two maps are around the coastal area on both of the maps. The ECan defines this area as low risk, whereas the DRASTIC map shows that this area is mainly very high vulnerability or high vulnerability. This also continues up along the Waimakariri River. So currently this area has low levels on nitrate concentrations in the groundwater, but with the DRASTIC model it is predicted that the groundwater in this area is very vulnerable to further nitrate contamination. On the ECan map of this key area (figure 20b) there is also an area of moderate risk further inland from this area of low risk. This also shows that there is a difference with the DRASTIC map for this study area (figure 20a), as this area consists of mainly high and very high vulnerability, making it also an area of groundwater that is vulnerable to further nitrate contamination in the future.

Second key area for comparison:

The second key area for comparison (figure 21) is found around Methven west of Christchurch. This was chosen as a key area to be compared, as the DRASTIC map for this key area (figure 21a) shows that there are very similar vulnerability ratings with the ECan map for this key area (figure 21b), apart from a few exceptions. These exceptions are that the DRASTIC map shows areas that are high vulnerability and a few small areas of very high vulnerability where the ECan map has a moderate risk rating. This area is around the foothills of the Southern Alps and in the centre of this key area, which continues towards the east. The areas that have a similar ratings are moderate vulnerability on the DRASTIC map and moderate risk on the ECan map. It can be gathered that these areas that have moderate ratings on both maps that the nitrate levels will only slightly increase. The DRASTIC map predicts that this area will only have a moderate vulnerability, but based on the ECan map it already is at moderate risk. There is still potential for moderate nitrate leaching to occur and make the nitrate concentrations increase, however it could be possible that the nitrates may naturally exit the groundwater, only to be renewed by the potential nitrate leaching in this area. This information can also be used to help understand the current nitrate concentrations on the ECan map. There are also the areas on the DRASTIC map (figure 21a) that show high and very high vulnerable, where the ECan map (figure 21b) shows moderate risk. The DRASTIC map predicts that these areas of groundwater are most likely going to be further contaminated in the future as the leaching is more susceptible in these areas.

Third key area for comparison:

The third key area for comparison (figure 22) is located around Lake Ellesmere in the Selwyn District. This area was chosen to be compared as the DRASTIC map for this key area (figure 22a) as the vulnerability ratings are generally higher than the vulnerability ratings on ECan map (figure 22b). On the ECan map it shows two areas that have low risk ratings next to the lake, but on the DRASTIC map these areas are mainly high or very high vulnerability, and there are some areas of moderate vulnerability. This same situation can also be applied to the moderate risk area on the ECan map. Since most these areas on the DRASTIC map have higher vulnerability ratings than the vulnerability ratings on the ECan map, it can therefore be determined that the groundwater in this area next to Lake Ellesmere is vulnerable to further nitrate contamination in the future.

Fourth key area for comparison:

The fourth key area for comparison (figure 23) is located in the eastern parts of the Ashburton zone. This area was chosen to be compared as the DRASTIC map for this key area (figure 23a) shows that the area is primarily moderate vulnerability, with a few areas of high vulnerability. However, on the ECan map for this key area (figure 23b) shows four areas with a high risk rating where it is only a moderate vulnerability or high vulnerability rating on the DRASTIC map. Based on the DRASTIC map, it predicts that nitrate leaching is only moderate, but the ECan map shows that the current levels of nitrate concentration in the groundwater is high. This shows that there is a clear difference between the two maps and that the DRASTIC map was unable to predict that this area would have a risk rating. The DRASTIC map does not take into account the cause of what is causing the nitrate concentrations to be over the 11.3 mg/L in the groundwater for this area. ECan have identified that meatworks wastewater discharges, arable farming practices and discharges of effluent from a feedlot have been the cause of the high nitrate concentration in groundwater for this key area (Scott & Hanson, 2013). It can be gathered that current land use activities are a limitation to the reliability of the DRASTIC model.

Fifth key area for comparison:

The fifth key area for comparison (figure 24) is located between the Rangitata River and the Opihi River. This area was chosen to be compared as the ECan vulnerability map for this key area (figure 24b) shows a range of different vulnerability ratings in the same area, which also showed many differences with the DRASTIC map for this study area (figure 24a). On the ECan map where it shows areas of low risk on the eastern side, the DRASTIC map shows that this area is either moderate or high vulnerability. The western low risk area on the ECan map, on the DRASTIC map this is either high vulnerability or very high vulnerability. Also the areas of moderate risk on the ECan map, the DRASTIC map shows a mixture of moderate, high and very high vulnerability. From this it is gathered that the DRASTIC map shows greater vulnerability ratings than the ECan map, which shows that these areas of groundwater are susceptible to further nitrate contamination from their current values shown on the ECan map. Another reason why this area was chosen as a key area, is because the ECan map (figure 24b) shows an area of high risk, but on the DRASTIC map (figure 24a) the vulnerability ratings are a mixture of low, moderate and high. These ratings on the DRASTIC map are lower than the current nitrate concentration rating in this key area. This is similar to what is seen in the Ashburton zone in the fourth key area map (figure 23). From this it can be gathered that the current land use activities may also be influencing this area shown as high risk on the ECan map, which has an effect of the reliability of the DRASTIC map.

Sixth key area for comparison:

The sixth key area for comparison (figure 25) is located around Lake Pukaki, Lake Tekapo and Tekapo River. This area was chosen for comparison as the DRASTIC for this key area (figure 25a), shows that there are two significant areas that have a very high vulnerability rating and the rest of the key area mainly consists of high vulnerability areas. However, the ECan map (figure 25b) only shows that this area is at low risk, as the nitrate concentrations in the groundwater in this area are not likely to be very high. The DRASTIC map shows that there is a major difference between the two maps, and that DRASTIC model predicts that the groundwater in this area is very likely to have further increased level of nitrates, based on the nitrate leaching potential of the land. This is especially in areas located on the DRASTIC map (figure 25a) that are in the area of very high vulnerability.

Seventh key area for comparison:

The seventh key area for comparison (figure 26) is located around the Hakataramea Valley in the Waitaki area. This area was chosen for comparison as the ECan map for this key area (figure 26b) shows that the area only contains low risk ratings. However, the DRASTIC map for this key area (figure 26a) has a mixture of vulnerability ratings. On the outer edges of the key area the DRASTIC map shows low vulnerability, then when it gets closer to the Hakataramea River the vulnerability ratings go up. Right next to the river, the ratings are mainly high vulnerability and very high vulnerability. The DRASTIC map predicts that the groundwater areas closer to the Hakataramea River have a greater chance of further nitrate contamination occurring.

Summarising the key areas for comparison

The seven key areas that were used for the comparison show varying results about the reliability of the DRASTIC map. In the first, second, third, sixth and seventh key areas used for comparison (figure 20-22, 25, and 26) showed that the DRASTIC map produces reliable results. This is based on the fact that in these key areas, the DRASTIC map was able to produce vulnerability ratings for predicting areas of groundwater that could potentially receive further nitrate contamination, as these groundwater areas had greater vulnerability ratings than the groundwater vulnerability ratings on the ECan map for nitrate concentrations. Even areas between the DRASTIC map and the ECan map that had the same vulnerability ratings and where the DRASTIC map identifies areas of greater vulnerability than the ECan map, show reliable results, as the DRASTIC map can be used as a tool for explaining some of the potential reasons why the current nitrate concentrations have occurred. However, the DRASTIC model did show some unreliable results, due to some differences between the maps, in the fourth and fifth key areas used for comparison (figure 23 and 24), where the ECan map showed greater vulnerability ratings than the vulnerability ratings on the DRASTIC map. These differences gave the DRASTIC unreliable results, as the DRASTIC model was unable to predict that these areas would be areas that would high risk to nitrate concentrations in the groundwater. Based on the DRASTIC vulnerability ratings, the ability for nitrates to leach into the groundwater is relatively low, but the current quantitative data shown on the ECan maps proves that these areas have nitrate concentrations that are over the MAV of 11.3 mg/L. ECan does explain that certain current land use practices are the reasoning for these high levels of nitrate concentrations, so from this we can gather that there are other parameters than influence nitrate concentrations that the DRASTIC model does not include. Overall, the DRASTIC method does provide reliable results when compared to the ECan maps, even though there are a few areas that did produce some unreliable results, which answers objective 2 of this research.

DRASTIC model as a monitoring tool for groundwater vulnerability

The comparison between the key areas between the DRASTIC map and the ECan map shows that the DRASTIC model can produce reliable results for predicting groundwater vulnerability from nitrate contamination, even though there are a few areas that shown on the DRASTIC map that produced some unreliable results. However, the reliable results were seen on majority of the key areas of comparison, which is information that is useful for protection of the groundwater resources in the Canterbury region. The aforementioned applications of the DRASTIC model identified by the EPA, can be used along with the model for predicting vulnerable groundwater areas, which can help with the protection this resource. These applications are that it can be used as for preventative purposes through the prioritisation of areas where groundwater protection is critical, it can be used as part of a strategy to identify vulnerable areas for monitoring purposes, and that it can be used as part of a strategy to identify areas where either additional or less stringent protection measures in the localised legislation may be required.

The DRASTIC maps can be used to identify where the most critical areas for groundwater protection are required, as the areas identified with a very high vulnerability rating will be at greatest, therefor this is where the greatest protection will be required. This is then followed by high vulnerability areas, then moderate vulnerability areas and lastly low vulnerability areas. These vulnerability areas identified in the DRASTIC map can also be used to determine the most appropriate locations for data collection for monitoring purposes. The areas with the greatest vulnerability rating will be the vital areas where data should be collected for nitrate concentrations, so that any major increase in nitrate concentrations can be detected, which will help with decision making. Finally these vulnerable areas of groundwater identified in the DRASTIC map can be used as part of a strategy to help with informed decisions on where additional or less stringent protection measures may be required. The areas of groundwater that have the greatest vulnerability rating identified in the DRASTIC maps, could be identified as areas that require more stringent protection in order to minimise the effects of further nitrate contamination. Examples of stringent protection methods on vulnerable areas that could be put in place are to adopt appropriate mitigation methods to reduce impact of nitrate contamination, control what land activities can occur on the land, and by providing maximum amounts of nitrogen fertilisers that can be applied to the land.

The DRASTIC model can prove to be a useful monitoring tool in the Canterbury region. There are many applications of the model, which can be used alongside other monitoring methods. The DRASTIC model could never be a sole tool used for identifying nitrate vulnerability in groundwater, due to the unreliable results identified in figure 23 and 24, which was a result of the DRASTIC model not including current land use activities. However, it can be used alongside other tools and methods that can make up for what the DRASTIC model cannot achieve, which answers objective 3 of this research.

7.2 Limitations

Even though the DRASTIC model showed many reliable results and that it would considered to be a good monitoring tool that can be used alongside other methods, it still has some limitations. The limitations range from the DRASTIC model specifically used for this research to limitations of the DRASTIC model itself. Six limitations have been identified, which will be discussed below.

The first limitation is that some of the data used for this research may have been out of data. For example, the rainfall data that was used for net recharge may have not been the most up to data, which will have an influence on the final outcome of the DRASTIC map. Rainfall varies from year to year, so using the most up to date data will produce the most reliable results.

The second limitation is that human error may have occurred when developing the final DRASTIC map. When inputting the values and weights for each of the ranges in the DRASTIC data layers, they may have accidentally received the incorrect value, or when sorting out the different types of soil media, aquifer media and the vadose zone into categories, they may have been placed into the incorrect category, resulting in receiving the wrong value.

The third limitation is that only seven key areas of comparison were identified for this research. It was important to get a good range of areas from across the Canterbury region, but it is possible to have missed an important area that should have been used for comparison. This would not have a massive impact on the results, but it could have made the results more reliable.

The fourth limitation is that the DRASTIC model does not provide any actual quantifiable results that can be used to directly compare with the ECan vulnerability map or other groundwater monitoring methods. This means that the DRASTIC model cannot provide any physical evidence, which limits it to only being used as a supporting tool alongside other groundwater monitoring methods.

The fifth limitation, which was mentioned during the review of the results, is that the DRASTIC model does not take into account any current land use activities. Based on the comparison between the DRASTIC map and the ECan map, there were areas identified on the ECan map that were considered high risk as the nitrate concentrations in the groundwater at those locations was above the MAV of 11.3 mg/L. ECan identified that these areas had high concentrations of nitrate due to current land use activities in the area. The DRASTIC does not include land use so it was not able to identify these areas, which resulted in some of the results from the DRASTIC map to be unreliable.

The final limitation of the DRASTIC model, is that it was difficult to assign realistic values to hydraulic conductivity. As mentioned in the discussion, the ranges for calculation hydraulic conductivity were very broad, so a worst case scenario was used to calculate the conductivity so that values could be assigned. This will have affected the reliability of the results of the DRASTIC model. However, with the weighting system that DRASTIC uses, hydraulic conductivity has the lowest weighting as it is the least significant of all the other DRASTIC data layers. This would have kept the impact of difficulty to calculate the hydraulic conductivity, based on figure 15, to a minimum.

7.3 Recommendations

A number of recommendations have been identified for the use of the DRASTIC model. The first recommendation is based off of the first limitation identified above, which is that the DRASTIC model in future use should use the most up to date data that is available. It is important to use the latest data available when making this map to increase the reliability of the results. The second recommendation is based off of the last limitation identified above, which is that the DRASTIC model should be adapted to utilise data on current land use activities and/or nitrate application rates in order to create the maps. This will potentially allow the DRASTIC maps to identify even more areas of groundwater that may be vulnerable to nitrate contamination. It would be a feasible option by adding either of these two types of information to the DRASTIC map, as much of this data is available and all it would require is the right values and weights depending on the land use or amount of nitrate application rate to make it effective to add to the current model. The third recommendation is that the DRASTIC model should be considered as a monitoring tool by ECan, along with other current groundwater monitoring methods. The model should never replace any current groundwater monitoring methods, but be another viable option to be used in the future. The DRASTIC model is an easy and cost effective method that uses data that is easily available, to produce results that can predict vulnerable areas of groundwater from nitrate contamination. This would be beneficial to refer to for management decisions and for the future management of the groundwater resources of the Canterbury region. The final recommendation is that the DRASTIC model should utilise the kriging variance model, which was identified in the New Zealand study that used the DRASTIC model. The kriging variance model utilises nitrate concentration data in groundwater and using geostatistical analysis it can determine the movement of the nitrate concentrations, which will influence the areas of nitrate contamination in groundwater. This will further improve the DRASTIC model as a monitoring tool and it can be used to identify the most vital areas for groundwater monitoring to take place in the Canterbury region.

8. Conclusion

The DRASTIC model is a widely used tool around the world and in many places it is used as the main tool for identifying vulnerable areas of groundwater from contamination. However, there is little evidence that the DRASTIC model has been used as a common tool. There have only been a few independent researches that have used this tool in New Zealand. The research aimed to identify whether the DRASTIC model could be used as a monitoring tool to produce a map that can be reliable in identifying vulnerable areas of groundwater from nitrate contamination for the Canterbury region, by comparing it with current nitrate concentration data represented as a map that was developed by ECan. When comparing the DRASTIC map with ECan the results suggested that the DRASTIC map could produce some reliable results by identifying areas of groundwater that are vulnerable to nitrate contamination and may further receive an increase in nitrate concentrations in the future. Five out of the seven key areas for comparison has suggested this, which is valuable information for the future use of the DRASTIC model. However, the other two key areas for comparison suggested that the DRASTIC model did produce some unreliable results. These were areas where the ECan map displayed the groundwater as having high levels of nitrate concentration that was above the MAV of 11.3 mg/L, which was identified by ECan as being influenced by current land use activities. The DRASTIC model does not consider current land use activities as a part of the models methodology, so it was therefore found to be a limitation of the model. There are a number of other limitations of the DRASTIC model, however many of these could be prevented in future study or future use of the DRASTIC model.

Overall, from the comparison of these seven key areas, the results suggest that the DRASTIC model could be a useful monitoring tool in the future, which can be used to identify nitrate contamination in groundwater. The DRASTIC model should be used alongside other current methods that are used for monitoring groundwater contamination. The model can also then be applied to the applications of the DRASTIC model that were identified by the EPA, which will be useful for future management of the groundwater resources in the Canterbury region. Therefore it is suggested that the DRASTIC model is a reliable and a viable method as a monitoring tool for identifying areas of groundwater that are vulnerable to nitrate contamination in the Canterbury region.

9. Acknowledgements

There are many people that I would like to thank for supporting me through my dissertation.

My parents, Grant and Dianne Pearson, and my sister Rachael, who have been a big part in encouraging me and keeping me motivated to do my best, and have supported me throughout this experience.

I would like to thank my supervisor, Crile Doscher, for guiding me in the right direction for my dissertation and going far beyond what was expected.

I would like to thank my friend, Chris Efford, who has been motivating me to keep on going during my dissertation.

I would also like to say a big thanks to all my other friends who have stayed by my side and have supported me.

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11. Appendices

Appendix A

Soil Media (S)		
Category	**Media type**	
Non-Shrinking and Non-Aggregated Clay	Calcareous Orthic Melanic Soils Mottled Vertic Melanic Soils	Pedal-calcareous Orthic Melanic Soils
Clay Loam	Typic Mafic Melanic Soils Mottled Orthic Melanic Soils Typic Rendzic Melanic Soils Weathered Rendzic Melanic Soils Typic Vertic Melanic Soils	Calcareous Orthic Gley Soils Melanic Orthic Gley Soils Typic Orthic Gley Soils Calcareous Argillic Pallic Soils Mottled Fluvial Recent Soils
Silt Loam	Mottled Orthic Brown Soils Typic Sandy Gley Soils Pedal Immature Pallic Soils Mottled Immature Pallic Soils Typic Immature Pallic Soils Mottled Argillic Pallic Soils Typic Argillic Pallic Soils Typic Laminar Pallic Soils Argillic-fragic Perch-gley Pallic Soils	Fragic Perch-gley Pallic Soils Argillic Fragic Pallic Soils Argillic-calcareous Fragic Pallic Soils Mottled Fragic Pallic Soils Weathered Fluvial Recent Soils Acid-weathered Orthic Recent Soils Typic Orthic Recent Soils Weathered Orthic Recent Soils Typic Orthic Podzols
Loam	Typic Fluvial Recent Soils	Mottled Orthic Recent Soils
Sandy Loam	Humose Orthic Brown Soils Typic Orthic Brown Soils Pallic Sandy Brown Soils	Typic Sandy Brown Soils Argillic-mottled Fragic Pallic Soils
Aggregated Clay	Typic Recent Gley Soils Saline Argillic Semiarid Soils Fluid Gley Raw Soils	Saline Recent Gley Soils Orthic Raw Soils
Peat	Peaty Orthic Gley Soils	Mellow Humic Organic Soils
Sand	Typic Sandy Recent Soils Typic Aged-argillic Semiarid Soils	Sandy-tephric Raw Soils
Gravel	Typic Rocky Recent Soils	Rocky Raw Soils

Impact of the Vadose Zone (I)	
Category	**Media Type**
Limestone	Limestone.
Metamorphic/ Igneous	Conglomerate, Plutonics, Lavas, Ancient Volcanoes and minor intrusives, Semi-schist, Schist.
Sandstone	Greywacke, Sandstone, Argillite.
Bedded Limestone/ Sandstone/Shale	Alluvium, Colluvium, Glacial Drift, Mudstone.
Sand and Gravel	Loess, Peat, Windblown Sand.

Aquifer Media (A)	
Category	**Media type**
Metamorphic/Igneous	Breccia, Ignimbrite, Melange, Metaconglomerate, Quartzite, Rhyolite, Syenite, Schist.
Weathered Metamorphic/Igneous	Conglomerate, Metapelite, Metavolcanics, Semi-Schist, Trachyte, Tuff.
Glacial Till	Till
Bedded Sandstone/ Limestone/Shale	Cataclasite, Mudstone.
Massive Sandstone	Claystone, Greywacke, Sandstone, Siltstone.
Massive Limestone	Limestone.
Sand and Gravel	Gravel, Greensand, Loess, Peat, Sand, Silt.
Basalt	Andesite, Basalt, Dacite, Diorite, Dolerite, Hawiite, Olivine Nephelinite.