GIS-BASED SITE IDENTIFICATION
FOR THE
LAND APPLICATION OF WASTEWATER

CHRISTCHURCH CITY, NEW ZEALAND

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Abstract

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Land application of wastewater can have the effect of treating effluent as well as disposing of it. In addition, nutrients and irrigation water can be recycled for the use in agriculture and forestry. Therefore, land application is an economical means of water reuse and effluent disposal. However, if inappropriately planned and managed, it can have negative impacts on the environment. Site selection is particularly crucial when planning a wastewater land application scheme. An appropriate site selection ensures the technical and economic feasibility of such a scheme and helps reduce environmental impacts and risks. In addition, social and economic aspects need to be considered for the site selection.

The present study aimed at identifying potential sites for the land application of the effluent of the Christchurch City Wastewater Treatment Plant. The analysis was carried out using a GIS, which enabled an efficient combination of all factors influencing the suitability of a site, and included the area of Christchurch City and its three adjacent districts; Waimakariri, Selwyn and Banks Peninsula.

To ensure technical feasibility, environmental sustainability, social acceptability and economic viability a number of factors had to be considered for the site selection. These include the following: Slope, climate, soil type, soil pH, soil depth, land use, distance to groundwater, distance to surface waters, and distance to dwellings.

Raster layers of these factors were overlaid in the GIS. This resulted in the elimination of all areas that are unsuitable for land application and the identification of candidate areas. A digital layer was created showing the candidate areas in the study area.

Four potential sites were identified from the candidate areas to highlight the relative suitability between the sites. A rating system using numeric values was used to assess and screen the candidate areas and the potential sites. The rating was based on five of the above mentioned suitability factors and the distance between site and plant.

Keywords: Geographical Information System (GIS), site identification, wastewater, effluent, land application, land disposal, Christchurch City, Selwyn, Waimakariri, Banks Peninsula.

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Abbreviations

CWTP	Christchurch Wastewater Treatment Plant
d	Day
DEM	Digital Elevation Model
GIS	Geographical Information System
ha	Hectare
LDF	Limiting Design Factor
N	Nitrogen
OF	Overland Flow
RI	Rapid Infiltration
SR	Slow Rate
y	Year

1 Introduction

1.1 Background

Land application of wastewater has been practised for centuries all over the world. It can have the effect of treating effluent either on its own or as supplementary treatment as well as disposing of it. Land treatment occurs through natural physical, chemical and biological processes within the plant-soil-water matrix (USEPA, 1981). These processes result in the retention, uptake and degradation of undesirable constituents. Biological treatment processes such as land application normally achieve a good reduction of the pollutants contained in the wastewater, while costing less to build and operate and requiring less energy than mechanical treatment alternatives (Reed et al., 1988).

In addition, land application of wastewater can have the purpose of recycling nutrients and irrigation water for the use in agriculture and forestry. The nutrients in the wastewater are recovered and provide for fertiliser requirements of irrigated crops. Organic matter contained in the water can furthermore improve the soil structure and the moisture holding capacity of the soil. Water recycling and reuse increases the total water supplies to cover for the growing demand in all regions of the world. According to de Villiers (1999), of the total fresh water available for human consumption, already more than half is being used and in many areas water scarcity makes it difficult to meet the demand. The population increase is expected to further diminish the supply of water per capita. Land application of treated and untreated wastewater ensures that water is used economically and contributes to the mitigation of water scarcity. It represents a means of considerate management of resources, which is a requirement for sustainable development.

However, if inappropriately planned and managed, land application of wastewater can have negative impacts on the environment. “Proper site selection can reduce or prevent pollution problems and contribute greatly to a better use of effluent water and nutrients” (Feigin et al., 1991, p.139). General criteria for the site selection are the maximisation of pollutant reduction and the minimisation of migration of pollutants. In other words, site selection aims at ensuring technical feasibility and environmental sustainability. In addition, social and economic aspects need to be considered during the site identification process. Since the site identification and selection for a land application scheme is influenced by a large number of spatially varying factors, a Geographical Information System (GIS) can provide assistance for this task. All required information can be combined in the digital format, which allows the efficient identification of potential sites.

1.2 Aim of the Study

This study aimed at showing how a GIS could be used to identify potential sites and assess the identified sites for the land application of wastewater. The following objectives contributed to the overall aim of the study:

- ☐ Determination of criteria affecting the suitability of a site.
- ☐ Development of an appropriate GIS model.
- ☐ Identification of suitable sites by means of the GIS model.
- ☐ Assessment and rating of the identified sites.

As a case study, Christchurch City in New Zealand was investigated. The effluent of the Christchurch City Wastewater Treatment Plant is currently disposed into the Estuary of the Avon and Heathcote Rivers. However, the resource consent to continue discharging into the Estuary was granted only for another five years. Therefore, alternative disposal options such as land application of the effluent have to be investigated. Christchurch City and its three adjacent districts Selwyn, Waimakariri and Banks Peninsula were evaluated to find potential sites.

The dissertation is structured as follows:

In section 2, general information about land application of wastewater is given. After an historic overview, the factors that influence the land area requirements and the site selection process are presented. The description of the technical, environmental, social and economic aspects that determine the suitability of an area forms the background for the development of a GIS model and the actual site identification.

The wastewater treatment plant and the study area are introduced in section 3.1. The concepts of GIS and its underlying vector and raster data models are briefly described in section 3.2. In section 3.3, an outline of the data used is given.

The site identification procedure is described in chapter 4. First, the system type had to be selected and the land area requirements had to be estimated (see section 4.1 and 4.2). Then it is shown in section 4.3 how the factors that influence the suitability for land application were combined in the GIS. An overlay of the different layers was used to eliminate those areas that are unsuitable and to identify candidate areas. In order to assess the candidate areas, a numeric rating system was used, which is described in section 4.3.3.

The results of the GIS analysis are presented and discussed in chapter 5. In section 5.1, the identified candidate areas, which represent all suitable areas in the study area, are illustrated. On the basis of the identified candidate areas four potential sites were selected and further assessed using the rating scheme (see section 5.2).

In the last chapter the results of the work are summarised and recommendations for further research are given.

Supplementary data are compiled in the appendix.

2 Wastewater Application onto Land

2.1 Overview

Land application systems have been traced back to 1531 in Bunzlau, Germany, where a sewage irrigation project was in operation for over 300 years (Crites et al., 2001). From the 1850s onwards wastewater irrigation became well organised in Europe and over the years many "sewage farms" were created all over the world. One of the most famous examples is Werribee Sewage Farm in Australia, which was established in 1897 and still treats most of Melbourne's wastewater (Reed et al., 1988). In the 19th century land application had been the main method for wastewater treatment, but as a result of the invention of modern technologies and biological treatment methods it gradually declined in popularity. Other reasons for the decreasing use of land application systems were the increase in urban population which resulted in increased sewage loads and rising land values as well as examples of mismanaged farms which became anaerobic and produced annoying odours. However, some cities still continue to use their sewage farms established in the late 19th century, for example, Paris, Braunschweig and Wroclaw (Dean & Lund, 1981).

Increasing environmental awareness as well as the recognition of the resource value of wastewater in terms of fertiliser and water has led to a revival of interest in land application systems during the last decades. Today, land application of wastewater is implemented in economically developed as well as developing countries and is now used throughout the entire arid, tropical and semi-tropical areas of the world (Dean & Lund, 1981).

According to the WHO (1989), thousands of schemes are currently in existence and increasing quantities of sewage effluent are used for irrigation in southern and western USA, Latin America, North Africa, Australia, the Middle East and Mediterranean countries. In arid and semi-arid climates intensive cropping cannot depend on rainfall alone, and wastewater is increasingly valued as an alternative source of irrigation water (Feigin et al., 1991). In countries such as Israel, Jordan and Peru it is now government policy to reuse all effluents from sewage treatment plants. One of the largest areas irrigated with effluent is located in the south-western part of the Hidalgo state, north of Mexico City. This system has been established in 1886 and is at present used to irrigate about 80,000 ha (WHO, 1989).

Land application of effluent is also practised in humid regions, but in contrast to arid and semi-arid climates mainly as a means of water treatment and disposal. Nevertheless, it can have beneficial impacts on agriculture even in those regions. Feigin et al. (1991) report that positive crop responses to effluent irrigation were obtained as a result of the additional water applied during the short dry periods which occur even under humid conditions. Furthermore, wastewater application increases the level of available nutrients throughout the year.

In New Zealand, the growing concern for ecosystem protection, increasing recreational use of waterways as well as rising respect for Maori spiritual values, which regard discharge of human effluent to waterways as unacceptable, has led to land application being increasingly considered as alternative disposal and treatment method (Balks, 1994). As a result of these driving factors, the Resource Management Act, which was adopted in 1991, requires every proposed waste treatment system to consider the feasibility of using a land-based treatment system (Barkle, 2001). Rotorua city, which has been irrigating tertiary treated sewage effluent onto the Whakarewarewa forest since 1991, is currently the largest scale sewerage irrigation scheme operating in New Zealand with an average of 27,000 m^3/d of effluent (Tomer et al., 1997).

2.2 System Types

In general, land application of wastewater can be divided into three main system types, namely slow rate, rapid infiltration and overland flow, which are briefly described in the following sections. As a result of their different application rates, the systems vary in treatment efficiency, site requirements and associated costs.

2.2.1 Slow Rate

Slow rate (SR) application of wastewater is sometimes also called irrigation treatment, since it is basically irrigation with effluent. The soil and plant system is used as supplementary treatment of the wastewater. However, there are some differences to conventional irrigation systems. For example, wastewater irrigation systems are usually required to operate all year round and not only when the water is needed to replace the soil moisture deficits (McIndoe & Borrie, 1996).

According to Reed et al. (1988), SR is the predominant form of land treatment of municipal and industrial wastewater. The wastewater is applied at a low rate over a large area of land, which is covered by vegetation like pasture, trees or row crop vegetables. Surface runoff of the wastewater should be avoided and the disposal of the water is mainly by evapotranspiration and percolation (Bell & Schipper, 1989).

Crops provide an essential part of SR systems, since they remove nutrients from the wastewater, reduce erosion and maintain the soil infiltration rates. The crop selection is critical for the success of the system and should be based on treatment requirements, wastewater characteristics, site properties and profitability (e.g., crop yield and availability of markets) (Bell & Schipper, 1989). In New Zealand, forest crops as well as pasture are the most common crops used with wastewater application systems. Advantages of forest systems include the removal of wastewater constituents from the food chain, lower risk of soil erosion, suitability of steep land and reduced pathogen transport in aerosols, whereas pastures usually have a better nutrient uptake and often higher economic returns than forests. For a more detailed description of the different crops suitable for irrigation with wastewater effluent used in New Zealand the interested reader should refer to Morton et al. (2000).

In SR systems, the wastewater is usually applied at rates below the hydraulic conductivity of the soil. The loading rates are the lowest of the three methods, which results in the widest range of acceptable soil types and permeabilities (Reed et al., 1988). Spray, surface or drip irrigation can be used to distribute the wastewater. The selection of an application method mainly depends on the crop, the slope of the site and the permeability of the soil. Surface irrigation is common to many older systems, while today mostly sprinkler systems are used (Reed et al., 1988).

Irrigation is a relatively expensive approach to land application of wastewater, since it requires large land areas and has high costs for the wastewater distribution. On the other hand it achieves the highest level of treatment of the three different approaches. According to Reed et al. (1988), SR systems can be designed to produce drinking water quality in the percolate. In addition, slow rate application may improve the soil fertility and increase the productivity of the agricultural system. Therefore, the water and nutrient value of the wastewater can partly offset the extra costs for this effluent disposal method.

2.2.2 Rapid Infiltration

Rapid infiltration (RI) is the controlled flooding of effluent onto well-drained flat basins of moderately to highly permeable soils. The wastewater is applied by surface spreading or sprinklers at high application rates and is treated as it percolates through the soil. This system type requires soils of adequate permeability overlaying well-drained strata. The treated water flows through the subsurface until it joins a water body or is recovered by pumping (Reed et al., 1988).

A vegetative cover can be used, but is not an essential element of RI systems, because the loading rates are too high for nutrient uptake. Therefore, vegetation serves mainly to maintain the soil permeability and stability and does not contribute significantly to the wastewater treatment process (Bell & Schipper, 1989).

The costs for rapid infiltration systems are generally lower than for slow rate systems, mainly because a smaller land area is required due to the high application rates. However, fewer sites are suitable and the degree of treatment, which varies depending on soil type and thickness, is lower (Bell & Schipper, 1989). Because the effluent purification may be minimal with this method, this system type is recommended only where the quality of the receiving water, e.g. an aquifer, is not critical (Stevenson, 1976).

2.2.3 Overland Flow

Overland flow (OF) stands for the application of wastewater on gentle slopes at relatively high application rates, where the effluent flows over the surface and little infiltration occurs. The effluent is applied at the upper reaches of grass-covered slopes on soils with low permeability and travels by thin sheet flow over the slope to runoff collection ditches. OF systems therefore require soils that are slowly permeable or have a restrictive layer such as clay pans just below the surface. Alternatively, the soil can be compacted during the construction of the site (Reed et al., 1988).

Vegetation provides a major treatment component for OF systems. The crops reduce the risk of erosion and serve as support medium for micro-organisms, which reduce the pollutants in the wastewater. Particularly recommended are perennial grasses because of their high moisture tolerance, the long growing season and a relatively high nutrient uptake (Bell & Schipper, 1989). In addition, the wastewater is further treated by interactions with near-surface soil.

OF systems generally achieve a good reduction of the organic and suspended solids content of the effluent, but only a limited nutrient removal (Stevenson, 1976). The cost is relatively low because the land area requirements are low. However, this approach does not provide for the final disposal of the effluent, since the runoff collected in the ditches at the end of the slopes needs to be either discharged or further treated.

2.3 Land Area Requirements

During the initial phase of the planning process preliminary estimates of the land area required need to be made. Those estimates are then used to determine if suitable sites in the study area exist. The estimates should be very conservative and should not be used for the final design of the system (Reed et al., 1988). For the final design, the exact land area requirements are refined considering the specific site characteristics, selected crops and all limiting wastewater components.

In the following, the estimation of land area requirements is illustrated only for slow rate systems, since these require the largest area. The preliminary land area requirements can be estimated by equation 2.1 using the loading rate of the wastewater (USEPA, 1981):

$$A = \frac{Q}{L \cdot 10{,}000} \tag{2.1}$$

With:

A: Land area [ha]

Q: Annual flow to land application site [m^3/year]

L: Average wastewater loading rate based on the limiting design factor (LDF) [m/year]

The wastewater loading L needs to be determined with respect to the type of slow rate system applied. Basically, two types of SR systems can be distinguished. Type 1 systems are designed to apply the maximum possible amount of wastewater on the minimum possible land area (Reed et al., 1988). The loading rate is then usually limited by either the hydraulic capacity of the soil profile or one critical wastewater constituent.

This means that the quantity as well as the quality of the wastewater needs to be considered. For municipal wastewater the critical component is usually the nitrogen content. For industrial wastewaters metals or toxic constituents can be the limiting design factor. However, other wastewater components such as phosphorus or pathogens should also be considered to be the limiting factors (Robb & Barkle, 2000).

Type 2 systems are designed to optimise the water reuse potential with the basic intent to irrigate the maximum possible amount of land. This means the water is applied at a rate just enough to satisfy the irrigation requirements for the crop being grown. The water loading rate depends on the climate, soil, crop, method of irrigation and leaching requirements (Reed et al., 1988). Type 2 systems are particularly applied in arid or semi-arid climates, where the emphasis of wastewater land application is on the reuse of the water.

In order to operate economically, wastewater land application schemes in New Zealand should be designed to apply the maximum possible amount of water. Therefore, in the following a detailed description of the land area estimation is given only for type 1 systems.

The maximum wastewater loading L is usually expressed in centimetres per week or metres per year to reflect an average loading (Reed et al., 1988). The determination of the wastewater loading is based on a number of considerations. First, the application rate should be low enough to avoid surface runoff or waterlogging of the soil layers. This is ensured by applying the water at a rate low enough to adhere to following equation (USEPA, 1981):

$$L_{ww,h} = ET - P - W_P \tag{2.2}$$

With:

$L_{ww,h}$: Wastewater hydraulic loading [m/year]

ET : Evapotranspiration rate [m/year]

P : Precipitation [m/year]

W_p : Percolation rate [m/year]

The design percolation rate, which is the amount of water allowed to percolate beyond the root zone, should not exceed the saturated hydraulic conductivity or permeability of the soil. USEPA (1981) recommends that for the design it should rather be about 4-10% of the minimum hydraulic conductivity.

The second limiting factor is usually the nitrogen content of the wastewater. For this, a preliminary nitrogen budget is set up to estimate how much nitrogen can be applied per year. Dean and Lund (1981) stress, that it is not necessary to limit the N applications to the quantity that the plants alone will remove, because some N can be reduced by denitrification within the soil matrix. In addition, volatilisation can occur and losses through leaching may be acceptable. Therefore, the nitrogen budget could be estimated as follows (see Robb & Barkle, 2000) (all parameters in [kg/(ha*y)]):

$$\text{Allowable nitrogen application } N_b = \text{nitrogen uptake by crops} + \text{denitrification} + \text{leaching loss} + \text{volatilisation} \tag{2.3}$$

The nitrogen budget helps find out the allowable amount of nitrogen (N_b) that can be applied onto land without excessive N leaching occurring. Together with the nitrogen content of the wastewater effluent (N_{ww}), this information can be used according to equation 2.4 to determine the acceptable wastewater loading rate.

$$L_{ww,N} = \frac{N_b}{10 \cdot N_{ww}} \tag{2.4}$$

With:

$L_{ww,N}$: Wastewater nitrogen loading [m/y]

N_b: Allowable nitrogen application [kg/(ha*year)]

N_{ww}: Nitrogen content in effluent [g/m^3]

The smaller one of the two wastewater loadings ($L_{ww,h}$ and $L_{ww,N}$) is indicating the limiting design factor and should be used for estimating the land area required according to equation 2.1.

In addition, the amount of land required for the land application system includes the area needed for storage, access roads, pumping stations, and maintenance and administration buildings. Buffer zones and irregularly shaped areas that are difficult to irrigate also need to be accounted for. Therefore, Robb et al. (2000) recommend increasing the calculated value by 25%.

2.4 Factors Influencing the Site Selection

Despite the differences in methodologies and principles of high-rate (i.e. overland flow) versus low-rate (i.e. slow rate) wastewater applications, the main factors that determine the suitability of a site are in principle the same. In the following, the factors that influence the site selection are introduced with a special emphasis on slow rate systems.

2.4.1 Technical Aspects

Several factors influence the technical feasibility of a land application site. Factors such as climate, soil properties and slope need to be suitable to ensure appropriate treatment of the wastewater and prevent the failure of the system.

2.4.1.1 Climate

The climate affects the overall feasibility of land disposal of effluent. The two main climatic features that affect effluent land application are temperature and moisture conditions, which need to be suitable to enable organic waste decomposition and the growth and development of the vegetative cover. Low temperatures reduce the biological activity and prolonged wet periods lead to saturation of the soil. This results in decreased renovation of the wastewater as well as increased surface runoff (Loehr et al., 1979). Most of New Zealand is located in the temperate zone in which organic matter can be readily broken down by soil organisms. In contrast, in sub-alpine and sub-antarctic regions the rate of plant growth is too slow for nutrient assimilation (Stevenson, 1976).

Freezing of pipes can limit the land application, but according to Dean and Lund (1981), sewage can be sprayed even in freezing weather and continuous applications can keep the soil from freezing unless temperatures fall very low. Particularly for the final site selection and system design the temperature, evapotranspiration as well as wind intensity and direction are important factors that need to be considered.

2.4.1.2 Soil

Soil is the single most important factor influencing the site selection. Oztekin et al. (1997) indicate that for a successful application of effluent the drainage characteristics of the soil are very important. If the soil drains too excessively, the water is rapidly removed and the treatment by soil processes may be minimised. Poorly drained soils are not suitable for land disposal of effluent, because the retention of large quantities of water for long periods can lead to the development of anaerobic conditions. In addition, low soil permeability limits the hydraulic loading and makes the crop management difficult. To sum it up, the soil needs to be permeable enough to pass the water and yet capable of retaining the water so that treatment occurs. Therefore, optimum condition for a slow rate system would be a hydraulic conductivity between 5 mm/h and 50 mm/h, which provides the best balance between drainage and the retention of the wastewater components (Tchobanoglous & Burton, 1991). However, usually the soil permeability is not yet known at the stage of site identification. Therefore, the suitability is normally determined using the soil texture, which is one of the major factors influencing the hydraulic conductivity of soils.

Medium-textured soils offer the best combination of water handling capabilities and waste renovation potential, and are therefore the most suitable soils for effluent application. Best suited are sandy loams to silty clay loams, whereas clay loams or clays are not suited for effluent application (Stevenson, 1976). Bowler (1980) described the interrelation between saturated hydraulic conductivity and soil texture as indicated in table 2.1.

Table 2.1: Interrelation between hydraulic conductivity and soil texture (Source: Bowler, 1980)

Saturated hydraulic conductivity	Approximate soil textural class
< 1 mm/h	Clay
1-5 mm/h	Clay loam
5-20 mm/h	Silty clay loam
20-60 mm/h	Silt loam
60-125 mm/h	Loam
125-250 mm/h	Sandy loam
> 250 mm/h	Sand

Furthermore, the suitability of a site depends on the pH of the soil. The soil pH affects soil chemical and biological processes, such as phosphorus fixation or ammonia volatilisation. A pH between 5.5 and 8.4 offers the most suitable conditions (Tchobanoglous & Burton, 1991). A relatively high pH also provides good conditions for denitrification with the optimum being at pH 7 to 8 (Bell & Schipper, 1989). A very high or low pH can limit the growth of many crops.

The retention of wastewater components like phosphorus and viruses is a function of the residence time of the wastewater in the soil and the degree of contact between the soil colloids and its components (Crites, 1985). Therefore, sufficient soil depth is important for the effluent renovation through retention of wastewater components as well as bacterial action. An adequate soil depth is also necessary for the root development of the crops. The minimum soil depth should range between 0.6 m and 0.9 m, which is considered as deep enough to allow normal root development and sufficient residence time of the wastewater (Feigin et al., 1991). However, the thicker the unconsolidated layer of soil is, the greater the capacity for purification of the effluent within the soil.

2.4.1.3 Topography

Topography is another factor influencing the technical suitability of a site. If the slope is too high, runoff and erosion is increased and the soil condition becomes unstable when the soil is saturated. Steep slopes can also make crop cultivation more difficult and the wastewater application can be more expensive. In addition, the topography influences the effluent distribution system that can be used, for example, surface flooding is only possible if the slope is less than 14% (Bell & Schipper, 1989). The maximum slope recommended depends on the type of cropping system. According to USEPA (1981) slopes less than 15% are most suitable for slow rate application. For noncultivated crops such as pastures slopes of up to 20% can be used and forests have been successfully irrigated with effluent on slopes of up to 40%. However, it is generally recommended that slopes greater than 35% should not be used for land application of effluent due to the high risk of surface runoff.

2.4.2 Environmental Aspects

Beside the technical feasibility, health aspects must be considered and environmental sustainability must be assured. As a result of an improper site selection, pollutants that are contained in the wastewater, e.g. nutrients or pathogens, can cause the contamination of drinking water supplies. For example, nitrate in underground or surface water supplies can cause methaemoglobinaemia in children. Therefore, the New Zealand drinking water standards require that the nitrate concentration in water used as a supply of drinking water is less than 50 mg (NO_3^-) per litre (Tipler, 2000).

2.4.2.1 Groundwater

To ensure that migrating pollutants do not affect the potability of groundwater supplies, it is important to keep an appropriate distance between the effluent application and the aquifer. Avoiding sites with shallow depths to groundwater also helps reduce the risk of groundwater mounding, which can lead to drainage water reaching the surface and therefore adversely affecting the land-use (Tipler, 2000). In addition, shallow groundwater can interfere with crop growth and limit root development. In general, effluent land application is suitable on sites with a minimum distance to the groundwater table of 1 m, although greater depths are usually preferred (Feigin et al., 1991). Furthermore, buffer zones of at least 20 m are required around bores used for drinking water supply, irrigation or stock water (Wellington Regional Council, 1999).

2.4.2.2 Surface Waters

Although wastewater application onto land is generally implemented to better protect surface waters, it can still sometimes affect the quality of surface waters. Because most soils retain phosphorus, this nutrient will tend to concentrate in the surface layer. As a result, soil erosion from agricultural land can lead to the discharge of soil particles with a very high phosphorus level into surface water causing eutrophication. In addition, the direct entry of wastewater into surface waters, for example through wind drift during spray irrigation, can result in pollution and degradation of the watercourses. Organic matter and nutrients contained in the wastewater may remove oxygen from the water and cause eutrophication, while pathogens impact on recreational and amenity values. Therefore, when applying wastewater onto land, it is essential to keep buffer zones of at least 20 m around surface waters and wetlands in order to prevent their contamination (Tipler, 2000).

2.4.3 Social and Cultural Aspects

Social and cultural factors, which are described in the following subsections, influence the acceptability of a land application site. Of particular interest in this context are residential areas and areas that are not acceptable for waste disposal for cultural reasons.

2.4.3.1 Land Use and Residential Areas

Land application systems must comply with the zoning regulation of a region. It is evident that land which is built upon is not suitable for effluent disposal. City or regional plans can be consulted to find out about future land use plans. Generally, agricultural and forested land is suitable for land application. Also open spaces and parkland may be selected for potential sites (USEPA, 1981).

As Robb et al. (2000) indicate, the neighbouring land use and location of dwellings are relevant to the social feasibility of a potential effluent disposal site. The Department of Health (1992, p.3) demands that “sewage must be applied to land in a way that does not cause a nuisance and does not endanger health”. Nuisance relates particularly to odour which is dealt with by buffer zones that are to be kept around residential areas. Although Dean & Lund (1981) indicate that there is no evidence that land spraying causes disease, even of the workers in the fields and still less among the surrounding inhabitants, buffer zones provide a certain protection against aerosol transmission for neighbours of land application sites. For spray irrigation systems on open grounds a buffer zone of 150 m to the nearest residential property is required (Department of Health, 1992).

Generally, it is recommendable to locate land disposal sites as far as possible away from existing dwellings, in order to avoid strong public opposition. In the long term, the construction of a land treatment site can result in decreasing property values in the neighbouring area.

2.4.3.2 Waahi Tapu

In principal, Maori support the land application of waste compared to the discharge into waterways, because waterways are viewed as “food bowls” in Maori culture (Gunn, 1991). However, some sites are not appropriate for land disposal, because they are of significant value to Tangata Whenua. These sites are known as waahi tapu and usually represent burial sites, sites of ancient marae or sites where taonga (treasured items) have been buried (Smith & Hania, 2000). Therefore, it is necessary to contact the Maori group who have Tangata Whenua status for the study area or other involved community organisations and find out about the location of traditional or sacred sites.

2.4.4 Economic Aspects

In the following subsections an overview of economic factors that are related to the site location of a land application system is given. Distance between plant and site and revenue from cropping influence costs and returns and thus affect the economic viability and profitability of a particular system.

2.4.4.1 Distance and Relief

Economic viability of a land treatment project mainly depends on the capital and operational costs. These can be partly influenced by an appropriate site selection. The distance and relief, which is the change in elevation between the sewage treatment plant and the disposal site, determine the pipeline and pump costs as well as the energy costs for operating the facility. The site selection (e.g., steep slopes, subdivided parcels etc.) also influences the costs of the application system and the operation. Furthermore, the current land use and property values are important factors for the capital costs of a land treatment facility.

2.4.4.2 Revenue

Another aspect regarding the economic viability is the revenue from agriculture or forestry on the land application site. For this the potential markets as well as the type of crop cultivated and its price are important information.

3 Method and Material

3.1 Case Study

The GIS-based site selection was carried out for the Christchurch Wastewater Treatment Plant as a case study. Christchurch as well as its three adjacent districts were investigated to determine if and where suitable sites exists. The treatment plant and the study area are briefly described in the following sections.

3.1.1 The Christchurch Wastewater Treatment Plant

The Christchurch City Wastewater Treatment Plant (Te Huingi Manu – The Place of the Gathering Birds) is located in Bromley in the East of Christchurch. It treats mostly domestic but also some industrial wastewater. Currently, about 136,000 households or a population of 320,600 is connected to the sewage plant and the daily total flow is on average 163,000 m^3 (CCC, 2002).

The wastewater is first treated by screening and sedimentation before trickling filters act as secondary treatment. The water is then released into the oxidation ponds covering an area of 230 ha, where it spends three weeks. Finally, the effluent is discharged twice a day following the hours after high tide into the Estuary of the Avon and Heathcote Rivers and eventually flows into the Pacific Ocean. The treatment processes achieve a relatively high removal of organic matter, suspended solids and micro-organisms. However, the concentration of nutrients, particularly nitrogen and phosphorus, remains rather high. For a more detailed description of the CWTP please refer to CCC (2002).

The Regional Council (Environment Canterbury) granted the resource consent to continue discharging the treatment plant effluent into the Estuary only for another five years. Therefore, alternative options for the effluent disposal need to be investigated. Beside the construction of an ocean outfall pipeline, the land application of the wastewater is an alternative disposal method.

3.1.2 Study Area

This study aimed to find potential sites for the land application of the CWTP effluent in Christchurch City as well as its three adjacent districts Selwyn, Waimakariri and Banks Peninsula. The four districts are located in the province of Canterbury and cover an area of 10,319 km^2 extending from the coast in the East, the Rakaia River in the South, north of the Ashley River in the North to the Southern Alps as the western boundary. Detailed information about area and population of the districts is listed in table 3.1. Figure 3.1 illustrates the location of the study area.

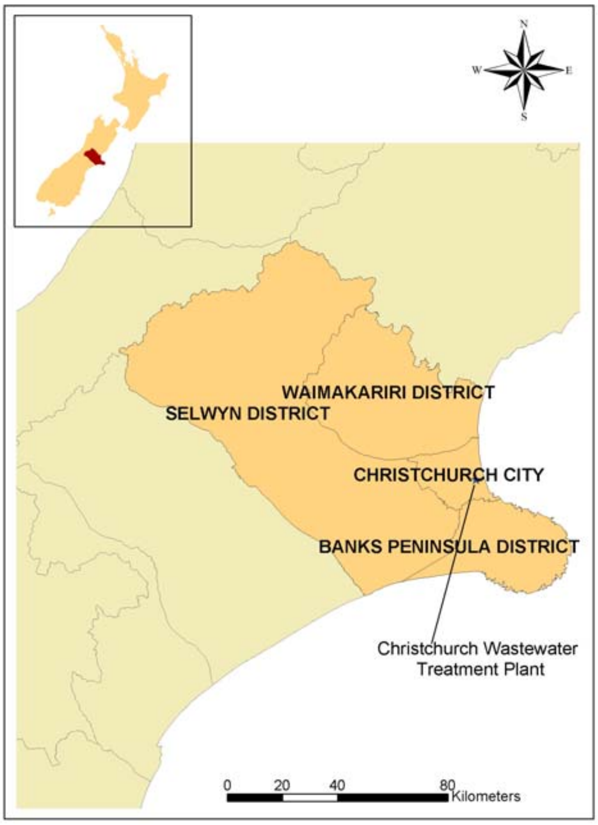

Figure 3.1: The study area

In the West, the study area is bounded by the crests of the Alps. The rolling foothills give way to a broad plain which extends to the coast. Banks Peninsula district is characterised by a hilly volcanic terrain and many bays. The plains are predominantly used for pastoral activities, particularly sheep production, but also beef, deer and dairy. Furthermore, the Selwyn district is a major cereal growing area, which produces large amounts of wheat and barley (Selwyn, 2003).

Table 3.1: Area and population of the four districts (Source: Stats NZ, 2003)

District	Area [km^2]	Population
Christchurch City	453	316,224
Selwyn	6,492	27,312
Waimakariri	2,216	36,900
Banks Peninsula	1,158	7,833

3.2 Why GIS? Why Raster?

Geographical Information Systems (GIS) are computer-based systems for the storage, analysis and manipulation of spatial data. A GIS is a tool that allows the analysis of all forms of geographically referenced information and identifying the spatial relationships between different geographic features. Or as Smith and Hania (2000, p.5) phrase it, “simply put, a GIS combines layers of information about a place”.

As a result of its ability to combine different layers of spatially varying information (e.g. suitability criteria), a GIS can represent a valuable tool for the site selection of a wastewater land application system. Every factor required for the suitability analysis can be represented in a digital layer which can be queried individually or overlaid with other layers. In contrast to manually querying and overlaying the different information sources, a GIS can prove to be very efficient, accurate and time-saving (Francek et al., 1999). This is particularly true for large areas or for a great number of variables, as is the case for this study. Therefore, using a GIS allows a relatively easy identification of those areas where all criteria are met.

Furthermore, a GIS enables the running of many scenarios and the easy alteration of the criteria that were used in the first run. For example, if the suitability of sites for another land application type should be investigated, the overlay of the information layers and the query can be changed easily and efficiently. Another advantage of using a GIS is the ability to clearly communicate complex spatial data to all decision-makers and stakeholders.

However, using a GIS is always dependant on the quality of the data. Often the lack of suitable or accurate data or the absence of digital data at all is impeding an appropriate

GIS application. In addition, a suitability analysis using a GIS can only be a preliminary investigation with the purpose of supporting the decision making process. Field observations and laboratory analyses to verify the digital data and provide further detailed information will always be required after a preselection has been made with the aid of the GIS.

A GIS can represent geographic information in different ways, of which the two most common are the vector data model and the raster data model. In the vector data model, features are represented as points, lines or polygons. Each location is precisely recorded as either a single x,y coordinate or as a series of ordered x,y coordinates. The vector data model is particularly suited for representing geographic features. In contrast to this, the raster data model focuses on location. It is therefore better suited to represent surfaces. The raster model is a regular grid or matrix of cells that are stored as rows and columns and can be filled with values. Every cell represents a particular location. Geographic features like points or lines can be represented as a value in a single cell or as a series of connected cells. However, the accuracy of the raster data model greatly depends on the resolution or the area represented by each cell. Therefore, the cell size of a grid can be a limiting factor for the application of raster data models.

The main difference between the two data models is that the vector data model represents location as x,y coordinates, whereas the raster model uses cells. In contrast to the vector data model, which represents the shape of geographic features accurately, the raster data model only represents square areas (or cells) and is thus more generalised and less accurate (ESRI, 1994). Therefore, the vector model can better represent well-defined boundaries, whereas the raster model is rather suited to represent gradual transition between features and surfaces, e.g. elevation.

Another difference of the two models, which is illustrated in figure 3.2, is their efficiency regarding overlay operations. Overlaying vector layers often results in a high fragmentation of polygons and is a lot more complex than overlaying layers in the raster data model, which allows simpler and faster overlays (ESRI, 1994). For this reason, the overlays in the present study were carried out using the raster data model. However, many factors that influence the suitability analysis, such as residential areas or rivers, are more precisely represented by the vector model. Therefore, it was decided to first process every digital layer in the data model that better represented its features (e.g. rivers as vectors, groundwater table as raster) and then later convert all layers into the raster format. For example, the process of buffering residential areas showed the advantages of carrying out the process of buffering in the vector format, since the buffering in the raster format resulted in a rather blurred output-layer and the disappearance of units that were too small to be captured in the grid. The final overlays of the different layers were then carried out in the raster data model, after every layer had been converted into a raster layer or grid.

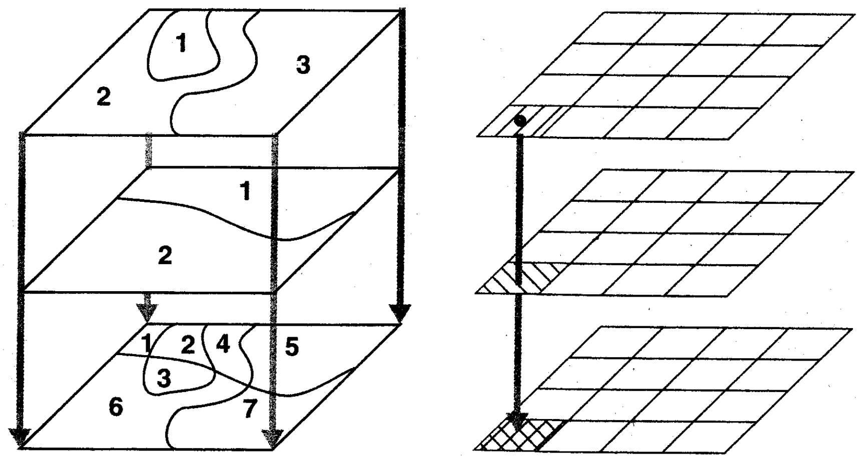

Figure 3.2: Comparison of raster and polygon overlay (Source: ESRI, 1994)

For the present study the ArcGIS software was used. This software by ESRI is able to integrate one spatial data model with the other, for example a digital layer can be converted from vector into raster data and vice versa. In addition, it provides all functions required for the suitability analysis. The cell size was set to the given cell size of the only source layer in raster format, which was 25 m. This cell size is large enough to keep the data storage demand relatively small, and yet provides a resolution high enough to allow for the presentation of the smallest entities (e.g. buffer zones around wells).

3.3 Data Used

A number of digital data were used for the analysis. Most of the layers were available for the whole of New Zealand. Therefore, the layers had first to be clipped in the GIS to the extent of the four districts. The projection of all layers had to be set to New Zealand Map Grid to ensure consistency and enable the overlay of several layers. In the following an overview of the data used is given.

TLA96

The Territorial Local Authorities layer from 1996 shows all districts of New Zealand.

Toposhapefiles

The toposhapefiles are part of a topographic database provided by Land Information New Zealand (LINZ, Toitu Te Whenua, 2000). They were sourced from the 1:50,000 Topographic Map 260 Series and provide information about a large range of geographic objects, such as rivers, roads, etc. Toposhapefiles are vector layers with point, line or polygon data. For this study, the digital layers with data on surface waters as well as residential areas and dwellings were used.

DEM – Digital Elevation Model

The digital elevation model used is a raster layer provided by Landcare with a cell size of 25 m.

LCDB – Land Cover Database

Terralink is the custodian for the land cover database. The land cover types are classified into 16 standard classes which are compatible in scale and accuracy with the 1:50,000 topographic database (Terralink, 2002). The digital vector layer represents the land cover of New Zealand about 1997 and the imagery has a positional target accuracy of plus or minus 25 m. The attribute accuracy of all vegetation landcover polygons is greater than 90%.

Wells

Environment Canterbury provided a digital point layer with all wells in the study area that are monitored by ECan. The attribute information for some of the wells included information about historical ground water level measurements like the highest water level ever recorded.

NZLRI – New Zealand Land Resource Inventory

The New Zealand Land Resource Inventory database is administered by Landcare Research (Manaaki Whenau). It is a polygon database that was digitised from NZLRI maps, which were completed in 1979. The NZLRI has since been revised and updated and describes parcels of land in terms of the five attributes rock type, soil, slope, erosion and vegetation. In addition, regional soil databases were included to provide information about soil attributes, such as soil fertility and soil physical properties (Landcare, 2002).

4 Analysis

4.1 Selection of System Type

The three different system types of land application described in section 2.2 can be applied to achieve different objectives. Overland flow processes are used almost exclusively for the purpose of water treatment, whereas rapid infiltration can also have the objective of groundwater recharge (USEPA, 1981). Slow rate systems can be operated to achieve a number of objectives, such as effluent treatment, gain of economic returns from crop production, and water conservation by replacing potable water used for irrigation with water of lower quality. In addition, combinations of the three system types are possible to achieve a high degree of treatment and combine the advantages of the different methods. For example, different processes could be used in cold and warm weather (USEPA, 1981).

The selection of one system type should be based on the specific requirements of each type and the characteristics of the area under investigation. For example, in an area with predominantly clay soils, an overland flow system should be considered.

In order to define the requirements regarding land area as well as specific factors influencing the site selection, a preliminary selection of a system type needs to be carried out. If the planning process shows, for example, that no sites are suitable for the chosen land application type, the selection should be reviewed.

The study area for this project includes the four districts Christchurch, Selwyn, Banks Peninsula and Waimakariri. For a more detailed description of the study area please refer to section 3.1. Since slowly permeable soils like clay or restrictive layers are rather uncommon in this area, overland flow type systems would entail the difficulties of achieving a compacted soil layer. Consequently, overland flow systems are excluded from the analysis. Rapid infiltration systems require a large depth to the groundwater and are not as efficient in pollutant removal as slow rate systems. In the study area, the groundwater level is generally high and the contamination of the aquifers would pose a serious threat to the provision of drinking water in the region. Therefore, the slow rate system type is chosen for this case study. Slow rate systems have many further advantages. In addition to allowing for the widest range of soil permeabilities and producing the highest water quality of the three system types, slow rate applications increase crop production and contribute to water conservation. This is a particularly significant factor for the Canterbury region, in which more water is used than in any other region of New Zealand and this mainly for irrigation purposes[1] (ECan, 2002). The relatively high capital and operational costs of slow rate systems are likely to be partly offset by the return that can be gained from the system.

4.2 Estimation of Land Area Required

Because the case study is a type 1 system (see section 2.3), the hydraulic loading as well as the nitrogen loading was considered as limiting design factors to estimate the required land area.

4.2.1 Hydraulic Loading

For the application of equation (2.2) information about evapotranspiration, precipitation and percolation was required. Evapotranspiration is the combination of evaporation from the soil and plants and the water use by plants. Usually a specific plant coefficient is required for the calculation of the evapotranspiration. However, USEPA (1981) report that in humid regions it is normally sufficient to use the potential evapotranspiration and assume a plant coefficient of 1. Evapotranspiration rates and precipitation for New Zealand weather stations are listed in Garnier (1958), where averages of a period of at least 15 years are given.

Regarding the percolation rate a minimum hydraulic conductivity of 5 mm/h was assumed (see section 2.4.1.2). In order to make conservative assumptions and to allow for the variability of the soil conditions, the allowable percolation rate was set to be 5% of the minimum hydraulic conductivity. USEPA (1981) recommends adjusting the monthly percolation rate for those months having periods of non-operation. Reasons for non-operation or downtime are soil frosts (days when the mean temperature is less than -4°C), crop management or seasonal crops. Since frosts in Canterbury are not severe and the selected crop will most probably be perennial and not require downtime for crop management, no adjustment for downtimes needed to be made.

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[1] 86% of the total allocation is for irrigation

Given this information the monthly wastewater loading rates were calculated and then summed to yield the allowable annual loading rate. This calculation (see appendix A) was carried out for three different stations (Christchurch, Akaroa and Darfield) to allow for the different conditions in the study area. The minimum of the calculated allowable wastewater loading rates based on the hydraulic loading is 1.88 m/y.

This value corresponds with values found in the literature. USEPA (1981) reports that annual loading rates for slow rate systems generally range between 0.5 and 6 metres. In the New Zealand context, Stevenson (1976) based the estimates of land area requirements on hydraulic application rates between 2.5 and 13 mm/day, which equals 0.9 m to 4.7 m/year. The Rotorua land application facility is designed for a loading rate of 80 mm/week (4.2 m/year), but is normally operating at 52 mm/week (2.7 m/year) (Gregorius, 1987).

4.2.2 Nitrogen Loading

For the estimation of the wastewater application rate based on nitrogen as the LDF, a nitrogen budget needed to be set up (see equation 2.3). For this, information about the nitrogen uptake by crops, denitrification as well as volatilisation and leaching losses was required.

The rate of nitrogen uptake in forests is affected by the age and stage of development of the trees. According to Tomer et al. (1997), the peak value for pines is about 140 kg/(ha*y) and their N uptake at the age of 9 is about 80 kg/(ha*y). However, they recommend that a conservative value of about 35 kg/(ha*y) should be assumed for the design of such systems. Eucalyptus crops are reported to assimilate about 140kg/(ha*y) (Bell & Schipper, 1989). Nitrogen uptake of pasture and other crop cultivars is usually higher than of forest and varies between 150 kg/(ha*y) (wheat and barley), 300 kg/(ha*y) (orchard grass) and 700 kg/(ha*y) (lucerne) (Bell & Schipper, 1989; Morton et al., 2000). For this study, the nitrogen budget was calculated for forests with an average N uptake of 35 kg/(ha*y) and for pasture with an average uptake of 150 kg/(ha*y). It should be noted that the nutrient in the wastewater can act as fertilisers for the crops. However, since the effluent needs to be applied all year round, the nutrient application does not necessarily correspond to the crop nutrient requirements.

Denitrification is influenced by a number of factors, such as soil temperature and moisture. Therefore, variable denitrification rates have been recorded ranging from 2.4 kgN/(ha*y) (sandy loam) to 110 kgN/(ha*y) (loam). As a preliminary approximation 5 kgN/(ha*y) can be assumed as average value (Barton et al., 2000).

As an initial conservative approximation it seemed reasonable to set volatilisation and leaching losses to zero. This ensures that nitrogen leaching, which could pollute groundwater resources, is minimised. The acceptable loadings were therefore for forest 40 kg/(ha*y) and for pasture 155 kg/(ha*y).

According to Bourke (CCC, pers. comm., 2002), the average total nitrogen content of the treatment plant effluent is 34.53 g/m^3, which is a relatively high value for a treatment plant effluent. With this information equations 2.3 and 2.4 resulted in an acceptable wastewater loading of 0.12 m/year and 0.45 m/year for forests and pasture respectively (see table 4.1). Because of the relatively high nitrogen content in the effluent, the loading rate for forestry is very low. This results in an unviable large area required for the disposal of the effluent. Therefore, it is recommended that pasture will be used as crop for the application system.

Table 4.1: Calculation of loading rate based on N as LDF

Crop	Acceptable N loading (N_b)	N content of effluent (N_{ww})	Loading rate based on N ($L_{ww,N}$)
Forest	40 [kg/(ha*y)]	34.53 [g/m^3]	0.12 [m/y]
Pasture	155 [kg/(ha*y)]	34.53 [g/m^3]	0.45 [m/y]

4.2.3 Land Area Requirements

The annual flow of effluent to the land application site was calculated based on the average daily flow, which is currently 163,000 m^3/d (CCC, 2002). Therefore, the annual flow amounts to about 59.5*10^6 m^3.

The nitrogen removal is the limiting design factor (see sections 4.2.1 and 4.2.2) and requires a wastewater loading of less than or equal 0.45 m/year. Applying equation 2.1, this resulted in an area of about 13,000 ha of pasture crops needed to dispose of the total effluent. This value needed to be increased by about 25% to account for additional land required (Robb et al. 2000), which means that approximately 16,000 ha of land is needed. For a pine plantation, a total area of about 62,000 ha would be required given the current quality of the effluent. This was regarded as being an uneconomically large area and it was therefore advised against selecting forests as crop.

Tipler and Keller (2000) report that for the land application of the CWTP effluent about 6,000 ha to 11,000 ha of land would be required for agricultural and forestry use respectively. However, they base their calculations on the assumption that the treatment plant is upgraded to achieve a higher nutrient removal. For the present study, this assumption was neglected and the land area requirements were therefore estimated to be 16,000 ha for pasture crops.

It should be taken into account that this is only an initial area estimation solely for the purpose of analysing if suitable areas are available. After potential sites have been identified, a detailed calculation of the final wastewater application rate as well the exact land area required needs to be carried out.

4.3 Identification of Suitable Sites

4.3.1 Site Selection Factors

In the following an overview is given of how the different factors that need to be considered for the site selection were included into the GIS analysis.

4.3.1.1 Technical Feasibility

Climate

According to MAF (1984), Canterbury is a relatively dry area. The rainfall is lowest near the coast, where the average annual rainfall is 500 to 625 mm, and increases inland. The upper plains receive an average of 750 mm and the foothills of the Southern Alps an average of 1000 mm. Temperatures are moderate. For example, for Christchurch the average temperature normals, which are the temperatures midway between maximum and minimum, vary between 6°C in June and 17°C in January. A more detailed weather chart for Christchurch is shown in appendix B. The average number of frosty nights is about 36 in Christchurch and 62 further inland in Darfield. Frosts in Canterbury are usually not severe.

Therefore, the study area is in principle climatically suited for wastewater application onto land. However, the western edge of the study area, namely the Southern Alps, is an area where the alpine climate with high rainfall and cold periods impedes irrigation with wastewater. Because alpine areas should not be considered for potential sites, cells of the DEM having an altitude of less than 1000 m above sea level were selected and excluded from the subsequent analysis.

For this study, detailed information on local variations of the climate was not included in the GIS analysis, because according to Robb et al. (2000), climatic features are usually not deciding factors for the site selection. However, for the final design, particularly for crop selection and irrigation management, climatic information like wind direction and intensity, rainfall and evapotranspiration needs to be considered. NIWA, which coordinates a database of climate stations throughout New Zealand, could be the source for such information.

Soil

The NZLRI was evaluated with respect to soil type, soil pH and soil depth. First, the attribute ‘type’ describing the soil type of each polygon was queried in the GIS resulting in the selection of all suitable soil textures (sandy loams to silty clay loams). Appendix C lists the soil types as listed in the LRI that were found to be suitable for the land disposal of wastewater. When the soil type specified in the LRI was ambiguous, such as, for example, the soil type ‘hill soils’, the Soil Bureau Bulletin 27 (DSIR, 1968), which includes an extensive list of all defined soil polygon attributes, was consulted in order to identify all suitable soil polygons.

Furthermore, for every soil polygon the LRI contains an attribute field ‘pH class’, which classifies the minimum soil pH over a depth of 0.2 m to 0.6 m. An attribute query in the GIS resulted in the selection of all polygons having a pH class between 1 and 4, which refers to a soil pH value between 8.3 and 5.5 (Newsome et al., 2000).

The LRI does not contain an attribute field concerning the actual soil depth. However, information about the potential rooting depth (PRD), which describes the depth to a layer that may impede root extension, is available for every soil polygon. In order to ensure that identified sites have an adequate soil depth, polygons with a PRD class between 1 and 3 were selected and converted into a grid. PRD classes between 1 and 3 refer to a potential rooting depth ranging from 0.6 m to 1.5 m (Newsome et al., 2000).

Topography

Using the ArcView Spatial Analyst the function *slope* was applied to the available DEM. This resulted in the creation of a raster layer showing the slope of each raster cell in percent. All raster cells having a value of greater than 35% were set to *NoData* to exclude them from the analysis. Although it was recommended to use agriculture as crop, for which slopes of around 35% are not suitable anymore, these areas were nevertheless included in the analysis to make an allowance for the upgrading of the wastewater treatment plant, which would result in forestry becoming a viable option.

4.3.1.2 Environmental Sustainability

Groundwater

Because no information on the groundwater table in the study area was available, the layer containing the location of wells and information about the highest water level was used to derive an approximation of the groundwater table. This was carried out using a surface generation model, which approximates a continuous surface by taking a sample of values at different points and then interpolating the values. The GIS software ArcGIS 3D Analyst provides a variety of surface interpolation models, of which the method ‘Inverse Distance Weighted’ (IDW) was used. This method, which is an exact and local interpolator, estimates the missing cell values by averaging the values of sample data points in the neighbourhood of each cell. This means, the closer a point is to the location being approximated, the more influence it has on the averaging process. Thus, the influence of each measured point diminishes with distance (ESRI, 2002).

About 11% of the total 18,249 wells represented in the digital layer had appropriate historic attribute data about the highest water level ever and the first step was to select those wells from the total. Then the IDW method was applied to these sample points. The variables for the IDW model were chosen as follows: The power was set to 2 and the number of points was set to 5. The resulting raster surface represented an approximation of the groundwater table in the study area.

However, several factors influencing the quality of the output layer that represents the water table must be kept in mind. First, using the recorded highest water level did not result in the average groundwater table but rather an estimate of the worst-case scenario. Since the groundwater levels in Canterbury show a high seasonal as well as interannual variability, the water table can be expected to be usually much lower than the calculated one.

Second, the availability of input sample points has a great influence on the quality of the interpolated output. Unfortunately, the available well data was very irregularly distributed and for a large part of the study area (particularly the Northwest and Banks Peninsula) no information existed. Therefore, parts of the calculated water table are extrapolations of the known points located particularly in the east of the study area, which could have resulted in an erroneous approximation.

Furthermore, many wells had positive values as highest water level indicating that in a large part of the study area confined aquifers are prevailing. In these areas, the recorded water level measured the piezometric head and not the actual depth of the groundwater below the surface. Therefore, the interpolation of the water table in these areas did not result in a realistic representation.

Nevertheless, because no other approximation of the groundwater table was available, the interpolated surface was queried using the ArcGIS Spatial Analyst. All cells having a value of less than 1, which indicated an approximation of the groundwater table of less than 1 m below the surface, were set to *NoData*, in order to exclude areas where the wastewater could pollute the groundwater from the analysis. The remaining cells were reclassified to allow for an assessment of the potential sites (see section 4.3.3).

In order to ensure that no drinking water supplies are contaminated through the direct entry of wastewater into boreholes, the buffer function in ArcGIS was used to create circular buffer zones of 20 m around every well. These buffer zones were converted into the raster format and later excluded from the total area of potential sites.

Surface Waters

The toposhapfiles were used to include the location of rivers (layer name: river_cl, river_poly), lakes (lake_poly) as well as lagoons (lagoon_poly) in the analysis. It must be noted that the river layer contained not only sizeable rivers but also drains and ditches. The consideration of these smaller waterways resulted in a rather conservative analysis regarding the surface water. However, small drains usually discharge into larger waterways and can therefore lead to their pollution. Therefore, this conservative approach was considered to be acceptable. The features of the four layers were buffered with a buffer distance of 20 m one by one since they had two different formats (line and polygon). Using the function *union* the buffer polygons were merged and later converted into a grid layer.

4.3.1.3 Social Acceptability

Land Use

The land cover database was used to identify those areas where a land application of wastewater is in principle possible. For this, all polygons that are assigned one of the following land cover classes were selected: primarily pastoral, primarily horticulture, shrub, tussock, indigenous forest and planted forest. Although forestry is expected to require an uneconomically large area of land (see section 4.2.2), forests were nevertheless included into the analysis to provide for the possibility of an upgrading of the wastewater treatment plant, which would result in a better quality of the effluent and therefore forestry becoming a viable option.

Residential Areas

In order to allow for buffer zones to be kept around dwellings, two layers of the toposhapefiles, which contained information about residential areas as well as buildings, were used for the analysis. The polygons ‘residential areas’ and ‘buildings’ were buffered with a distance of 150 m. These buffers were then converted into the raster format and later excluded from the total area of potential sites.

Waahi Tapu

The New Zealand Archaeological Association runs a national site recording scheme providing information about historic places, which might be unsuitable for wastewater application. The records also include the grid reference of the sites. However, the locations of waahi tapu sites, which are of extreme significance to Ngai Tahu, are not recorded electronically and it is very likely that most Runanga do not want to disclose their locations for protection purposes (Takerei Norton, Te Rünanga o Ngäi Tahu, pers.comm., 2003). Therefore, waahi tapu sites could not be integrated in the analysis, which necessitates contacting Ngai Tahu after an initial site selection has been made to include the considerations of Tangata Whenua.

4.3.1.4 Economic Viability

Distance and Relief

Distance and relief between site and plant were not included into the identification of candidate areas, since they do not affect the overall feasibility but rather the degree of suitability of a specific site. However, as Reed et al. (1988) emphasise, the transport distance is a critical factor and should be included in the ranking procedure. Therefore, the distance between plant and potential sites was used as a rating factor. First, a layer containing the location of the treatment plant was created with the aid of a topographic map (Linz, 2000). Using the function *pathdistance* a grid was created that showed the distance between every cell in the study area and the treatment plant. This function calculates the actual surface distance considering any elevation differences on the way between raster cell and plant. This grid was reclassified according to the rating categories chosen.

The relief, which affects the pumping energy required and thus the operational costs, was not taken into account, since this would require a more site-related investigation and cannot be done on a cell-by-cell basis. In addition, the site identification analysis showed that suitable areas are mainly located on the Canterbury Plains, which indicates that for the case study relief is not a determining factor for the site selection. However, elevation changes influencing the operational costs should be considered in a more detailed site investigation.

Revenue

Since the crop had not been selected at this stage, the potential revenue was not included into the site selection. Distance to markets can reduce the returns from the crop production and are an important factor for the site selection. For the case study, the distance to the market was already included by considering the distance between site and treatment plant. Although it is expected that potential revenues will not vary significantly between the identified sites, it is recommended to conduct a financial analysis during the later stages of the site selection and the system design process.

4.3.2 Overlay

The above mentioned and described factors had to be combined in order to identify those areas where all criteria for a successful land application of wastewater are met.

Figure 4.1 gives an overview of the process of identifying suitable areas (i.e. candidate areas) and the main GIS operations involved.

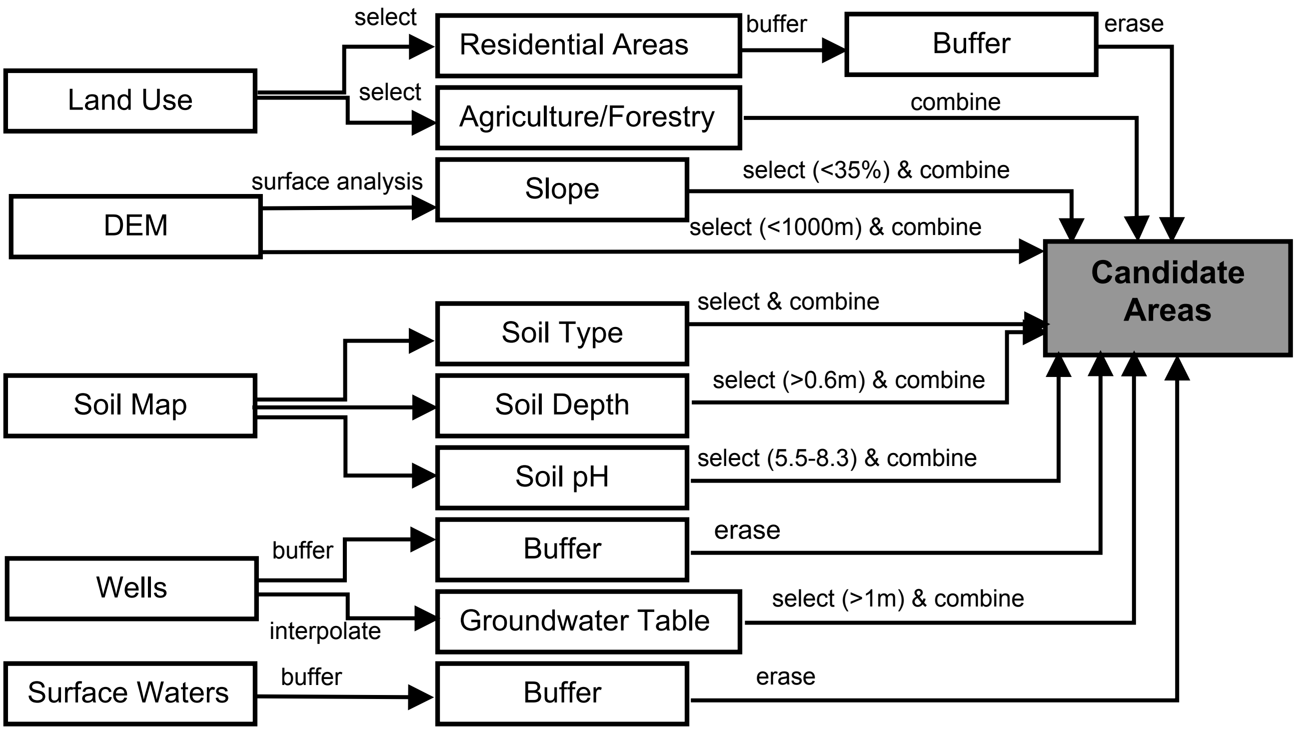

Figure 4.1: Flow diagram of the site identification process

First, the buffer zones around wells, surface water and dwellings were erased or masked out in the GIS from the total area of the four districts. This resulted in the exclusion of all buffer zones from the subsequent analysis. Then an overlay layer of the study area without the buffer zones and all factors that are prerequisites for potential wastewater application sites had to be created. The grid function *combine* was used to overlay all factors on a cell-by-cell basis and to create an output layer showing all suitable areas. This function combined only those areas, where all layers had valid data, in other words, if an area was identified as being unsuitable because of one specific factor, it was also shown as unsuitable in the output layer. Furthermore, the function *combine* has the advantage that every cell in the output layer is assigned the respective cell values of the input layers as attribute data, which is necessary for subsequent queries of the output layer.

4.3.3 Rating

A rating system was applied, in order to be able to assess the identified areas, to compare them and to make a decision which candidate sites should be investigated more thoroughly. For example, a site with a greater soil depth shows better purification capacity than a site with a lower soil depth and, thus, should be preferred.

The following site selection factors were included into the rating system: slope, depth to groundwater, soil pH, soil depth, soil type and distance between plant and site. These factors were divided into two to four suitability categories and each category was assigned a rating value. This was done using the reclassification option in ArcGIS. Numeric values from 0 to 9 were used as rating factors. A rating factor of 0 was assigned to classes that are only suitable under certain conditions. For example, a steep slope can be used for forestry but should not be used for agriculture. The values were assigned in unequal steps to allow for the non-linearity of the factors regarding the site suitability. Furthermore, the site selection factors have different significance with respect to their influence on the overall suitability of a specific site. Therefore, the numerical system could also be used to include a weighting of the different factors. Table 4.1 shows the rating factors, which were in most instances assigned according to USEPA (1981) and Reed et al. (1988).

Table 4.2: Rating factors for site selection

Slope [%]	Class	0 - 5	5 - 10	10 - 15	15 - 35
	Rating	8	6	4	0
Groundwater [m]	Class	> 3	3 - 1.2	1.2 - 1	
	Rating	6	4	0	
Soil ph [-]	Class	8.3 - 6.5	6.4 - 5.8	5.7 - 5.5	
	Rating	5	3	1	
Soil depth [m]	Class	1.5 - 1.2	1.2 - 0.9	0.9 - 0.6	
	Rating	9	8	3	
Soil type	Class	Sandy loam to silty clay loam			Clay loam
	Rating	8			3
Distance [km]	Class	0 - 8	8 - 16	16 - 24	> 24
	Rating	6	3	1	0

Using the GIS, all rating values were summed up on a cell-by-cell basis, which classified the identified candidate areas into overall suitability categories. The overall rating values range between 7, which indicates a very low suitability, and 42, which indicates a very high suitability.

5 Results

The GIS analysis resulted in the identification of candidate areas that are suitable for land application of wastewater. These candidate areas were further investigated and four potential sites were identified and classified. In the following subsections, the location and rating of areas suitable for wastewater application are described.

5.1 Candidate Areas

The overlay of the suitability factors resulted in a grid layer, where all unsuitable cells were masked off as *nodata*. The cells that contained values represented areas suitable for land application of wastewater. These candidate areas are illustrated in figure 5.1.

Most of the candidate areas are located on the Canterbury Plains, particularly near the coast. The western part of the study area, namely the Southern Alps and their foothills, is in general not suitable for wastewater land application due to the high elevation, steep slopes and unsuitable soil pH values.

Generally, a high fragmentation of suitable areas can be identified, which is a result of the large number of suitability factors that were combined and the relatively large area of buffer zones that had to be accounted for. The fragmentation results in problems in establishing a land application system in practice, since a high number of single divisions are more difficult and expensive to operate. Furthermore, several single divisions are more cumbersome to purchase.

In total, 147,547 ha, which corresponds to about 14.3% of the total study area, are suitable for wastewater land disposal. Soil depth was the factor that resulted in the exclusion of most raster cells. About 56% of the total area is unsuitable due to insufficient soil depth. In this context it must be noted that the soil attribute 'potential rooting depth' was used to analyse the soil depth. However, this is only an approximation of the soil depth and, thus, more exact results could be achieved by including measures of the actual soil depth into the analysis. Furthermore, the data used were from a relatively general soil survey. Therefore, more exact data could possibly alter the results.

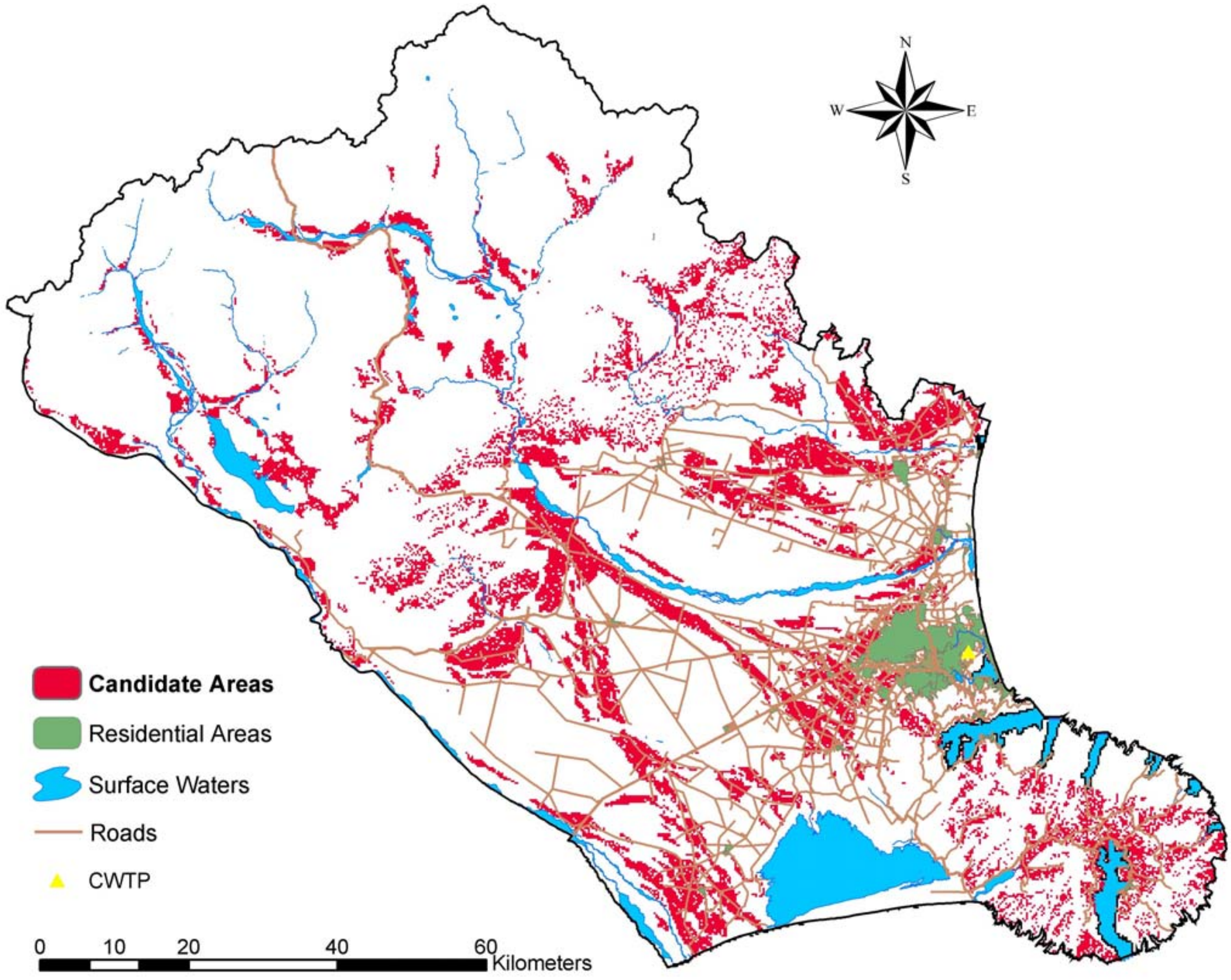

Figure 5.1: Candidate areas

Beside the soil depth, slope and soil pH were the other two most critical factors for the site suitability. Unsuitable slopes resulted in the exclusion of about 36% of the study area particularly in the West and on Banks Peninsula. The soil pH resulted in 31% of the study area being unsuitable for wastewater land application. In general soil type, land use and distance to groundwater were of little influence. However, the latter one was found to be very critical in the East, where high groundwater levels prohibit the wastewater land application. This resulted in the exclusion of large areas close to the treatment plant, which would be preferable from an economic point of view. However, since the interpolation of historical well data was only an approximate estimation of the groundwater level, particularly because some of the aquifers are confined, it is expected that the use of another groundwater layer for the analysis could produce more exact results.

The addition of all layers containing rating factors resulted in a layer showing the overall suitability of all candidate areas. Figure 5.2 illustrates the overall suitability rating of the candidate areas. Theoretically, the rating values could range from 7 to 42, but the analysis showed that the overall rating in the study area varied between 12 and 37. The mean rating of all candidate areas was 26. The best overall rating was achieved particularly in the East along the coast and on the Plains. The candidate areas on Banks Peninsula and on the foothills of the Southern Alps have a rather low overall suitability.

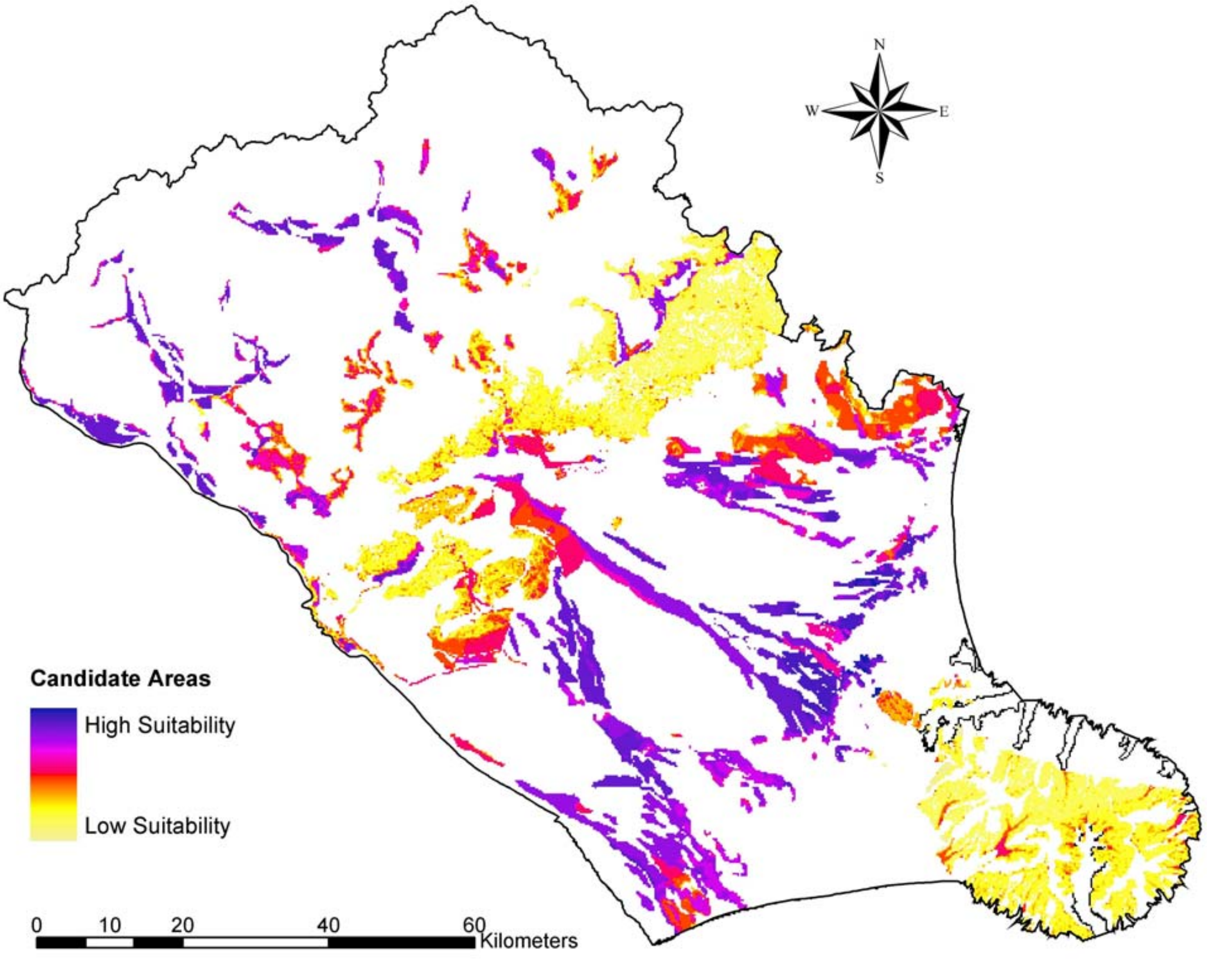

Figure 5.2: Overall rating of candidate areas

5.2 Potential Sites

Based on the identified candidate areas, potential sites that complied with the area requirement of 16,000 ha were selected. In the following subsections an overview is given of the identification of the potential sites and their assessment.

5.2.1 Identification of Potential Sites

The site screening process usually requires having a number of potential sites to provide for the "adequate consideration of alternative" sites as stated in the Resource Management Act and to allow for the later disregard of some sites once more detailed information is obtained (Robb et al., 2000). Therefore, four different sites were identified from within the candidate land areas. For this, the layer containing the candidate areas as raster cells was converted into the vector format. Since no single polygon was large enough to represent a suitable site, all sites had to be made up of several areas or polygons. For each site a number of polygons was manually selected on-screen and assigned a common site number. This was done by adding a new field to the attribute table. The selection process continued until the size of each site was about the area requirement of 16,000 ha. The identified sites were afterwards converted back into the raster format.

The main criterion for assigning a particular polygon to one site was its location. Overall suitability rating was also considered to be a selection criterion. However, because of its great variability it could only provide some additional assistance to the manual selection process, but could not be used as main criterion. It was tried to select only reasonably sized polygons or polygons only in immediate vicinity to others, in order to avoid small-sized parcels, which are generally difficult to operate. It must be noted that more than four potential sites could have been identified. However, the candidate areas on Banks Peninsula and in the West of the study area showed a relatively low overall suitability and a high fragmentation. Therefore, only four sites, which was considered to be an adequate number, were used for the screening process. The identified sites are illustrated in figure 5.3.

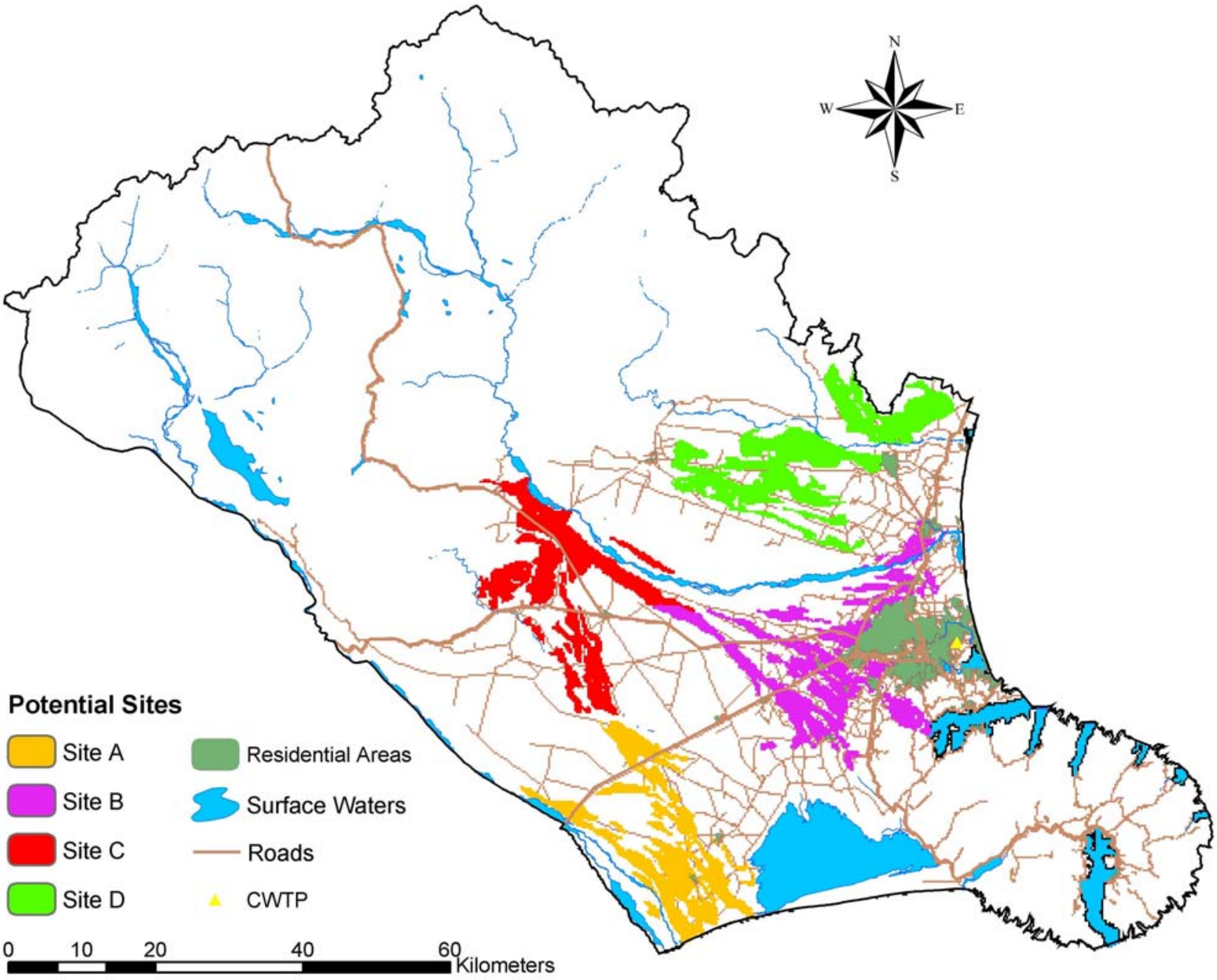

Figure 5.3: Potential sites

5.2.2 Assessment of Potential Sites

Generally, as a result of the large area required the individual sites are very disjointed and spread out. For example, regarding site B the East-West and North-South extent is about 40 km and 33 km respectively. The extent of the other sites is also in the dimension of about 30 km. The gaps within a site occasionally amount to up to 2 km. These site characteristics are rather unfavourable for a large-scale land application scheme in terms of costs and ease of implementation.

The grid functions *zonalstats* and *zonalstd* were used to assess the potential sites with respect to their suitability. Using the identified sites and their assigned numbers as zonal identifiers and the rating grid as value grid, the functions calculated the mean rating, the standard deviation and the range of rating values within each site (see table 5.1). The lower the rating value, the less suitable is a site.

Table 5.1: Overall rating values for each site

Site	Mean rating	Standard deviation	Min rating	Max rating	Size [ha]
A	**31**	2.87	20	34	15,500
B	**32**	3.57	19	37	16,700
C	**28**	5.32	12	34	16,200
D	**27**	4.48	12	35	20,100

Site B shows the highest mean rating and has the advantage of having a relatively high minimum rating. This means site B has a low overall risk of technical failure and environmental pollution and would be most suited to a land application system. In addition, the average of every suitability rating factor was calculated for each site. Table 5.2 shows that considering the distance between site and plant site B is the only acceptable site. Site D has the lowest rating of all four sites with respect to every investigated factor. All in all, however, the differences in the single factors are not very significant for the four sites. The average ratings for soil pH and distance to plant are rather low for all sites, whereas the other factors are in a satisfactory span.

Table 5.2: Average rating factors for each site

Site	Soil type	Soil pH	Soil depth	Ground water	Distance	Slope
A	8.0	1.6	8.2	5.1	0	8
B	8.0	2.2	8.0	5.4	1.2	7.6
C	8.0	1.6	5.8	5.6	0	6.9
D	7.8	1.6	5.3	4.7	0	7.6

Figures 5.3 to 5.6 show the four different sites with their overall suitability rating in detail. As indicated in table 5.1 and table 5.2, sites B and A are the most favourable sites, since they have the best overall ratings and the most homogenous range of rating. In contrast, site C and D show a very high variability of rating values and a lower suitability concerning most of the rating factors.

On the whole, it can be concluded that all sites have a satisfying overall suitability, but have the drawback of being located far away from the treatment plant. The great distance between plant and site can result in high operational costs for pumping the effluent to the site. Since the overall differences between the sites are not very significant, it is recommended that for the final site selection field investigations and other criteria such as land prices are considered in addition to the suitability rating.

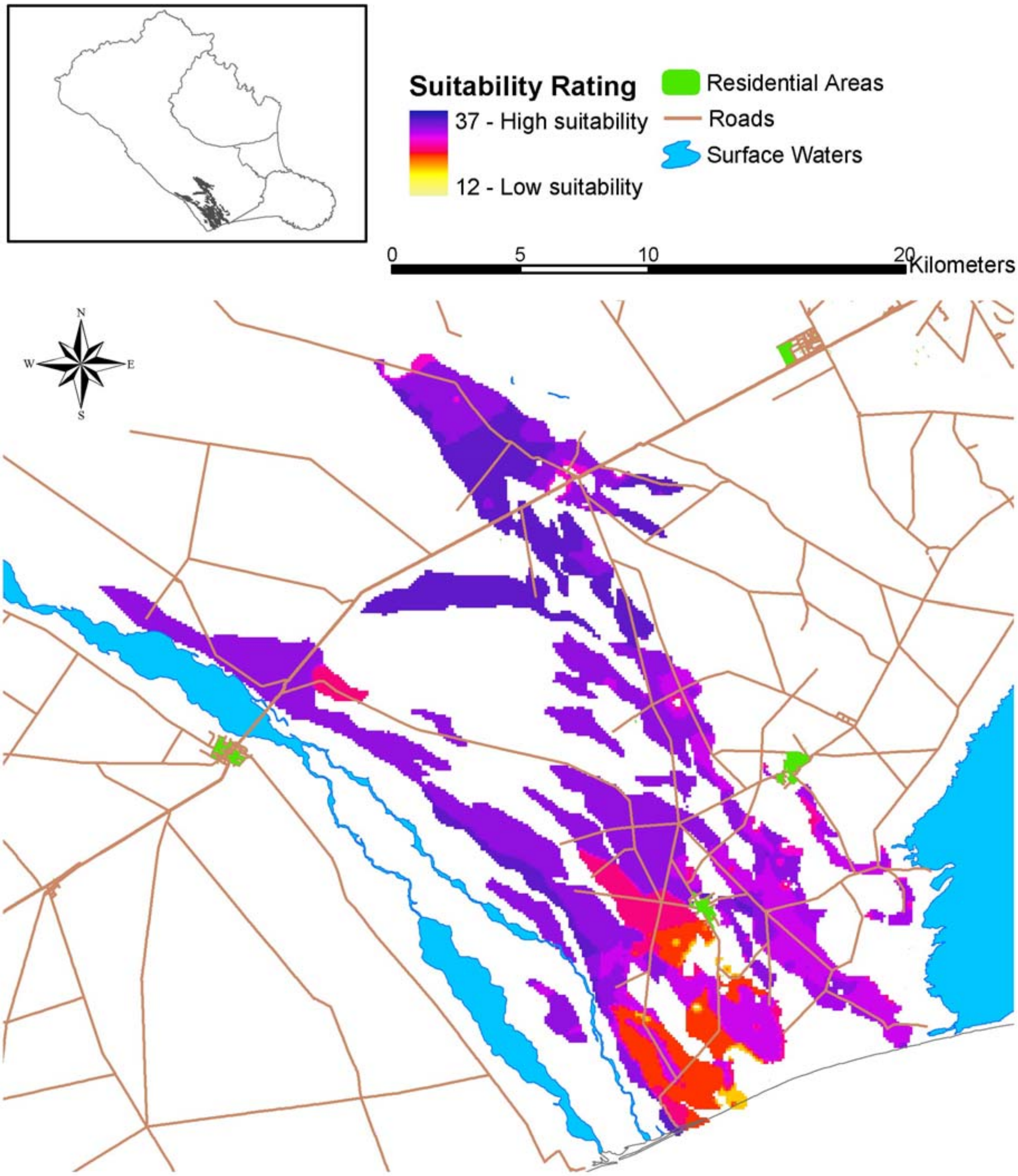

Figure 5.3: Site A

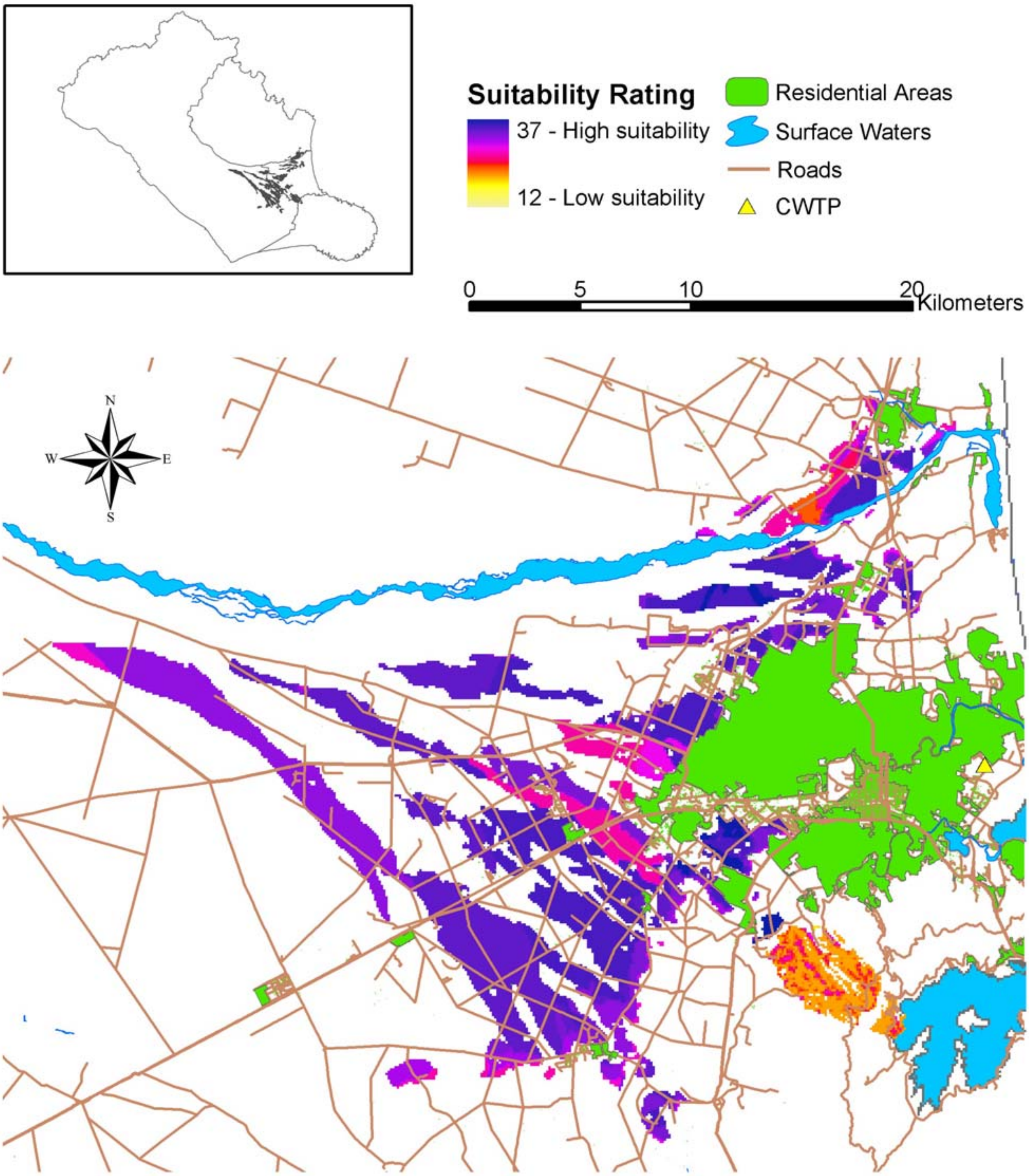

Figure 5.4: Site B

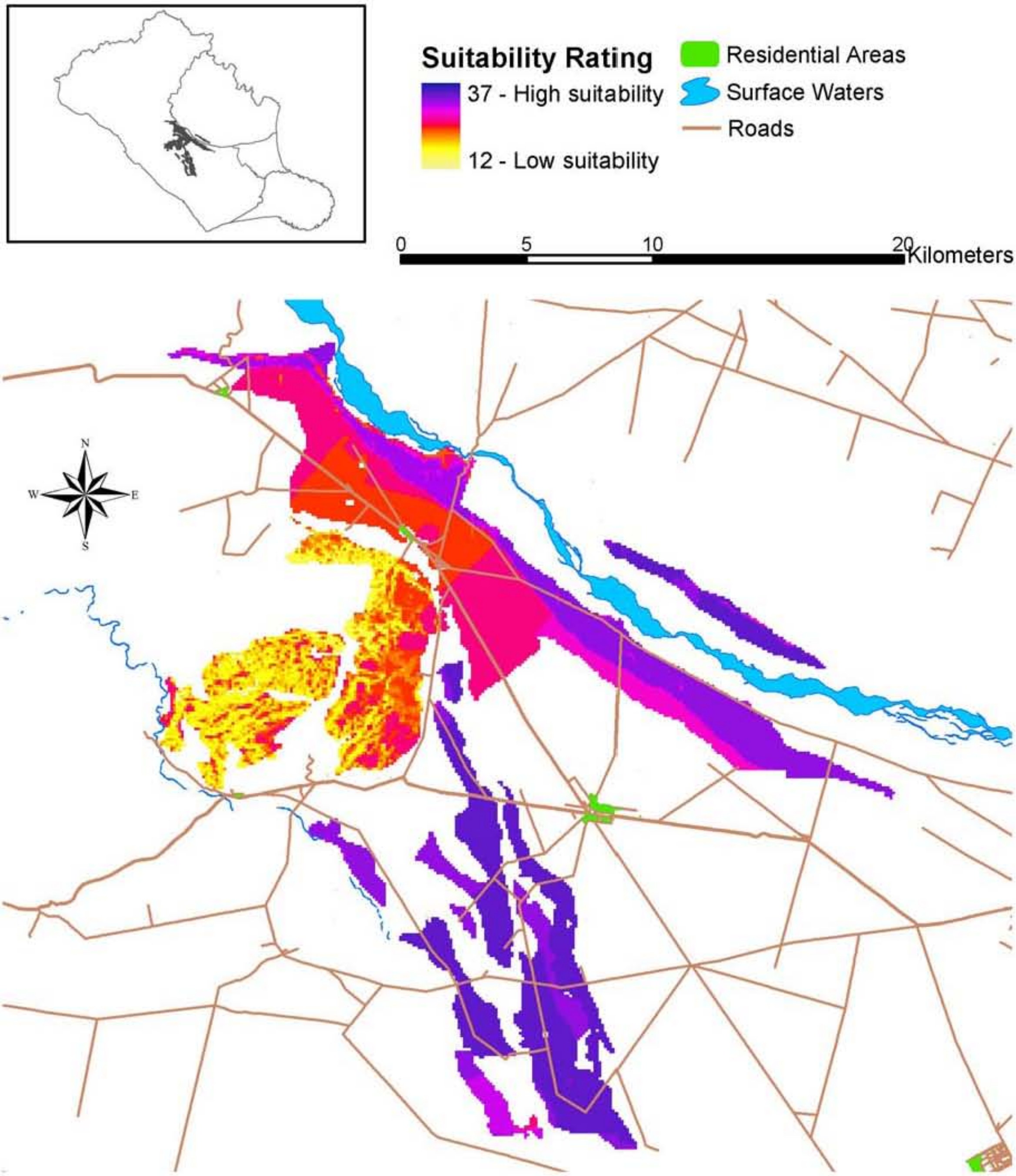

Figure 5.5: Site C

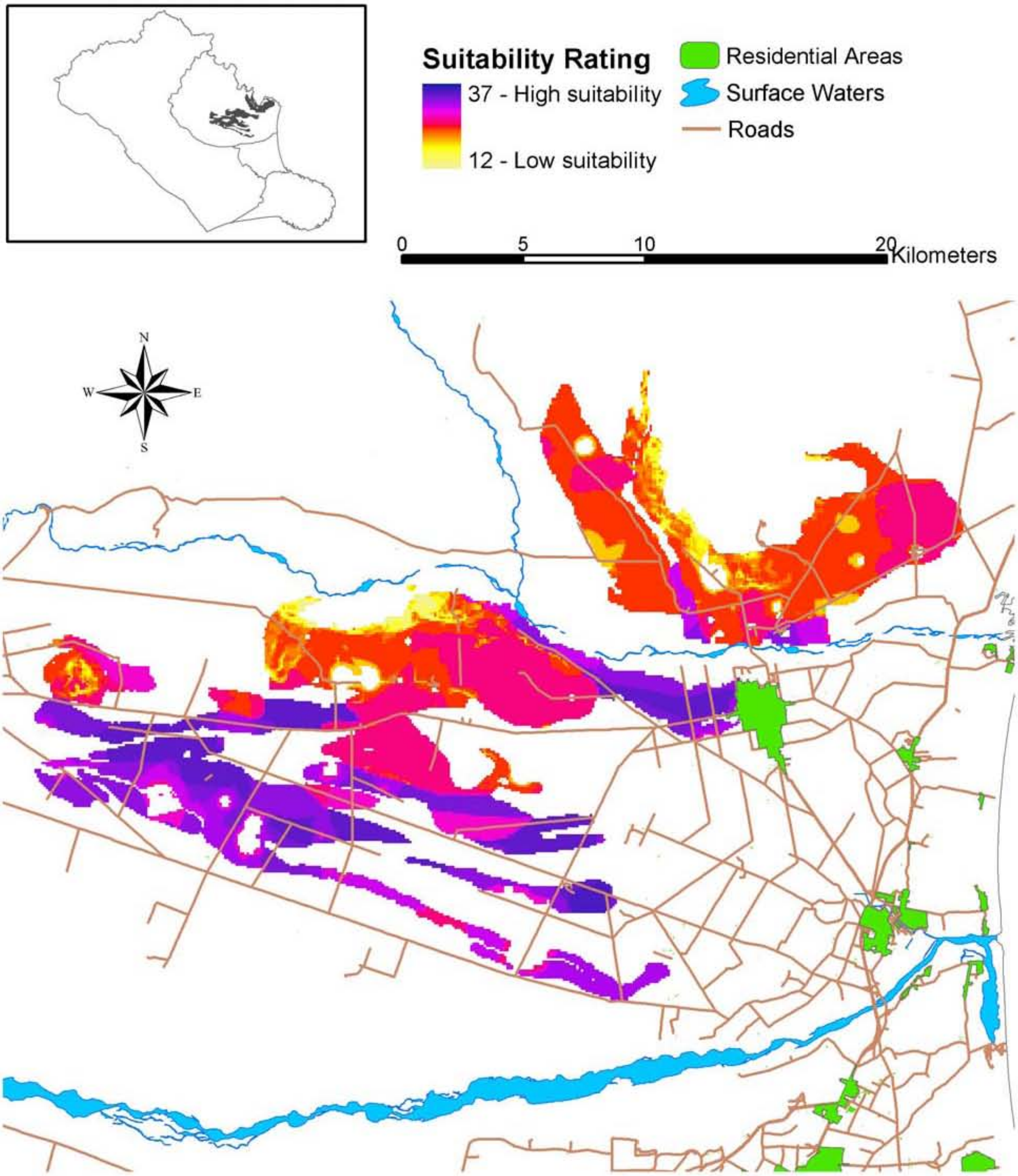

Figure 5.6: Site D

6 Conclusion

The site selection is a crucial step when planning a wastewater land application scheme. An appropriate site selection ensures the technical and economic feasibility of such a scheme and helps reduce environmental risks and impacts. The present study aimed at identifying potential sites for the effluent land application of the Christchurch City Wastewater Treatment Plant. The analysis was carried out using a GIS and included the area of Christchurch City and its three adjacent districts; Waimakariri, Selwyn and Banks Peninsula. Given the characteristics of this area it was decided that a slow rate system would be most appropriate. The calculation of the allowable wastewater loading based on the hydraulic loading as well as the nitrogen loading resulted in an area of 16,000 ha that would be required for applying the daily effluent of 163,000 m^3 onto land.

To ensure technical feasibility, environmental sustainability, social acceptability and economic viability a number of factors had to be considered for the site selection. These include slope, climate, soil type, soil pH, soil depth, land use, distance to groundwater and surface waters and distance to dwellings. Raster layers of these factors were overlaid in the GIS, which resulted in the elimination of all areas unsuitable for land application and, thus, the identification of candidate areas. A map was created showing these candidate areas in the study area. It was found that in total 147,547 ha, which corresponds to 14.3% of the study area, are suitable. Most of the candidate areas are located on the Canterbury Plains, particularly near the coast, whereas the western part of the study area is in general not suitable. The candidate areas are in most cases very disjointed. This is a drawback for a large land application scheme as the present case study. However, the digital layer of the candidate areas can also be useful for the site selection of small-scale land application schemes within the four districts.

For the case study, four potential sites each having a size greater than 16,000 ha were identified from the candidate areas. A rating system using numeric values was used to assess and screen the candidate areas and the potential sites. The rating was based on five of the suitability factors (slope, soil pH, soil type, soil depth and distance to groundwater) plus the distance between site and plant. The average rating of the four potential sites was 30, which indicates a medium suitability considering a rating range from 7 to 42. The main factor degrading the suitability of the sites was their great distance to the treatment plant. Only one of the four sites had an acceptable distance.

Beside the distance from the plant, the overall suitability of the selected four potential sites differed not significantly. Thus, it is recommended that all four sites will be evaluated in more detail to allow for the consideration of additional factors like land prices before a final decision will be made.

Using a GIS for the identification of candidate areas and potential sites proofed to be very efficient, particularly with respect to the great size of the study area and the large number of factors that had to be combined. The produced digital layers can be used not only for the case study, but can also provide a means of facilitating the site selection of smaller land application schemes. Furthermore, the cell-based rating scheme was easy to implement and very helpful in assessing and screening the potential sites. The GIS analysis could now be altered without problems, if changes in the suitability criteria or the rating factors should be required.

However, the quality of the available digital data affected the results of the present analysis. The interpolation of well data was a rather inaccurate way to obtain information about the groundwater level. This was because of the irregular distribution of the wells and because some well data appeared to represent piezometric heights rather than actual water levels below the surface. In addition, the soil depth was only approximated by the potential rooting depth. Therefore, more exact layers containing the groundwater level in the study area and more accurate information about the soil depth could improve the analysis. Further possible amendments might be the more comprehensive consideration of economic and social factors, for example, through the inclusion of culturally significant sites (e.g., waahi tapu) and the elevation difference (relief) between site and plant into the analysis. Since waahi tapu sites could not be included in this study due to the lack of an appropriate digital layer, comprehensive consultation with Tangata Whenua is required regarding the identified potential sites. The inclusion of the relief could provide a more detailed economic assessment of the alternatives. In addition, the economic evaluation could be further improved by including estimations of potential revenues depending on site characteristics and location.

The illustrated identification of potential sites represents the first phase of the planning procedure of a wastewater application scheme. The second phase generally includes field investigations and a more detailed evaluation of the alternatives before the final site selection is made and the design of the system is carried out (see USEPA, 1981). Field investigations are required to verify the data used during the site identification process. For example, soil surveys are necessary to confirm the LRI data and determine further parameters, like the drainage characteristics, which influence the feasibility and success of wastewater application on land. Groundwater surveys need to be undertaken to provide information about direction and rate of flow of aquifers as well as the existent water quality. This helps assess the risk of groundwater contamination. In order to further evaluate the potential sites, ownership and property values need to be considered. For this, the use of the GIS can again prove to be very efficient. An overlay of the selected potential sites with a digital layer containing property data facilitates the identification of the owners of the selected areas and, thus, the acquisition of the required land.

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Appendix A: Calculation of Allowable Hydraulic Loading

Source of ET and P: Garnier, 1958

W_p = min. hydraulic conductivity * 24 (h/d) * 0.05 * no. of operating days/month

with: min. hydraulic conductivity = 5 mm/h

Christchurch

Month	ET (mm)	P (mm)	W_P (mm)	L_{WW} (mm)
Jan	99	56.6	186	228.4
Feb	83	45.7	168	205.3
Mar	70	49.3	186	206.7
Apr	48	47.0	180	181.0
May	30	72.4	186	143.6
Jun	19	65.8	180	133.2
Jul	18	66.0	186	138.0
Aug	24	52.1	186	157.9
Sep	39	52.3	180	166.7
Oct	60	49.5	186	196.5
Nov	76	46.2	180	209.8
Dec	95	64.5	186	216.5
Annual	**661**	**667.5**	**2190**	**2183.5**

Darfield

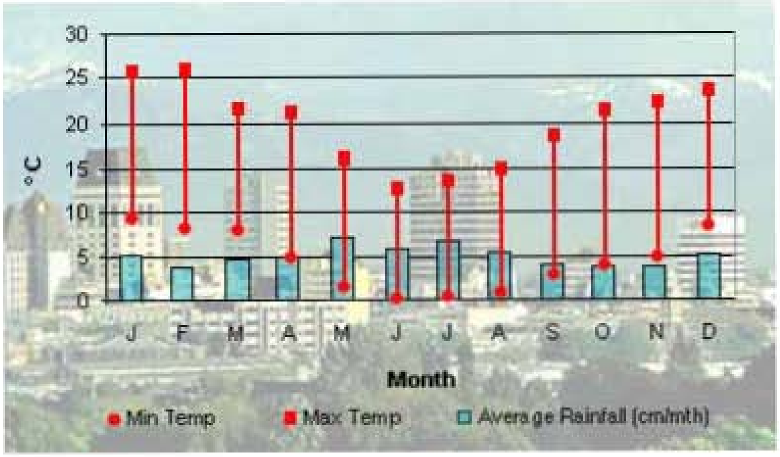
Month	ET (mm)	P (mm)	W_P (mm)	L_{WW} (mm)
Jan	98	70.6	186	213.4
Feb	80	64.3	168	183.7
Mar	70	51.8	186	204.2
Apr	48	58.2	180	169.8
May	29	76.5	186	138.5
Jun	17	88.6	180	108.4
Jul	16	55.1	186	146.9
Aug	24	62.7	186	147.3
Sep	37	70.1	180	146.9
Oct	59	68.3	186	176.7
Nov	73	61.7	180	191.3
Dec	92	72.4	186	205.6
Annual	**643**	**800.4**	**2190**	**2032.6**

Akaroa

Month	ET (mm)	P (mm)	W_P (mm)	L_{WW} (mm)
Jan	99	58.9	186	226.1
Feb	79	62.7	168	184.3
Mar	72	67.3	186	190.7
Apr	52	68.6	180	163.4
May	33	110.0	186	109.0
Jun	22	117.6	180	84.4
Jul	25	121.4	186	89.6
Aug	27	101.1	186	111.9
Sep	40	83.3	180	136.7
Oct	59	62.0	186	183.0
Nov	72	57.9	180	194.1
Dec	92	68.6	186	209.4
Annual	**672**	**979.4**	**2190**	**1882.6**

Appendix B: Weather Chart of Christchurch

Source: The Canterbury Pages, 2003



Appendix C: Suitable Soil Types as Listed in the LRI

Clay loam, deep fine sandy loam on sand, deep fine sandy loam, deep sandy loam and silt loam, deep silt loam on sand, deep silt loam, deep soils, gravelly sandy loam, gravelly silt loam, hill soils, loam, moderate deep clay loam, moderate deep fine sandy loam, moderate deep sandy loam, moderate deep silt loam, sandy loam on silt loam, sandy loam, shallow sandy loam, shallow silt loam, silt loam and fine sandy loam, silt loam and gravelly loam, silt loam, soils, steepland soils, stony and shallow silt loam, stony and very stony silt loam, stony fine sandy loam, stony loam and sandy loam, stony sandy loam, stony silt loam, very gravelly sandy loam.