Waituna Catchment

Water Quality Review

Report 1051-3-R1

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Lincoln Agritech Ltd

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EXECUTIVE SUMMARY

The Waituna catchment in coastal Southland flows into Waituna Lagoon, a brackish lagoon and wetland complex that falls within the category of Intermittently Closed & Open Lagoon or Lake (ICOLL) coastal water bodies. In recent years, the lagoon has undergone rapid deterioration in water quality and ecological health. The lagoon is already eutrophic, and is tending towards a sudden loss of original benthic macrophyte coverage (dominated by *Ruppia sp.*), which could lead to the lagoon having undesirable turbid, murky water dominated by algal slime. One of the causative factors attributed to the eutrophication process is the contribution of freshwater inflows of nitrogen, phosphorus and suspended sediment from farming activities in the Waituna catchment. These nutrients are transported to Waituna Lagoon by surface and sub-surface flow paths, including the catchment creek network.

Land use in the Waituna catchment is predominantly high productivity improved pasture that has been established by a long-term process of land clearance and drainage of formerly scrub-covered land and wetlands. Relevant to the effects of this land use change process on water quality, is that high productivity pasture generates higher nutrient and sediment losses than the original native vegetation. The creek network in the Waituna catchment drains entirely into Waituna Lagoon, which is blocked from outflow to the sea for the majority of the time by a barrier spit. Consequently, a large proportion of these contaminants can become trapped in lagoon water column, sediments and biomass.

The Waituna catchment comprises the following sub-catchments:

- Waituna Creek;
- Moffat Creek;
- Carran Creek;
- Craws Creek;
- Lagoon margins catchment.

In addition to the surface water network, water also flows to the lagoon via the shallow gravel aquifer and to a lesser extent the deeper Gore Lignite Measures multi-layer groundwater system. We found limited evidence from existing lignite mining and groundwater studies to suggest that there is significant interchange between the lignite measures groundwater system and surface waters that would influence the lagoon's nutrient loading. However, the shallow gravel aquifer in the upper and mid catchment zones show evidence of dynamic transfer of nitrate nitrogen from oxidised brown (Waikiwi) soil series with high leaching potential, through the shallow aquifer. This nitrate-enriched groundwater augments Waituna Creek flow immediately downstream of the Mokotua settlement, particularly from the early winter period.

We have examined the Mokotua Infiltration Zone (MIZ) concept which was proposed in the most recent groundwater technical report on the Waituna catchment (Rissmann, et al., 2012). The occurrence of nitrate-enriched base-flow in Waituna Creek has been confirmed by a subsequent Surface Water Quality Study of surface water composition. However, our evaluation of the mechanisms for nitrate nitrogen infiltrating to groundwater, seeping into creek water, and the timing of these processes, differ from those of the original MIZ concept. There is evidence that areas of the Waikiwi soil type in the upper Waituna Creek catchment, upstream of the Mokotua settlement, are associated with the infiltration of significant loads of nitrogen to the shallow aquifer. Nitrogen appears to accumulate in the soil profile and shallow aquifer over the drier, warmer months when potential evapotranspiration is high, and soil drainage is low. We predict that up to 90% of the annual nitrate nitrogen mass load may be flushed into Waituna Creek during late autumn to early winter. The soils are vulnerable to rainfall-driven leaching events at this time because of lowering evapotranspiration rates and soil nitrogen uptake. We estimate that area-based nitrogen loadings of 42 to 64 kgN/ha mobilised from the Waikiwi soils upstream of the Mokotua settlement during this time, and are discharged to Waituna Creek over a 1 to 2 month period. Once the stored nitrate nitrogen in soil and shallow groundwater is exhausted by winter flushing, subsequent winter and spring soil leaching events contain low nitrogen loads.

A contrasting set of geochemical processes applies elsewhere in the Waituna catchment, associated with large areas of podzols, gley, and organic soils. The soils form anoxic conditions in shallow groundwater where oxygen reduction occurs, including the denitrification of Dissolved Inorganic Nitrogen such as nitrate. Anoxic, or reduced, groundwater geochemistry also leads to a decline in the phosphorus buffering capacity of soils due to the release of oxidised iron (Fe^{3+}) and a subsequent reduction in phosphorus adsorption. Accordingly, nitrate nitrogen concentrations are very low in areas of reducing soils, while dissolved phosphorus may rise to concentrations not usually observed in oxic groundwater.

We have also assessed the catchment boundaries assigned by Environment Southland on the basis of land surface gradient. It appears that the actual contributing areas of different sub-catchments are difficult to clearly define because of the following tendencies:

- Manipulation of drain base slopes can produce an artificial drainage pattern different to the drainage patterns implied by land surface slope;
- Catchment flow divides are quite unclear where they cross peat wetlands, such the Waituna catchment adjoining the Awarua Wetland complex;
- Shallow groundwater in the north of the upper Waituna Creek has a flow gradient that may flow beneath the surface water divide with the Waihopai catchment.

In the latter case, the presence of significant areas of Waikiwi soils in the Waihopai catchment may enable additional nitrate nitrogen to contribute to Waituna Creek base-flow *via* the shallow aquifer. A similar, but potentially less significant, inflation in Carran Creek headwaters' nitrogen load may also occur.

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1 INTRODUCTION

1.1 BACKGROUND

Waituna Lagoon is an Intermittently Closed & Open Lake or Lagoon (ICOLL) with degraded water quality. A changing aquatic ecological condition and an increasingly eutrophic nutrient status are threatening a rapid change in its trophic state. The dendritic network of creeks upstream of Waituna Lagoon is a dominating influence on the supply of nutrient, water clarity and microbial load entering the lagoon. The coastal discharge point of the lagoon is intermittently closed for extended periods. Consequently, the lagoon hydrology has limited ability to flush the water column or contaminants deposited within lagoon sediments.

The Lagoon Technical Group[1] (2011) called for a 75% reduction in nitrogen and 50% reduction in phosphorus loading from the upstream catchment. The intention of these proposed reductions were to avoid further deterioration of Waituna Lagoon, and support healthy macrophyte and fish communities. Nutrient loadings entering the lagoon are, to some extent, related to the intensity of pastoral land use and farm management practices predominating within the upstream agricultural land. A more nuanced understanding of the mechanisms controlling and areas of principal nutrient transfer will enable targeted application of management actions to be implemented.

The “Mokotua Infiltration Zone” (MIZ) is a concept that was first introduced in a groundwater technical report that examined the role of groundwater in transferring inputs of contaminants to Waituna Lagoon (Rissmann et al., 2012). The proposed MIZ was defined as being associated with highly permeable marine terrace deposits. These sediments were considered to receive and conduct high nitrate nitrogen water from agricultural activities rapidly into the creek network *via* the shallow aquifer.

In order to increase the understanding of the active processes, Environment Southland undertook, commissioned, and encouraged follow-up investigations. These included a catchment-wide surface water sampling programme (Surface Water Quality Study), geophysical survey, and calculation of mass loads. The investigation effort subsequent to 2011-2012 was not integrated and reviewed in a manner that allowed the MIZ concept to be re-examined, while the subject had arisen in recent dairy conversion resource consent hearings (e.g. Milk Power Limited application number APL-20147087).There is also the future prospect of land use control centred on the MIZ as a protection area. Accordingly, Environment Southland commissioned a scientific review process, which forms the basis of this report.

[1]The role of the Lagoon Technical Group was to provide expert scientific advice to Environment Southland on lagoon and water quality science for the short-term Waituna Response Project which ended mid-2013.

1.2 STUDY OBJECTIVES

The following objectives are referenced in undertaking this investigation and review:

1. To review previous relevant technical/scientific reports and publications on the Waituna catchment, and identify the critical aspects relating to groundwater, surface water and the transport of nutrients to Waituna Lagoon.
2. To examine and test the current scientific concepts of water balance, hydro-chemistry, catchment hydrology and spatial generation of nutrient loads in terms of the most likely transport mechanisms.

1.3 SCOPE & NATURE OF THE REVIEW

This review is intended to update and extend similar work reported in 2012 by Clint Rissmann, Karen Wilson and Brydon Hughes (Rissmann et al., 2012) by incorporating knowledge generated from the "Surface Water Quality Study". Our assessment is that the need for critical review lies in the question of the status and mechanism of the Mokotua Infiltration Zone. Furthermore, in the brown soils of the upper catchment the principal nutrient of concern for lagoon eutrophication is nitrate nitrogen. Phosphorus is definitely a concern for the nutrient status of the lagoon; however the transfer of phosphorus is dominated by sediment entrainment and surface runoff transfers rather than sub-surface bypass to waterways involving shallow groundwater. Nitrate nitrogen is a more recalcitrant nutrient in terms of its ability to bypass surface water control measures and the small list of effective options for limiting its discharge into the aquatic environment. For these reasons, the review authors have elected to concentrate on the hydrological and hydro-chemical processes active in the upper catchment, and those factors pertinent to future controls on nitrate nitrogen loading to water.

Figure 1 Orientation map (adapted from National Wetland Trust)

http://www.wetlandtrust.org.nz/Site/Ramsar_Convention/Awarua_Waituna_Lagoon.ashx

2 CATCHMENT INTRODUCTION

2.1 LOCATION

The Waituna Lagoon is located on the south coast to the east of Invercargill. Environment Southland has delineated a catchment boundary of the lagoon. Five sub-catchments within the wider Waituna catchment have also been identified (Figure 2, adapted from Rissmann et al., 2012):

- Waituna Creek;
- Moffat Creek;
- Carran Creek;
- Craws Creek;
- Lagoon margins catchment.

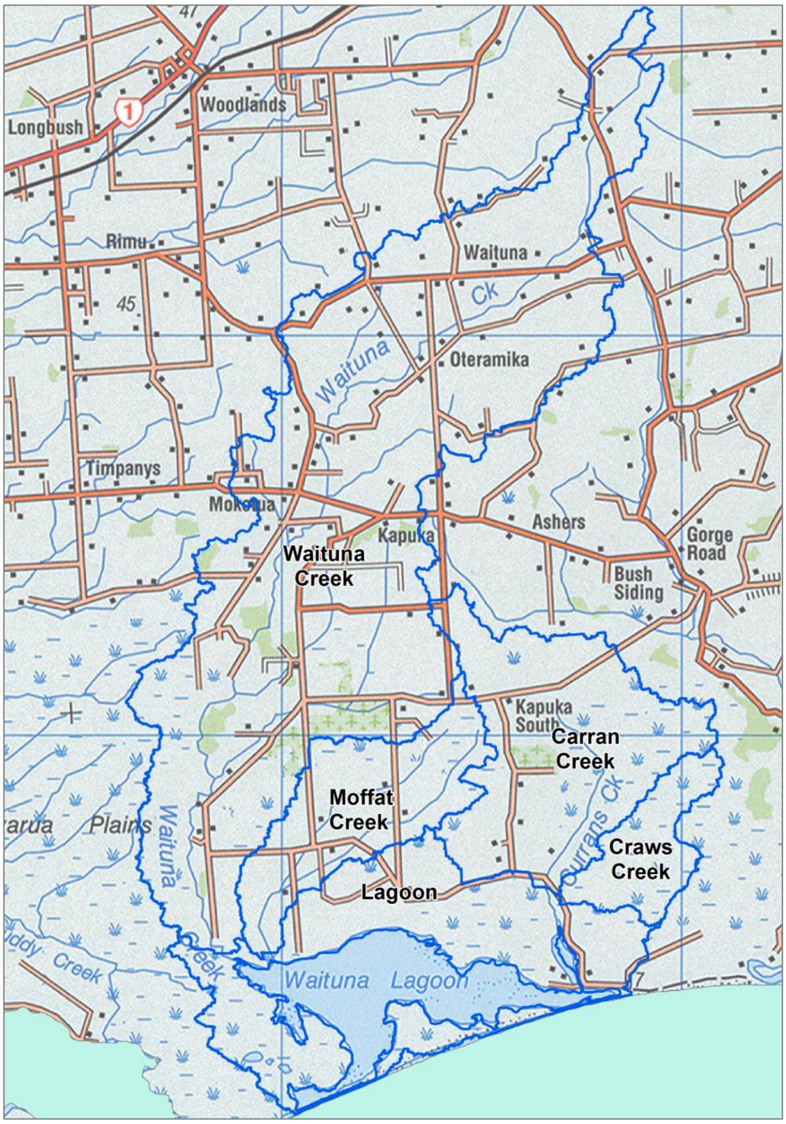

Figure 2 Waituna Lagoon, wider catchment and sub-catchments

2.2 TOPOGRAPHY

The topography of the Waituna catchment is very subdued. Its elevation ranges from 69m in the far north of the catchment down to sea level in the south, over a linear distance of 27.5 km. Within this range there are some clear topographic features which are manifest as distinct breaks in slope on an otherwise subdued terrain. These changes in slope (we'll call them "escarpments" for want of a better term) can be discerned from slope maps derived from DEM data, and are identified in Figure 3.

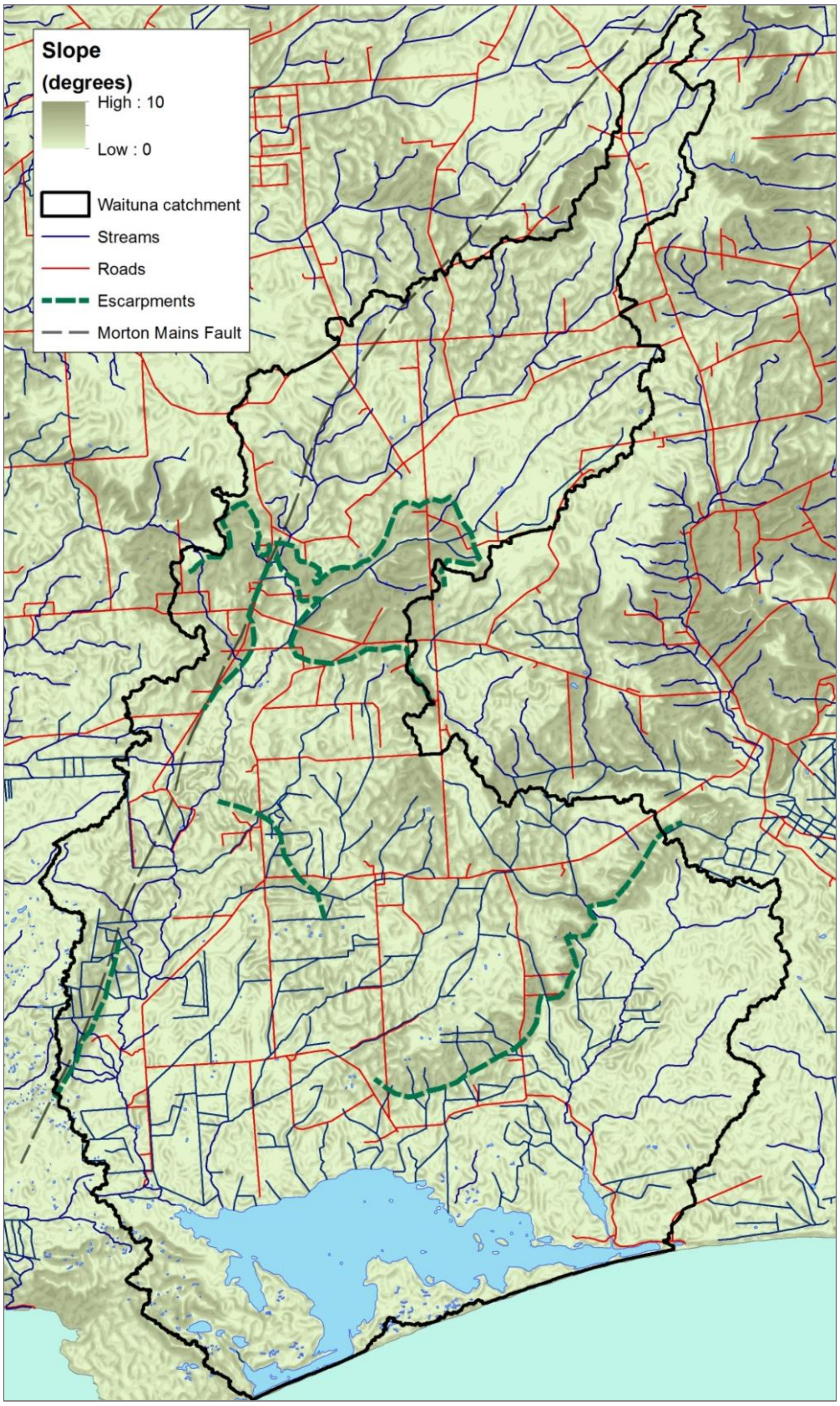

Figure 3 Map of topographic slope with surface features

Two of the escarpments align with the Morton Mains Fault, which is shown on the QMap geology (Turnbull & Allibone, 2003), and can be traced through the western part of the catchment. An area of increased slope is also evident in the Mokotua area where the catchment pinches to its tightest point. This pinching may be related to recent reactivation of old west-northwest trending faults. This escarpment creates a vertical offset of approximately 10 m between the main upper and lower terrace surfaces on mid-Quaternary gravels that are found in the Waituna Creek catchment.

A third prominent feature can be seen near Kapuka South trending northeast. This feature, and reactivation of the Morton Mains fault, both post-date a 70-130,000 years Before Present (BP) paleo-shoreline along the northern edge of the peat flats. This shoreline was identified by Turnbull & Allibone (2003) and recognised as having an important hydrological influence by Rissmann et al (2012).

2.3 CLIMATE

Rainfall and recharge values for the Southland region were calculated by Wilson *et al.* (2014). The area weighted median rainfall for the Waituna catchment is 1,045 mm/year. Annual rainfall within the catchment ranges spatially from 960 to 1,190 mm (in the period 1 July 1991 to 1 March 2013), and is predicted to be slightly higher in the eastern part of the catchment, which is closer to the Forest Hills. The calculated soil drainage is 280mm/year for the catchment as a whole, which is 27% of rainfall, and approximatively the annual rate of base-flow in the catchment's creeks.

Rainfall is fairly evenly distributed throughout the year, but is slightly lower during the winter to spring period. Rainfall events, including higher intensity rainfall events that promote runoff are more common during the spring and summer period.

Daily Potential Evapotranspiration (PET) is also highest during summer (4 mm) and lowest during winter (0.4 mm). The very low winter PET results in soil moisture levels that are close to saturation during July to September for most soils in the catchment.

In summary, the climate in the Waituna catchment promotes soil drainage to the water table or fixed artificial drainage during winter, when PET is lowest. The catchment is more prone to surface runoff during high intensity rainfall events that occur during the summer period.

2.4 LAND USE PATTERNS

The spatial distribution of land use in 2012 is shown in Figure 4 Land use for 2012 (Source: LCDB 4.1 database)

. The most widespread land use within the Waituna catchment is high production pasture (63%), followed by herbaceous freshwater vegetation associated with peatlands (15.3%).

Land use has been quite stable in the catchment since 1996. The LCDB 4.1 database shows a shift from 62% to 63% high production grassland from 1996 to 2012. This change was accompanied by a small increase in low production grassland and a small decrease in freshwater vegetation, gorse and Manuka.

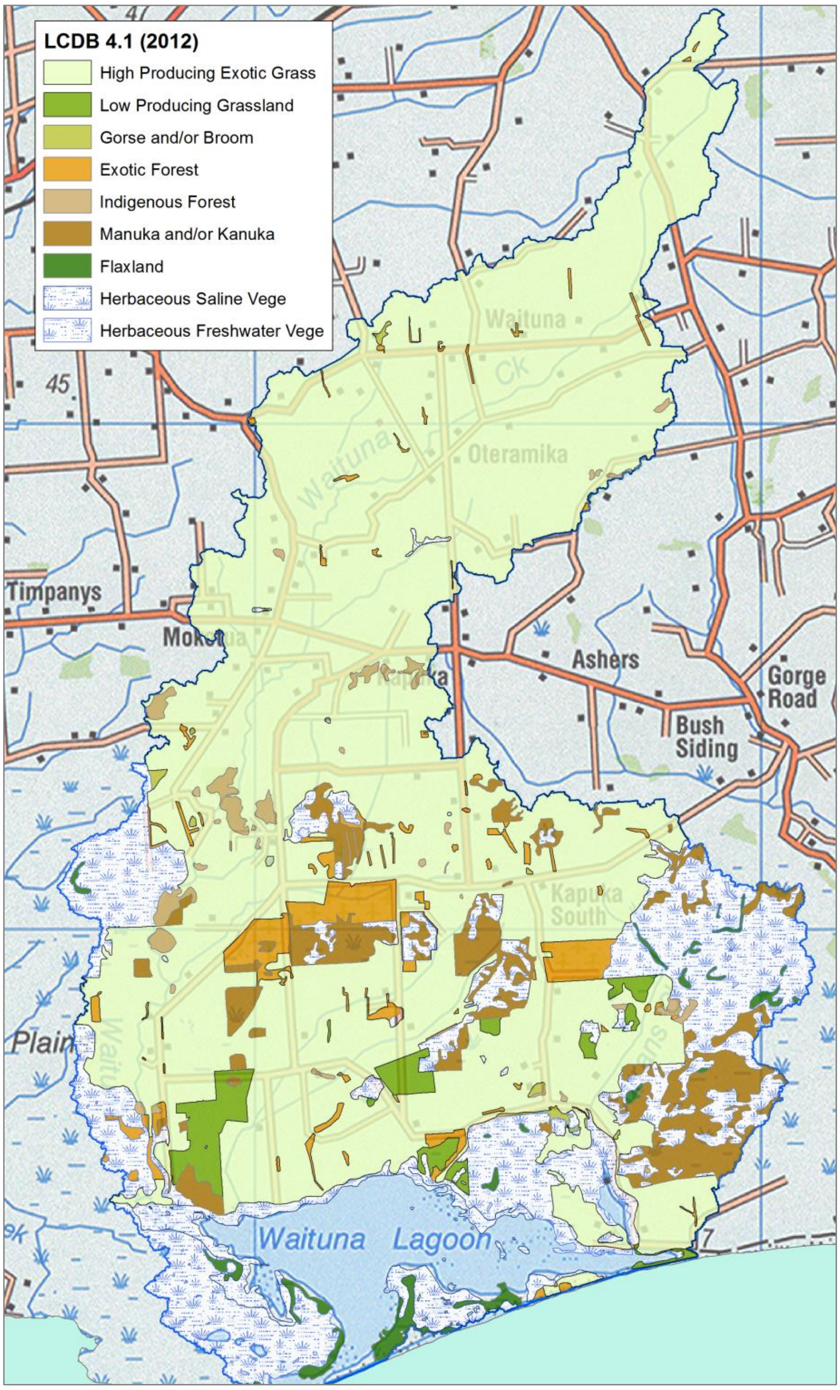

Figure 4 Land use for 2012 (Source: LCDB 4.1 database)

2.5 SOILS AND DRAINAGE

Soils impart a fundamental control on drainage in the Waituna catchment. This is partly due to the thin unsaturated zone that exists throughout much of the catchment, including the upper Waituna Creek sub-catchment. By definition and supported by shallow bore water level measurements, the unsaturated zone is thin in the lower catchment, adjoining wetlands, and Waituna Lagoon. The unsaturated zone thickens slightly towards the upper catchment, but the rising base of the shallow gravel aquifer keeps the water table close to the land surface. Having a thin unsaturated zone and moderate to high hydraulic conductivity in the shallow gravel aquifer, means the drainage of soils would impart quite direct connection between the soil profile and the underlying aquifer. Table 1 lists the soils in the Waituna catchment and their key hydraulic properties as mapped by the S-Map database. The S-Map New Zealand Soil Database (NZSD) soil series do not have much usage in the Waituna catchment due to the better characterisation site coverage provided by the Topoclimate survey of the late 1990s – 2000s (Hewitt et al, 2012). To account for this, Table 1a is coupled with a comparable Table 1b comprising the data available for the Topoclimate database within the Waituna catchment.

Brown soils are the most abundant soil order in the catchment, and they comprise 35% of the land area. These soils are all imperfectly drained with the exception of the Waikiwi typic firm brown soil, which is well-drained. The next most abundant soil is the organic soil order, which is found in 32% of the catchment area. These soils have the potential for high phosphorous leaching (highlighted in red in Table 1).

Gley soils, associated with saturated anoxic conditions, cover 20% of the catchment. Podzols are the least abundant soil order in the Waituna catchment. The four podzols found in the catchment are all classed as pan podzols, and are imperfectly drained. Soils that are considered to have potential for nitrate leaching due to their high drainage rates or lower PAW are highlighted in blue. These soils are classed in S-Map as having a medium susceptibility for nitrate to leach beyond the root zone into groundwater. As outlined in the following, we also think the Waikiwi soils may be susceptible to nitrate leaching, partly on the basis of elevated nitrate nitrogen concentration in the shallow aquifer beneath areas of Waikiwi soils.

The Waikiwi soils are classed as having a low leaching vulnerability in the S-Map database, but are classed as vulnerable to leaching to groundwater in the Topoclimate database. Waikiwi series soils are the only soil type in the catchment which are considered to be well-drained. This suggests that they are more prone to nutrient loss through drainage, and are more likely to drain to groundwater rather than near-surface routing to tile drains. Accordingly, nitrate accumulation vulnerability in underlying shallow, oxic groundwater is largely associated with Waikiwi soils in the Waituna catchment.

Gley soils are a good indicator of prevailing saturated conditions, and the Waimairi, Longbeach and Eureka soils are all orthic gleys, which form in shallow groundwater conditions. These soils are quite widespread south of Caesar Road (see Orientation Map), indicating that the regional water table in the alluvial gravels approaches the land surface in the vicinity of Caesar Road. In addition to gley soils, the shallow water table manifests in the emergence of spring-fed tributaries of Waituna Creek (Maher Creek) and also at the headwaters of the Carran and Moffat Creeks. In the lower catchment shallow water table areas, the soil types are either gley, podzol or organic.

Table 1a Soils of the Waituna catchment sorted by area (Data source: Landcare S-Map database)

S-Map code	Name	Area (ha)	Area (%)	Order	Drainage	PAW	% Pretention	Bypass flow	N-leaching
Otwy_3a.1	Otway	3,519	19.5	Organic	V poor	V high	26	High	V Low
Moko_12b.1	Mokotua	2,506	13.9	Brown	Imperfect	High	36	High	Low
Waiki_34a.1	Waikiwi	2,315	12.8	Brown	Well	High	43	High	Low
Piak_17a.1	Piako	2,283	12.6	Organic	V poor	V high	37	High	V Low
Asher_6a.1	Ashers	1,322	7.3	Podzol	Imperfect	V high	44	High	Low
Wood_29a.1	Woodland	1,210	6.7	Brown	Imperfect	High	43	Medium	Low
Ymai_25a.1	Waimairi	1,152	6.4	Gley	Poor	V high	38	High	V Low
Long_12a.1	Longbeach	1,037	5.7	Gley	Poor	High	38	High	V Low
Orik_6a.1	Orikaka	943	5.2	Podzol	Imperfect	Mod	60	High	Med
Paro_4a.1	Paroa	900	5.0	Gley	Poor	V high	35	High	V Low
Ymai_26a.1	Waimairi	262	1.4	Gley	Poor	V high	38	High	V Low
Wood_28a.1	Woodland	231	1.3	Brown	Imperfect	High	43	Medium	Low
Eure_6a.1	Eureka	118	0.7	Gley	Poor	High	38	High	V Low
Kapuk_3a.1	Kapuka	113	0.6	Podzol	Imperfect	Mod	44	High	Med
Asher_4a.1	Ashers	98	0.5	Podzol	Imperfect	Mod	44	High	Med
Gamm_3a.1	Gammacks	60	0.3	Gley	Poor	High	35	High	V Low

Table 1b Soils of the Waituna catchment in terms of local Series (Source: Topoclimate database)

Topoclimate Series	Area (ha)	NZSC Order	Drainage	Permeability	PRAW	P retention	N leaching risk
Ashers	96	Podzol	Imperfect	Slow	High	High	Slight
Dacre	900	Gley	Poor	Slow	High	Mod	Slight
Invercargill	2,255	Organic	Poor	Slow	Mod high	V low	Slight
Jacobs	59	Gley	Poor	Mod	High	-	Slight
Kapuka	1,393	Podzol	Imperfect	Slow	High-mod high	High	Slight-mod
Mokotua	3,168	Brown	Imperfect-poor	Slow	High	Mod-high	Slight
Otanomomo	3,907	Organic	Poor	Slow	Mod high	V low	Slight
Tisbury	1,262	Gley	Poor	Slow	High	Mod	Slight
Titipua	1,445	Gley	Poor	Slow	V high	Mod	Slight
Tiwai	910	Podzol	Imperfect	Slow	Mod high	High	Mod
Waikiwi	2,308	Brown	Well	Slow	High	Mod-high	Mod
Woodlands	1,461	Brown	Imperfect	Slow	High-mod high	Mod	Slight-mod

The soils and related surface drainage network are hypothesised to bear a large influence on nitrogen and phosphorous migration pathways. Figure 5 shows the location of organic and gley soils (very poorly and poorly draining respectively), together with imperfectly drained soils.

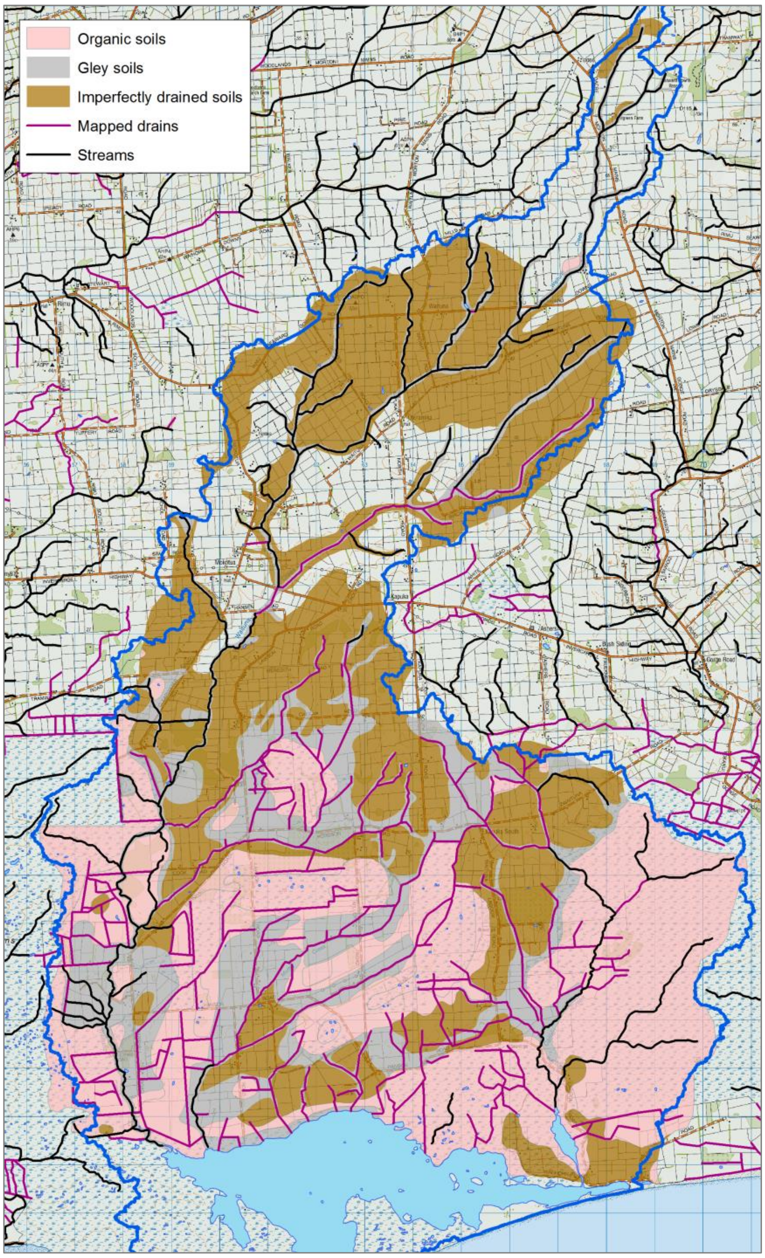

Figure 5 Map of imperfectly drained soils with the mapped drainage network

Most, if not all, of the very poorly to imperfectly drained soils require the installation and maintenance of mole and tile drains to reduce the risk of water logging during wet periods. Over 35% of the catchment consists of imperfectly drained soils and over 51% of the catchment consists of soils that are poorly to very poorly drained. The imperfectly drained Mokotua and Woodlands, have a propensity for waterlogging during wet periods because of their slow permeability subsoils. The well-drained Waikiwi soils are slightly vulnerable to water logging due to a slowly permeable B-C horizon.

Characterising artificial drainage practices and densities is an area of catchment studies in Southland that has lagged behind soil and groundwater studies. One result is that it is difficult to correlate soil drainage properties and water table depth with artificial drainage practices. However in general terms, the heavier soils and shallow water tables tend be associated with artificial open and tiled drainage.

The drainage network as mapped by the NZMS Topo 50 series mostly follows the distribution of pastoral land use over organic and gley soils in the southern half of the catchment. Not shown on the Topo 50 map, or on Figure 5, are the networks of buried mole and tile drains. Drainage networks are expected to be extensively distributed across the imperfectly to very poorly drained soils. When considering the brown soils of the northern half of the catchment, the Mokotua and Woodlands soils would require drains of some sort to remove water from their impeded drainage.

2.6 SURFACE HYDROLOGY

The Waituna catchment is generally considered a closed system. This conclusion is based on the observation that the discharge into Waituna Lagoon through the surface water network (and direct groundwater discharge) can be explained by the calculated rainfall surplus (rain minus evapotranspiration) generated within the topographical catchment boundary. However, there are indications that minor quantities of groundwater may enter the Waituna Creek sub-catchment from the neighbouring Waihopai catchment. The uncertainties associated with the water balance calculations do not currently allow us to clarify this issue (see section 8.3).

Five surface water catchments have been identified by Environment Southland (Figure 2), although the catchment boundaries can only be defined imprecisely because the topography is subdued. The catchments cover the drainage networks of Waituna, Carran, Moffat and Craws Creeks, as well as the proximal lagoon catchment.

Table 2 lists the main physical characteristics of the five Waituna sub-catchments. Waituna Creek is by far the largest sub-catchment. The mean land surface slope is less than 1° for all sub-catchments, which is a reflection of the subdued terrain in the catchment. Waituna and Carran creeks are located at the headwaters of the greater Waituna catchment and have the greatest overall land surface slopes.

Table 2 Physical characteristics of the five Waituna sub-catchments

Subcatchment	Area (ha)	Area (%)	Mean land slope (degrees)	Elevation (m)		
				Max	Min	Mean
Waituna Creek	10,604	55.7	0.51	69.0	7.0	30.5
Carran Creek	2,871	15.1	0.54	41.2	8.4	16.0
Moffat Creek	1,733	9.1	0.37	31.3	6.1	14.6
Lagoon	3,041	16.0	0.36	20.3	1.5	7.8
Craws Creek	788	4.1	0.26	11.6	6.9	9.8

2.7 GEOLOGY

The geology of the Waituna catchment has previously been outlined by Rissmann *et al*. (2012). Much of the discussion of Waituna catchment geology to date has focused on the Q5 beach gravels which have been mapped in the vicinity of Hanson Road (Turnbull & Allibone, 2003). These gravels have been interpreted to be formed by a Q5 shoreline (70,000-130,000 years BP) that stretched in an arc to the north of the low-lying wetlands (Rissmann *et al*., 2012). To the southeast of Invercargill the Q5 beach gravels are mapped as lying along the base of an east-west oriented escarpment (Turnbull & Allibone, 2003).

The main geological units as mapped in QMap (Turnbull & Allibone, 2003) are shown in Figure 6 together with the "escarpments" and projection of the Morton Mains Fault which have been identified from slope data.

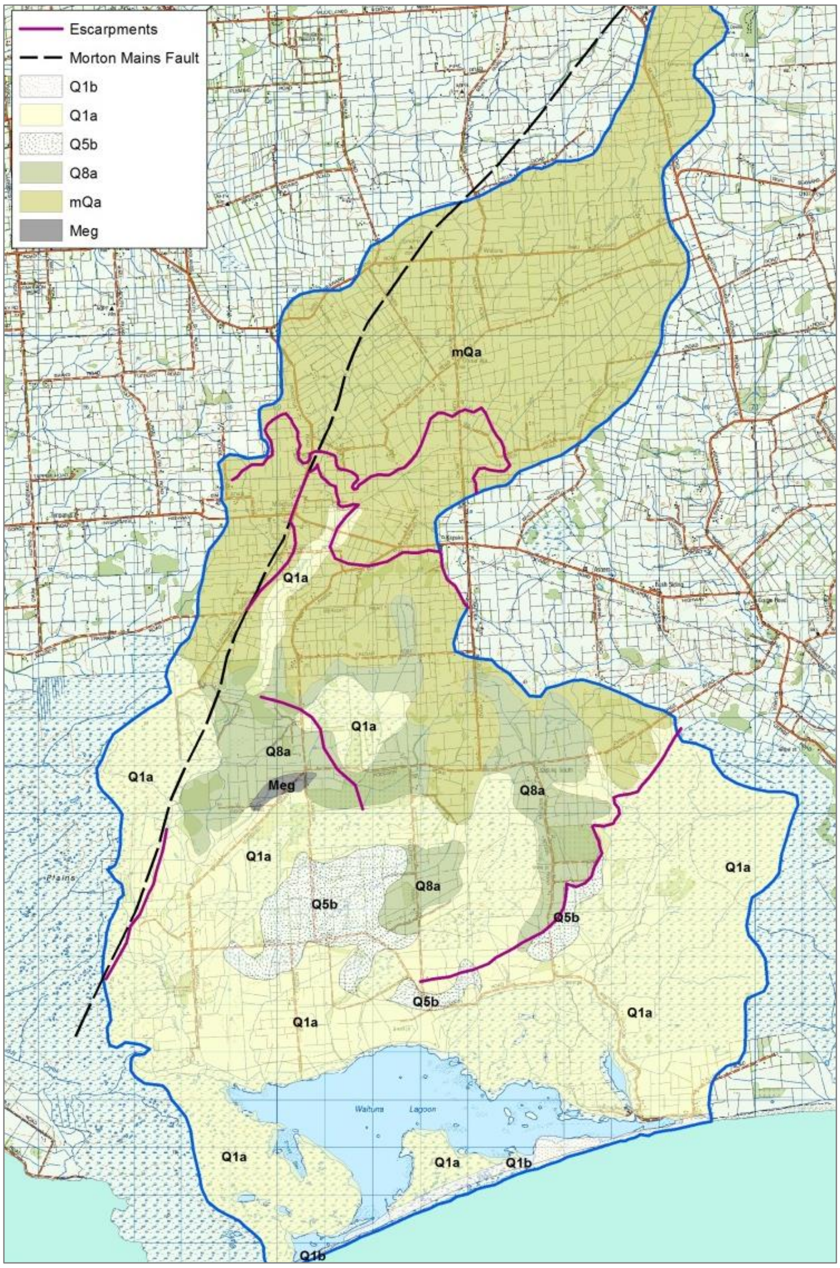

Figure 6 Main geological units mapped in the Waituna catchment

Another notable feature in the slope map is the apparent surface expression of the Q5 beach gravels-Q8 alluvium contact to the south of Caesar Road. This feature is evident in the slope map, and has been drawn on Figure 6. Its location accords with the position of this contact as proposed by Southern Geophysical (2014). We agree with the Southern Geophysical interpretation (see section 2.8) that this unit is actually Q5b gravel based on the geomorphology, although it has been mapped on QMap (Turnbull & Allibone, 2003) as Q8a.

Contouring of the Quaternary-Tertiary contact has been carried out by identifying the contact on bore logs. Tertiary sediments are easily identified in the bore logs as a change from gravels to sand/sandstone, clay/mudstone, or lignite. In some places the Tertiary sediments are clearly of marine origin, being described as blue-grey silt, pug, or clay, sometimes with shells. Figure 7 shows our interpreted structure contour map of the Tertiary sediment surface which has been created using the available bore log data.

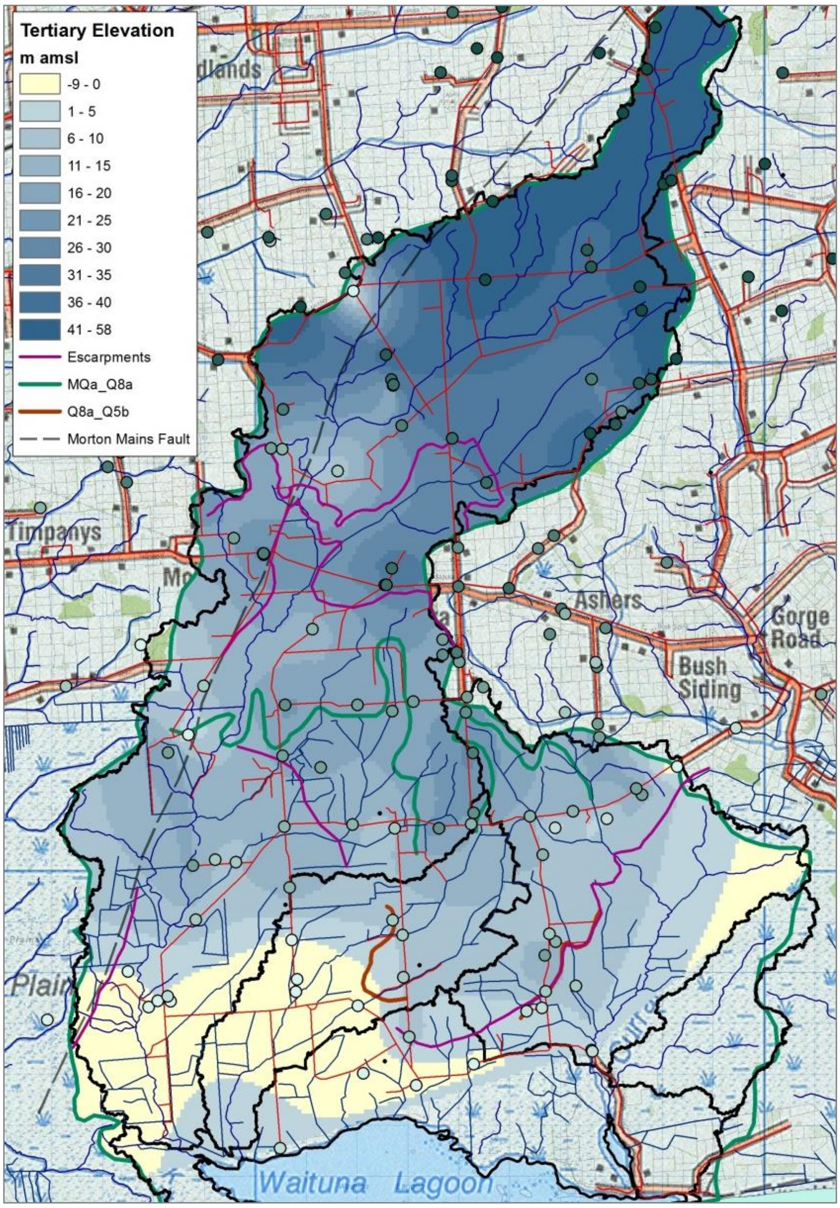

Figure 7 Structural contours of the top of the Tertiary sediments with respect to Mean Sea Level

The thickness of Quaternary gravels has been estimated by subtracting the Tertiary contact intercepts from the surface elevation. There is a decrease in gravel thickness southwards, with an abrupt change occurring across the mQa-Q8a contact (see Figure 6 and Figure 8). The gravels tend to be less than 10m thick to the south of this contact, and over 20m thick to the north. This thinning of the gravels greatly reduces the aquifer transmissivity, which manifests as a zone gley soils associated with spring emergences in the vicinity of the mQa-Q8a contact.

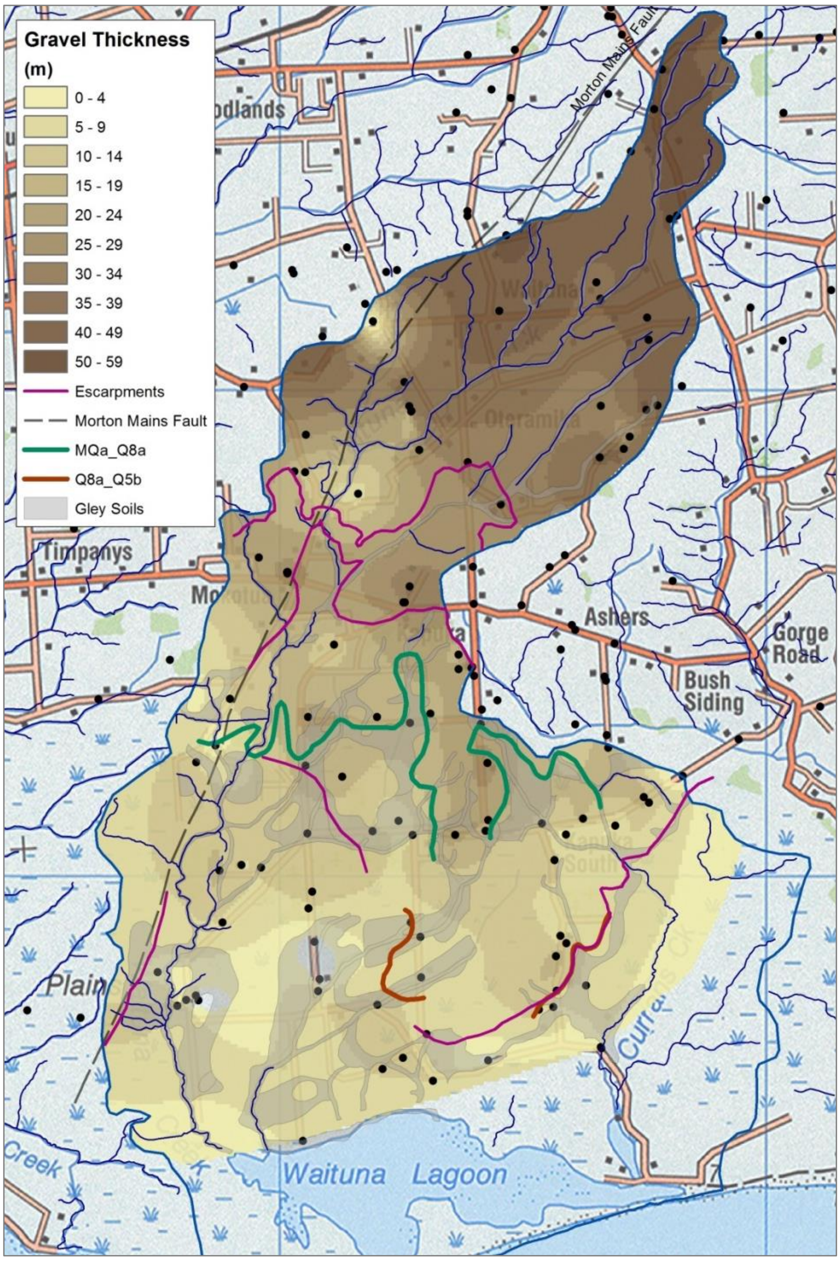

Figure 8 Interpolated thickness of the Quaternary gravels

2.8 GEOPHYSICAL SURVEYS

Southern Geophysical Ltd undertook a limited scope geophysical survey in the Waituna catchment in November 2014. The objectives of the surveys included determining the feasibility of using geophysical tools in delineating the lateral boundaries of the MIZ, and identifying internal structures characteristic of paleo-channels within the MIZ. The survey methodology had to be adjusted due to the inability to gain private land access across most of the MIZ. Instead of using extensive Time Domain Electro-Magnetic (TDEM) surveying as initially planned, linear Ground Penetrating Radar (GPR) lines along public roadway verges were undertaken. The GPR soundings done in this manner (100-200 MHz antennae) had a shallower focus (5-11 m) that mostly failed to pick up the Quaternary-Tertiary geological basal contact (generally greater than 15 m). However, the GPR surveys allowed longitudinal profiles of reflectors within the Quaternary sediments to be drawn.

Conclusions from the provisional Southern Geophysical report (Southern Geophysical Ltd, 2014) can be summarized as follows:

- The differentiator of the geophysical facies composition is the paleo-shoreline:
  - North of the paleo-shoreline large-scale steeply dipping moderate to high amplitude reflectors (often sigmoidal) fluvial sediments dominated by (cut-and-fill) paleo-channels ranging in width from 3 m to 200 m (often containing a basal lag) correlated with Q8a alluvial deposits.
  - South of the paleo-shoreline the sediments are finer grained and lack large-scale fluvial structures such as cross-bedding and are correlated with Q5 alluvial deposits. The depositional environment was inferred by Southern Geophysical to be lacustrine or (marginal) marine.
- This facies composition varies from the Groundwater Technical Report (Rissmann et al, 2012), in that the older facies were identified as coarser grained, although in a fine-grained ground-mass.

The reason for commissioning the geophysical survey was to provide better information on the distribution of Quaternary deposits such as paleo-shoreline deposits that were considered significant to the MIZ. Analysis of the GPR survey resulted in the recommendation to consider shifting the contact between older fluvial gravels and paleo-shoreline sediments south-west by approximately 1 km. The paleo-channels identified in GPR profiles within Q8a fluvial sediments potentially have a role as enhanced hydraulic conductivity zones within the shallow aquifer, contributing to the observed groundwater contribution to Waituna Creek base-flow south of the Invercargill-Gorge Road Highway (see sub-section 5.1.1. of this review).

2.9 GROUNDWATER

A piezometric survey of the Waituna catchment was undertaken by Environment Southland in 2012, and the results are contoured in Figure 9. The piezometric contours show that groundwater flow is very strongly controlled by discharge to surface waterways, particularly Waituna Creek, and to a lesser extent Carran Creek. In addition to the groundwater level contours, Figure 9 also shows the topography as a DEM. There is a general trend of land surface elevation declining from north to south, which is the general trend of groundwater flow in the catchment. The water table contours mimic the trend of the land surface until the surfaces join near Waituna Lagoon.

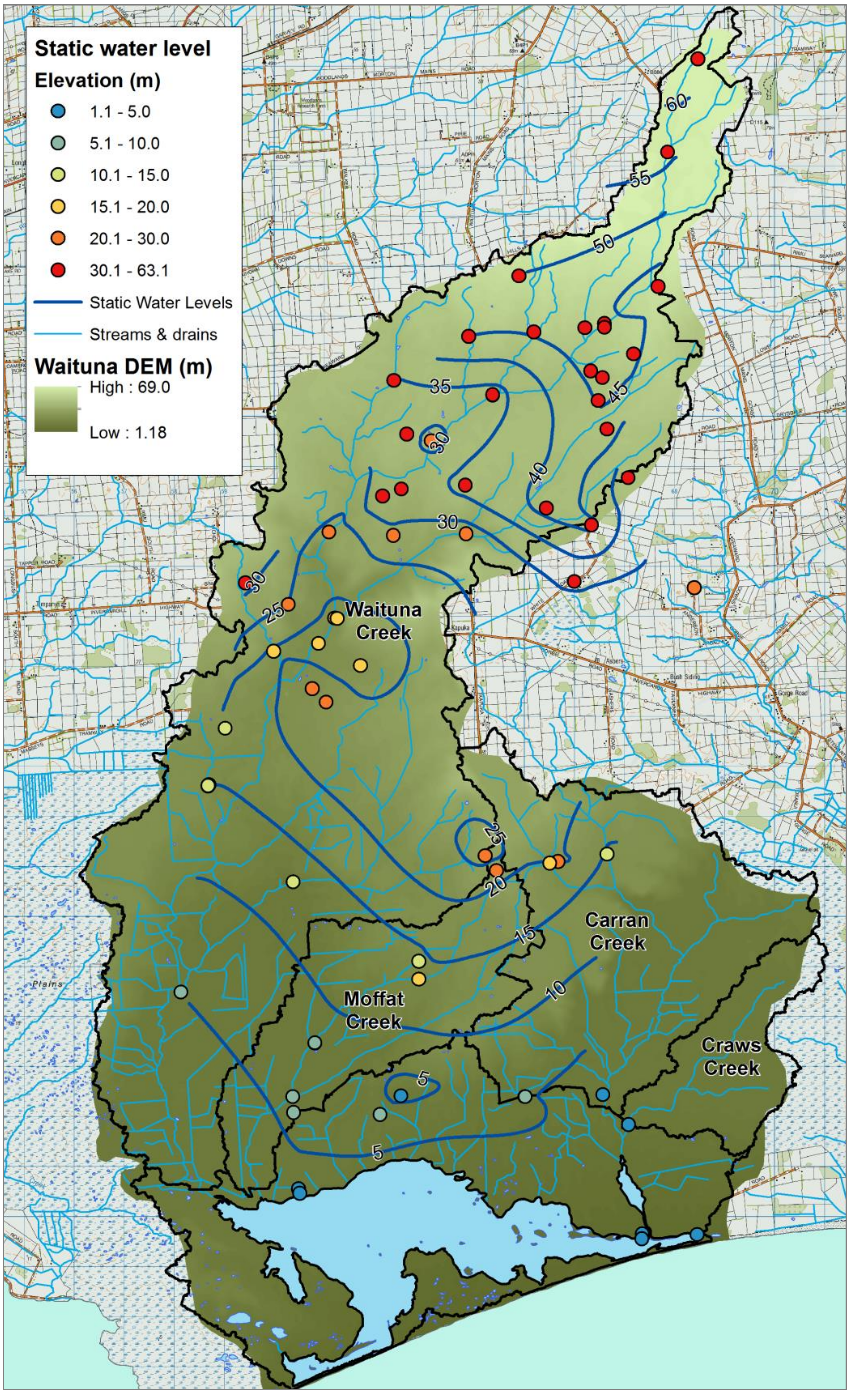

Figure 9 Static water levels from a survey carried out in 2012

3 SURFACE WATER QUANTITY

3.1 CATCHMENT MORPHOLOGY

The Waituna catchment comprises the Waituna Creek, Moffat Creek and Carran Creek sub-catchments. These all drain into Waituna Lagoon, and ultimately into Foveaux Strait. To the east, the lower Mataura River gains flow from lowland creek catchments adjoining Waituna and Carran creeks, and these drain into the Toetoes Estuary. To the west, the Waihopai River adjoins the upper reaches of Waituna Creek and drains into the New River Estuary at Invercargill. The Awarua Wetland complex adjoins the lower catchment and drains into Awarua Bay. In this manner, the Waituna catchment intervenes between the major Mataura and Oreti catchments. The catchment and sub-catchment flow divides between the three catchments concerned (and internally) are often poorly defined due to low relief, indistinct slopes, and dug or open drains that are graded to conduct drainage against the prevailing land slope.

Much of the current creek channel network has been modified. Modifications include the straightening of reaches to increase the farmable area, burial/tiling of swales undertaken for increases in land productivity, and excavation of drains within former or residual wetlands to achieve land reclamation.

Waituna Creek has a feather-shaped upper catchment, including a significant north east tributary (Jordan Creek) of first and second order drains and creeks, upstream of Mokotua settlement. The catchment morphology changes once it crosses the escarpment transition near the Invercargill-Gorge Road Highway. Waituna Creek tends to meander southwards to the lagoon, although the channel has been straightened in some reaches.

3.2 GAUGING NETWORK

Waituna Creek has a continuous flow gauging and recording point at Marshall Road, approximately 4 km upstream of the creek's outfall into Waituna Lagoon. Moffat Creek did have a continuous flow gauging and recording site at the Moffat Road crossing, approximately 2 km upstream of the creek's outfall onto Waituna Lagoon. This site was damaged in August 2015 and subsequently removed. The third catchment included in the gauging network is Carran Creek with a measurement site approximately 1 km upstream of Waituna Lagoon Road.

Additional sites available for the hydrological characterization of the Waituna catchment include: monitored lagoon levels at the Waghorn Road recorder and the instrument platform in the lagoon; monitored bore water levels; and spot-gauging sites on sub-catchments or reaches of the catchment creek network.

For the Environment Southland Surface Water Quality Study, gauged flow measurements were combined with water quality samples taken at the same time. This enables instantaneous mass loads to be calculated for those sites. Table 3 lists the sites that were sampled and gauged for the Environment Southland Surface Water Quality Study.

Table 3 List of waded flow gauging sites in the Waituna catchment

Waded Gauging Site Description	Easting	Northing
Waituna Creek SE tributary 20m u/s Waituna Creek confluence	1258355	4838917
Jordan Creek 10m u/s Waituna Creek confluence	1261257	4845964
Waituna Creek at Rimu Seaward Downs Road	1266605	4851793
Waituna Creek at Waituna Road	1261099	4847710
Waituna Creek at Marshall Road	1258185	4838526
Moffat Creek 20m u/s Hanson Road	1262043	4837367
Moffat Creek South tributary 1.2km u/s Miller Road	1264016	4838470
Moffat Creek at Moffat Road	1260293	4836329
Carran Creek drain 800m u/s Waituna Lagoon Road	1267016	4837130
Carran Creek 800m u/s Waituna Lagoon Road	1267034	4837130
Carran Creek 3km u/s Waituna Lagoon Road	1268096	4839102
Carran Creek 1km d/s Waituna Gorge Road	1267166	4840210
Carran Creek west branch d/s Waituna Gorge Road	1265502	4841074
Carran Creek east branch u/s Waituna Gorge Road	1266651	4841251
Carran (Craws) Creek 1km u/s Waituna Lagoon Road	1267930	4836161
Carran (Craws) Creek at Waituna Lagoon Road	1267116	4835870

Note: Sites highlighted in **bold** are continuous monitoring sites. Abbreviation “u/s” = upstream; “d/s” = downstream.

The complete historical flow record of Waituna Creek at Marshall Road and Carran Creek upstream of Waituna Lagoon Road are shown as hydrographs in Figure 10 and Figure 11, respectively. These two sites show flow characteristics that are typical of small lowland creek catchments in a humid, temperate climate and with significant base-flow contribution from groundwater.

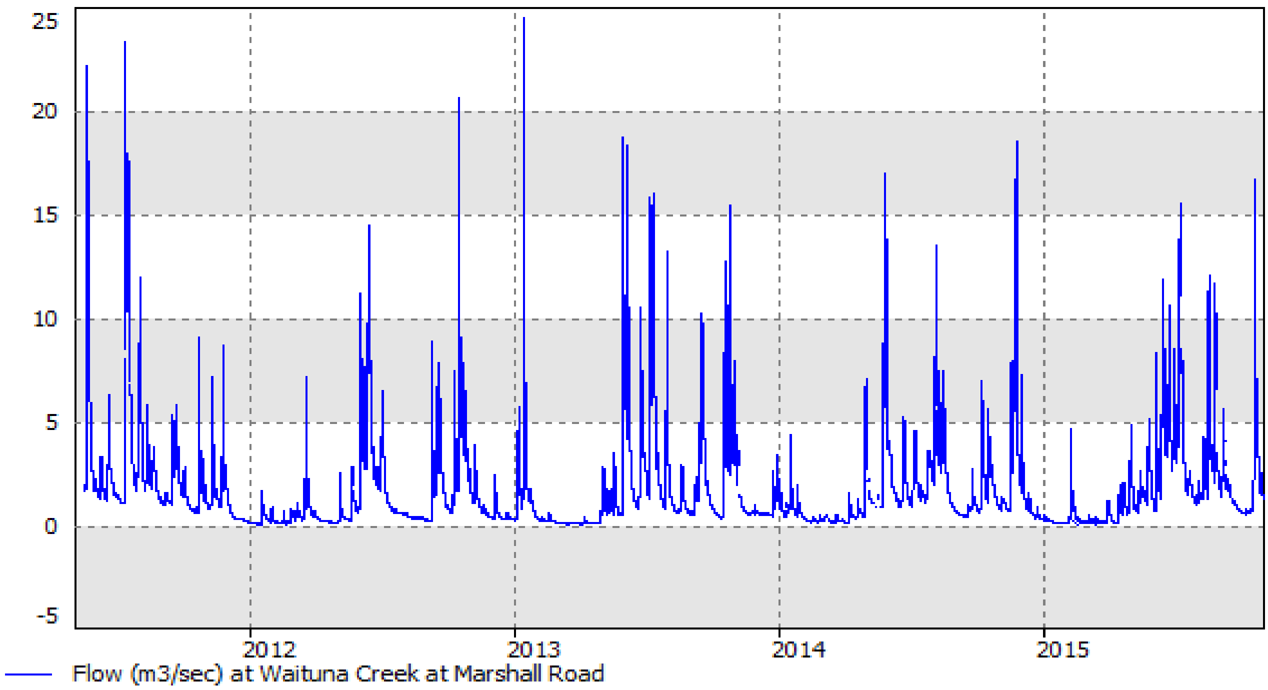

Figure 10 Continuous flow record for Waituna Creek at Marshall Road, mid 2011 to present (m3/s)

The hydrograph shows a pattern of significant runoff concentrated in the winter and shoulder seasons, occasional summer floods, and a distinct flood recession characteristic probably sustained by base-flow buffering.

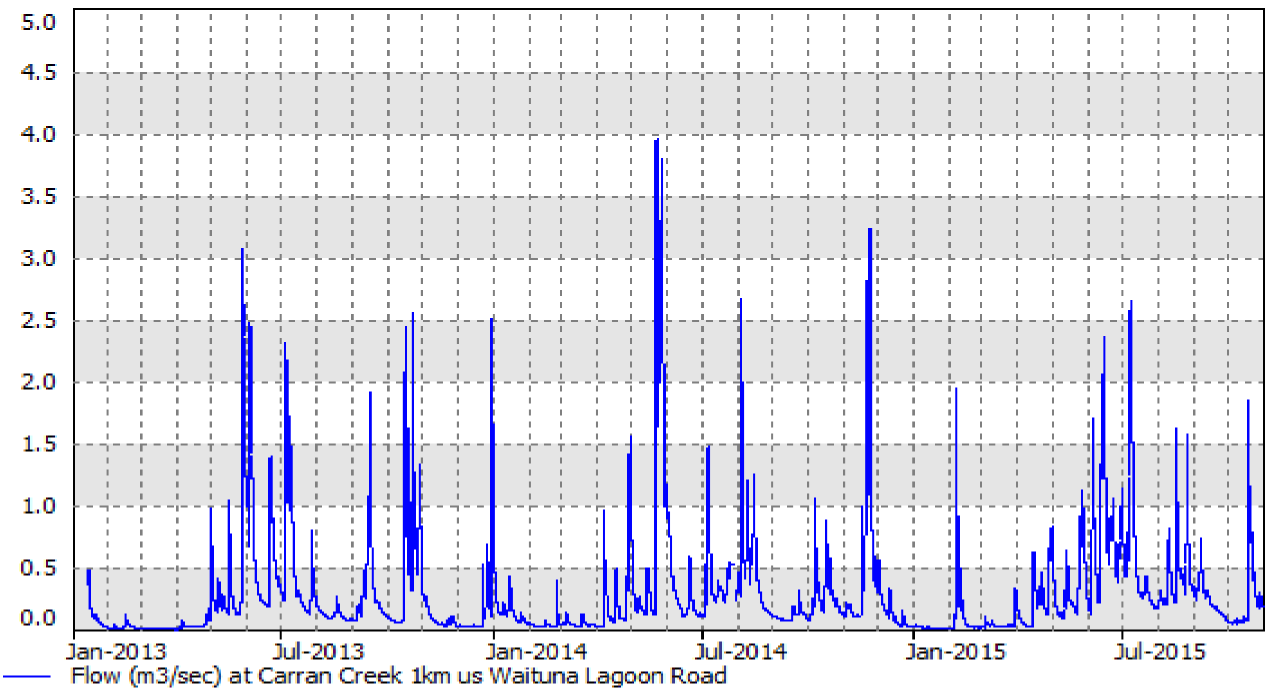

Figure 11 Continuous flow record for Carran Creek at a point 1 km upstream of Waituna Lagoon Road crossing, 2013 to present (m3/s)

The hydrograph of Carran Creek in its mid reaches indicates lower overall runoff, a sustained autumn-winter-spring period of runoff peaks, and a small base-flow in the summer.

3.3 WAITUNA LAGOON

Waituna Lagoon is a shallow (mostly less than 1.5 m), brackish, coastal lagoon cut off from coastal waters by a pea-gravel coastal barrier. It has a significant freshwater input from Carran Creek, Waituna Creek, Moffat Creek and direct groundwater seepage. The lagoon itself has an area of 1,350 ha and when considered with adjoining wetlands, the Waituna Scientific Reserve comprising lagoon and wetlands, has a combined area of 3,500 ha. The lagoon and adjoining wetlands were designated a Ramsar site in 1976, the Scientific Reserve status in 1983, and in 2008 additional areas of wetland were added to the Ramsar site creating a total of approximately 20,000ha known as the Awarua Wetland.

3.4 LAND DRAINAGE & WETLANDS

The pre-European landscape of the Waituna catchment comprised large areas of Manuka scrub and raised bogs, leading down to peat marshes and fens fringing the lagoon. The lagoon itself is thought to have formed following the onset of the Holocene sea level stabilization about 7,000 years BP and maintained a higher than current water level. The lagoon in its natural state periodically overtopped the coastal barrier spit, until longshore currents and gravel accumulation closed the natural breach.

Surrounding land in the Mataura and Waihopai catchments was developed for agriculture in the late 1800s, earlier than the Waituna catchment. Land clearance required drainage to prevent water-logged pastures. As the land clearance and the formation of farms has moved progressively throughout the Waituna catchment, the intensity of drainage efforts using creek cut-offs, excavation of open drains and laying of tile drains has increased. Developed grazing land is currently pushed up against the fringes of peat swamps and marshlands, or the boundaries of government-owned reserves. Indeed, several of the raised bogs located in the upper and middle parts of the creek catchments contain attempts at drainage that have not yet been successful in facilitating the establishment of pasture.

Since the initiation of land clearance and drainage of parts of the lagoon fringes, artificial openings of the lagoon barrier have been undertaken on a semi-regular basis to prevent lagoon water levels reducing drainage efficiency in surrounding lands. Breaches of the barrier have been made using drag-lines, and more recently using mechanical excavators. The openings allow the rapid outflow of lagoon water and eventually inflow of seawater, until the combination of weather, lagoon outflows, ocean currents and southerly swells in Foveaux Strait act to close the breach. The openings are triggered by rising water levels of the lake, typically when lake levels are 2 m above sea level.

3.5 ESTIMATED FLOWS

Average inflows and incident rainfall into Waituna Lagoon during a 12 month period (winter 2011 to winter 2012) between lagoon openings were estimated as 2.56 m^3/s or 80.7 million m^3/year (*pers. comm.*, Chris Jenkins, 25 May 2015), which approximately quantifies catchment yield from all sources. Waituna Creek makes up about 50% of inflows to the lagoon with its measured flow of 1.32 m^3/s, or 41.5 million m^3/year (as measured at Marshall Road) during the same period in 2001 and 2012.

Creek network catchment flows are detailed further in sub-section 5.1.1., and summary statistics for Waituna Creek at Marshall Road are listed in Table 4.

Table 4 Summary of flow statistics for Waituna Creek at Marshall Road, 2012-2014 (m^3/s)

Year	Min	Max	Mean	Std Dev	Lower Quartile	Median	Upper Quartile
2012	0.057	20.63	1.31	1.93	0.281	0.55	1.49
2013	0.038	24.49	1.9	2.92	0.385	0.76	1.97
2014	0.118	18.49	1.58	2.05	0.442	0.92	1.81
All Years	**0.038**	**24.49**	**1.60**	**2.42**	**0.33**	**0.76**	**1.94**

4 GROUNDWATER QUANTITY

4.1 HYDRO-STRATIGRAPHY

The hydro-stratigraphy of the Waituna catchment can be summarised as follows:

- Unconfined, shallow Quaternary deposits typified as a sand and gravel layer atop the lignite measures;
- Semi-confined to fully confined aquifers within the Gore Lignite Measures, which are relatively stagnant and have little interchange with surface environments.

4.2 QUATERNARY DEPOSITS

The presence of the Q5 paleo-shoreline does pose some unresolved questions for the Waituna catchment, since its surface expressions are not as readily apparent as they are further to the west along the Waimatuku-Riverton coastline:

- Why does the older Quaternary gravel outcrop to the south of this shoreline?
- Why are Q5 beach gravels mapped inland of Q8 alluvium in the Moffat Creek catchment?
- Why is there a steep southwest-trending escarpment at Kapuka South?

To try and resolve these questions we have generated a map of the land surface slope from the 8m DEM (Figure 12). The darker areas represent steeper slopes, and the Q5 beach gravels and Murihiku Basement outcrops have also been drawn after Turnbull & Allibone (2003). This slope map helps to clarify the geomorphology of the region because the locations of surface features such as the “escarpments” can be readily seen.

A feature that is evident in the slope map is the presence of fault traces in the land surface, and that these faults dissect the Q5 marine escarpment. The Morton Mains Fault can be observed to continue southwards and traverse the western edge of the Waituna catchment. An east-northeast trending escarpment located just north of Hanson Road may represent the western extension of the Waimahaka Fault. Both of these faults are thought to be down-thrown to the northwest, and are regarded as inactive (Turnbull & Allibone, 2003).

The escarpment located to the north of Hanson Road turns to a northeast direction at Waituna Lagoon Road and becomes more pronounced. This lineament appears to be a structural expression of the folding that gave rise to the Gorge Road platform, where Jurassic Murihiku Group basement rocks have been exposed at the surface. The escarpment is likely to be the southern extension of the fault which has exposed Murihiku Group.

The presence of linear traces on the surface topography suggests that older faults have been remobilised as accommodation faults during tectonic movement during the late Quaternary. This more recent fault movement suggests that a small amount of block rotation may have occurred between faults, with the downthrown block being to the southeast. If this hypothesis is true, the significance is threefold:

1. The Q5 beach gravels have been largely eroded and removed from the Waituna catchment. A small remnant can be found in the vicinity of the intersection between Lawson and Hanson roads. The Q5 beach gravels mapped below the escarpment to the north of Hanson Road are most likely re-mobilised gravels that have been eroded off the upper terrace.
2. The Quaternary gravels dip gently westward towards Waituna Creek.
3. The Quaternary-Tertiary contact surface in the Kapuka[2] catchment probably also dips westward. This would imply that groundwater flow in the Kapuka catchment flows south-westward into the Waituna catchment.

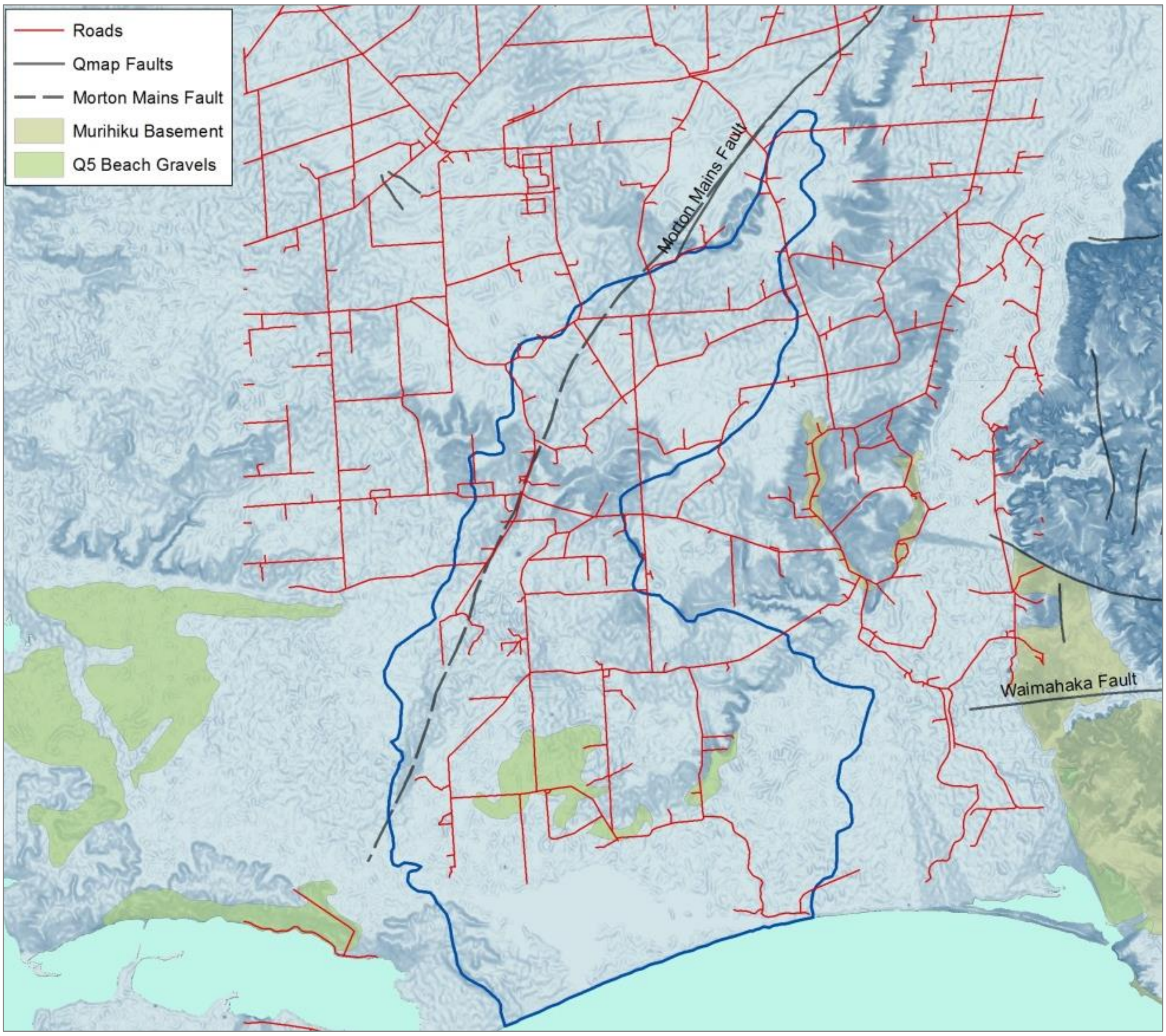

Figure 12 Plot of surface slope, Q5 beach gravels, and basement outcrops

[2] Kapuka Creek is the informal name of the unnamed creek draining into the lower Mataura River in the vicinity of the Kapuka locality.

This interpretation of fault block rotation does explain why potential paleo-channels in the lignite measures appear to be oriented in a predominantly southwest direction (Rissmann *et al*., 2012). This also explains why Quaternary gravels are thinnest in the Carran Creek catchment, and are thickest in the Moffat Creek catchment to the south of the outcropping Gore Lignite measures.

4.3 LIGNITE MEASURES

The Upper, Middle and Lower lignite measures of the Gore Lignite Measures formation are represented in the Waituna catchment. The lignite is Miocene in age and is approximately 250m thick. The lignite deposits are structurally folded into a syncline with its axis centred in the middle of the Waituna catchment. The limbs of the syncline are anchored at the margins by the Gorge Road basement platform and the basement Green Hills at Awarua-Omaui.

Underlying the lignite measures is the Chatton Formation sandstone and shell-bed coquinas. These sediments are only known from water bores drilled in the Clifton-Awarua area.

The lignite measures extend over much of lowland Eastern Southland between the basement blocks (Hokonui Hills, Green Hills and Catlins Block). In fact the Gore Lignite Measures are included as principal components of the named Eastern Southland Group (Isaac and Lindqist, 1992), such is the formation's extent through much of the middle and lower Mataura catchment. The lignite measures comprise lightly to moderately consolidated siltstone, claystone, sandstone, quartz pea-gravel, carbonaceous mudstone and lignite-rank coal seams. The measures are vertically stratified with lignite seams tending to dominate the upper lignite measures. As terrestrial deposits derived from a series of meander plains, the lignite measures have significant lateral variability, but recognizable sedimentary groupings can be traced laterally as revealed in cored drill holes (Applied Geology et al., 1986).

The Gore Lignite Measures were the focus of a substantial economic geology investigation from the late 1970s to present, based around the lignite resource (Hooper, 2005). Geotechnical investigations of Ashers-Waituna lignite deposit in the middle of the Waituna catchment highlighted the presence of sandstone aquifers located between lignite seam horizons (Applied Geology et al., 1986). These sandstone and fine gravel aquifers were further studied in terms of their groundwater resource approximately 15 years later (Durie, 2001) as the water requirements of dairy sheds had necessitated the development of bores from wherever sufficient yield could be obtained.

There has been significant speculation (Durie, 2001; and Wilson, 2011) as to the exchange of groundwater between the Gore Lignite Measures Aquifers (GLMAs) underlying the Waituna catchment and surface water or the lagoon itself. The mudstones and fine grained materials intervening between the GLMAs and the shallow quaternary aquifer would limit the potential for vertical groundwater exchange. The vertical flow resistance (c) of siltstones and mudstones confining the silty sand and quartz pea-gravel aquifers within the Gore Lignite Measures was measured at between 5,950 days and 9,300 days (Applied Geology et al., 1986), which is sufficiently resistive to prevent any appreciable vertical circulation.

5 WATER QUALITY

5.1 SURFACE WATER QUALITY STUDY

5.1.1 HYDROLOGICAL FEATURES OF THE SURFACE WATER QUALITY STUDY

Data from eleven flow gauging surveys were available for the Surface Water Quality Study, from January 2012 to November 2012 (Environment Southland, 2014 unpublished). The locations of the Surface Water Quality Study sites and their average nitrate-nitrite-nitrogen values are shown in Figure 13.

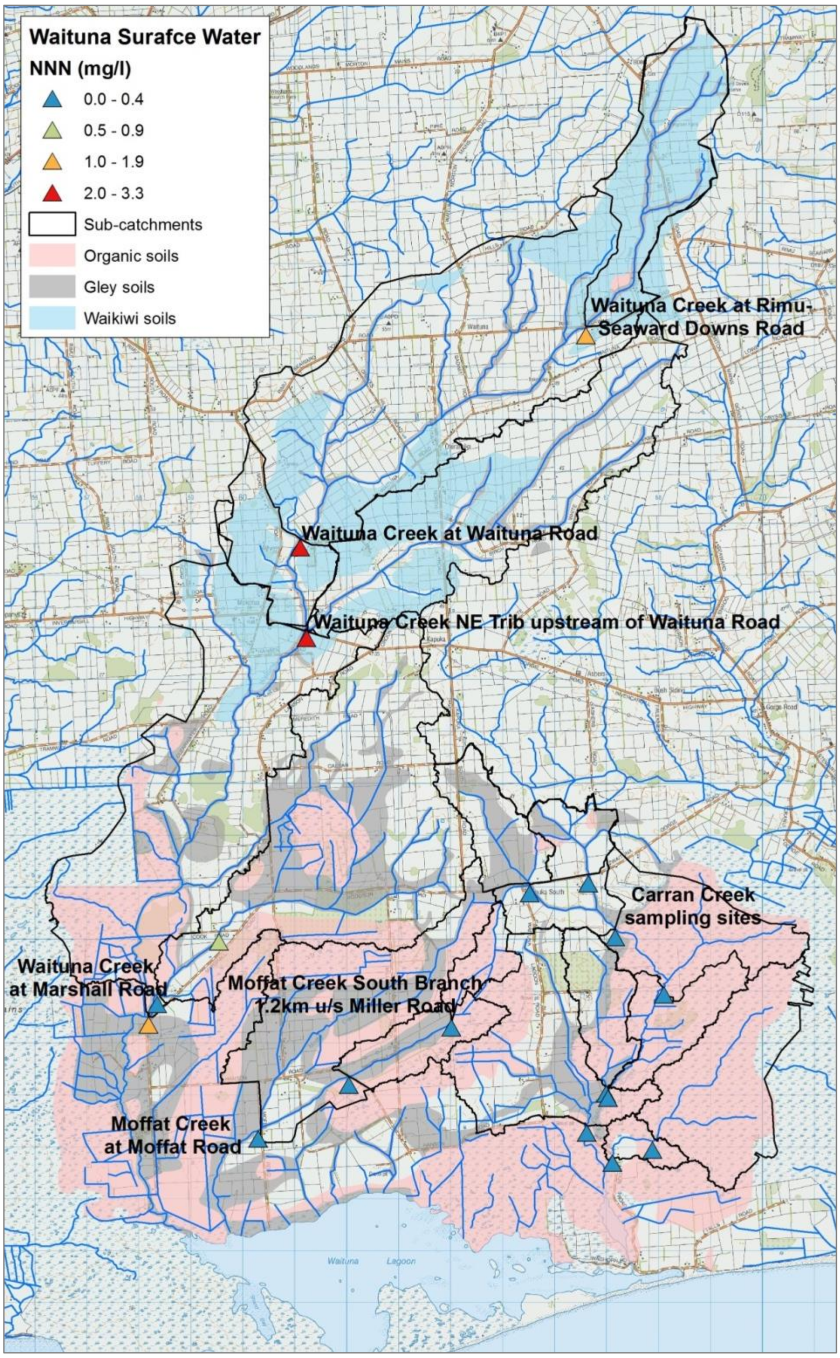

Figure 13 Surface water monitoring sites for the Surface Water Quality Study and NNN values

For understanding the relationship between nutrient leaching and stream flow, it is most useful to study the specific discharge at the flow gauging sites. The specific discharge is the stream flow divided by the catchment area, and the result reflects the contribution of infiltration, runoff, or groundwater interaction upstream of the flow observation. Specific discharge statistics for the Surface Water Quality Study sites are shown in Figure 14.

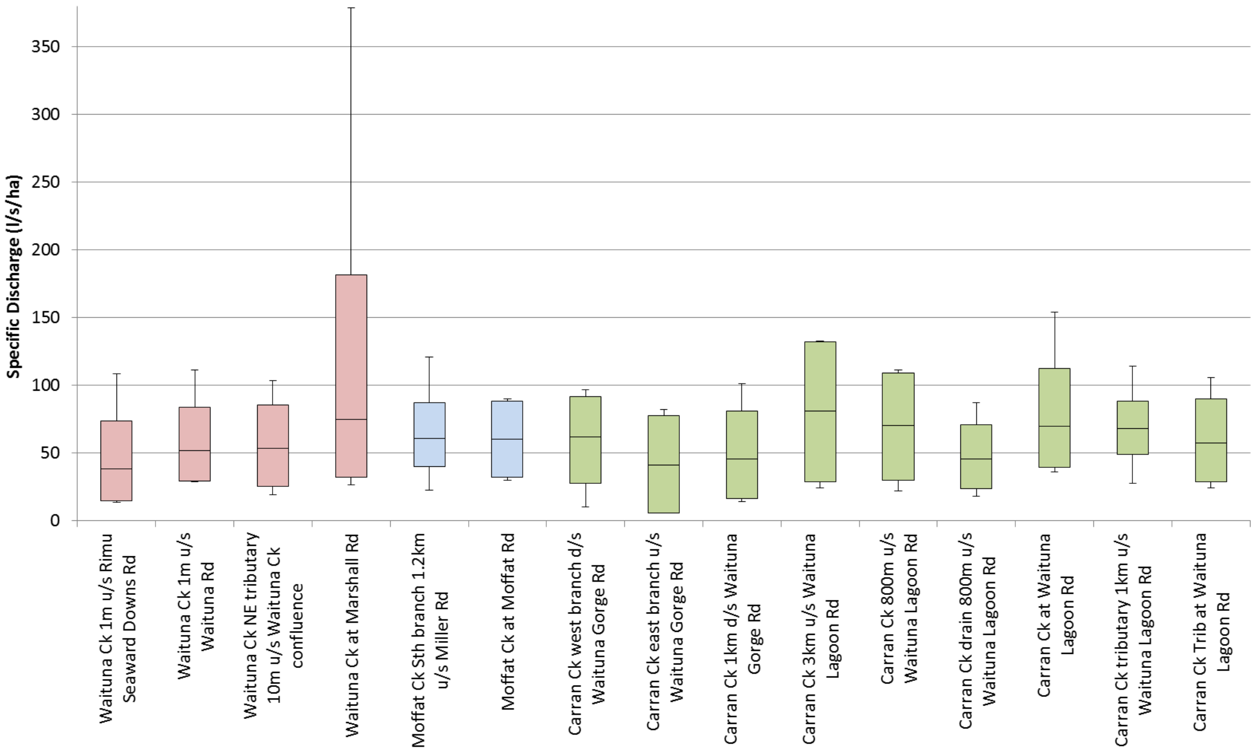

Figure 14 Box and whisker plot of specific discharge at the Surface Water Quality Study sites

Table 5 lists the typical response observed for the three main catchments, indicating areas where relatively high and low specific yields are observed. The picture that emerges from the eleven surveys is one of higher yields from the lower catchments when flow is low, particularly those with a shallow water table (gley soils). This suggests that stream flow is largely sustained by groundwater discharge in the lower catchments under stable conditions.

During higher flows, the yield of the Waituna catchment increases, which indicates a rapid flow response to rainfall recharge. These high yields are not sustained during lower flows, which suggests there is rapid discharge to Waituna Creek due to its relatively steep hydraulic gradient. During higher flows the smallest yields are seen in the low-lying parts of Carran and Moffat creeks, which is presumably a response to their small hydraulic gradient.

We note a significant gain in the specific discharge of Waituna Creek downstream of the Invercargill-Gorge Road Highway. This increase in specific yield indicates that recharge occurring upstream under well-drained Waikiwi soils begins to discharge to the creek as groundwater under the influence of the steepening of the creek bed in the escarpment area.

Table 5 Flow and specific discharge summary for the Surface Water Quality Study

	Catchment	August	September	October	November
Flow	***Waituna Ck***	246 (64%)	3,539 (91%)	1,079 (67%)	317 (68%)
(l/s & % of total catchment flow)	***Moffat Ck***	47 (12%)	129 (3%)	125 (8%)	43 (9%)
	Carran Ck	93 (24%)	258 (6%)	403 (25%)	105 (23%)
Specific Discharge	***Waituna Ck***	26.4	378.5	115.5	33.9
(l/s/ha)	***Moffat Ck***	32.8	90	87.4	29.9
	Carran Ck	35.7	98.6	153.9	40.2
		August	**September**	**October**	**November**
Areas with high specific discharge		*Carran & Moffat with organic & gley soils*	*Lower Waituna*	*Carran Creek, Lower Waituna*	*Lower Waituna & areas with gley soils*
Areas with low specific discharge		*Upper catchments with brown soils & podzols*	*Lower Carran, lower Moffat*	*Moffat Creek, areas of gley soils*	*Upper catchments with brown soils & podzols*

5.1.2 HYDRO-CHEMICAL ZONATION

Samples of groundwater underlying brown soils show a composition indicative of groundwater that has evolved with water-rock interaction in mQa gravels. These samples show Na enrichment relative to Cl due to cation exchange with clays, and low HCO_3-Ca ratios (Rissmann et al., 2012). Samples in this area are either oxic (type 2b) or anoxic (types 1a, 1b or 1d) (Environment Southland, 2012 unpublished, see also detail on Hierarchical Cluster Analysis).

The determining factor for the redox status of samples from the mQa gravels appears to be the spatial distribution of soils. The imperfectly drained Woodland and Mokotua brown soils promote anoxic conditions, whereas the freely drained Waikiwi brown soils promote oxic conditions. Groundwater samples from beneath or down-gradient of Waikiwi soils show characteristics of fresh land surface recharge. These samples have relatively lower concentrations of HCO_3 (<45 mg/L), low pH (<6.2), and elevated concentrations of NO_3 (>3mgN/L), K (>1.5 mg/L) and SO_4 (>10 mg/L).

The key criteria indicating land use impacts on groundwater quality have been identified by Rissmann, et al. (2012) as a high NO_3/SO_4 combined with a high K/SO_4 ratio. Groundwater samples from areas within Waikiwi soil show the highest NO_3/SO_4 ratios. However, samples of tile drain waters draining gravels with brown soil pastures show a very similar composition (Rissmann et al., 2012).

The ability to link water compositions characteristic of soil drainage to underlying groundwater chemistry is conclusive evidence that the Waikiwi soils are the main rainfall infiltration pathway in the Quaternary alluvial gravels. The question remains as to whether this nitrate-enriched groundwater becomes de-nitrified as it passes through or underneath anoxic gley sub-soils on its pathway to the surface water network. Waituna Creek waters have a similar composition to both groundwater recharged through Waikiwi soils and tile drain waters from imperfectly drained brown soils. It is therefore difficult to know whether artificial drainage or groundwater base-flow is the dominant nitrate pathway to the Waituna Lagoon.

Infiltration from land surface recharge is also evident in samples beneath Orikaka podzols, which have been interpreted by Landcare Research as being sensitive to nitrate leaching. Hierarchical Cluster Analysis (HCA) shows that these samples are type 2a (Environment Southland, 2012 unpublished), with a mixed redox status and evidence of land use impacts. Like the samples beneath the Waikiwi soils, these samples show elevated NO_3, and low HCO_3 and pH which are characteristic of recent recharge.

5.2 SURFACE WATER QUALITY: HIERARCHICAL CLUSTER ANALYSIS

Clint Rissmann of Environment Southland carried out a statistical analysis of surface water quality data collected between December 2011 and November 2012. Data was collected over this period on an approximately monthly basis at key sites. The results of study are known as the Waituna “Surface Water Quality Study” (Environment Southland, 2012 unpublished), and were written as a draft report in 2012 but not published.

The approach used by Dr Rissmann for statistical analysis was (HCA), which was a means, in this case, for grouping samples into similar water types. The italicised text below is the section on HCA results from the 2012 draft report. We have included this section because of its importance in aiding an understanding of surface water quality in the Waituna catchment. Some minor editing for the purposes of clarity has been included in this section.

The HCA dendrogram produced two major surface water types that are very different from each other at a coarse level (800 phenon line). Type 1 waters account for 87.5 % of the waters sampled and Type 2 the remainder (12.5 %). All Type 1 waters are associated with intensively farmed land and exhibit a high degree of variability whereas Type 2 waters exhibit minor variability and are the only surface waters originating from a relatively unmodified peat wetland complex. Type 1 waters are characterised by 17 different hydro-chemical facies whereas Type 2 waters are all Na-Cl waters.

At this coarse level, Type 1 waters are defined by greater dissolved concentrations of Ca, Mg, K, SiO_2, SO_4 and HCO_3 but similar Na and Cl to Type 2 waters. Type 1 waters are also more oxidised, with near neutral pH and lesser dissolved organic carbon relative to Type 2 waters. Total Nitrogen (TN) is twice as high in Type 1 waters with a greater proportion of dissolved inorganic forms relative to Type 2 waters where dissolved organic forms dominate. Total Phosphorus (TP) concentrations are similar between Type 1 and Type 2 waters and yet the composition of the phosphorus pool differs markedly. Within Type 2 waters

~100% of the phosphorus pool occurs as Dissolved Organic Phosphorus (DOP) whereas only 33% of the total phosphorus pool for Type 1 waters occurs as DOP - the bulk occurring as particulate phosphate.

At a finer HCA resolution (600 phenon line) Type 1 waters diverge into two distinct sub-clusters, Type 1A and Type 1B. These sub-clusters account for 65.6 % and 21.9 % of the total data set, respectively. The larger category of Type 1A waters are associated with Carran and Moffat creeks within the southern wetland portion of the catchment. All Type 1B waters are associated with Waituna Creek and mostly occur in the north of the catchment.

Type 1A waters constitute a more reduced variant with three times the organic carbon concentration and markedly smaller concentrations of oxidisable nitrogen species and SO_4 than Type 1B waters. A proportionately greater wetland signature for Type 1A waters is also reflected in lower pH, Ca and HCO_3 concentrations relative to Type 1B waters. Type 1B waters from Waituna Creek contain 8 times the NO_3 concentration of Type 1A waters as well as having lower concentrations of organic carbon, reduced Fe/Mn and TP. In both Type 1A and Type 1B waters Particulate Phosphorus (PP) is the dominant Phosphorus (P) fraction. Type 1A and Type 1B waters reflect a split between high organic carbon, organic soils of low oxygen status setting in the south and low carbon, mineral soils of high oxygen status in the north, respectively.

At the finest HCA resolution (200 phenon line), Type 1A waters are further segregated into Type 1A-1 and 1A-2 waters, which account for 43.7 % and 21.8 % of the data set, respectively. The sites classified as Type 1A-2 waters, although all occurring within the southern wetland section of the catchment, are associated with a greater proportion of mineral soils and alluvial gravel aquifers when contrast with the more common Type 1A-1 waters. Type 1A-2 waters are restricted to headwaters of Carran Creek, an area where reduced mineral soils have developed on top of mid Quaternary clay, silt, sand and gravel. In contrast, all but one of the sites that are designated as Type 1A-1 waters occur within areas mapped as former peat swamps. This difference in source environment is reflected in greater concentrations of organic carbon, reduced Fe and Mn, but lower SO_4 and Total Dissolved Nitrogen (TDN) relative to Type 1A-2 waters. Calcium and K are also lower in Type 1A-1 relative to Type 1A-2 waters reflecting the lesser mineral content of soils and aquifer materials at these sites.

Figure 15 shows the results of the Surface Water Quality Study HCA at each sample point within its associated sub-catchment. The water type identified by HCA closely reflects the soil distribution upstream of each site. The headwaters of Carran Creek are represented by Type 1A-2 water, springs south of Caesar Road by Type 1A-1, Waituna Creek by Type 1B, and Craws Creek by Type 2 water. Waituna Creek at Marshall Road seems to oscillate between Type 1A-2 and 1B water. This variation does not appear to be associated with flow, although it is likely that it reflects a change in the contribution from different flow paths.

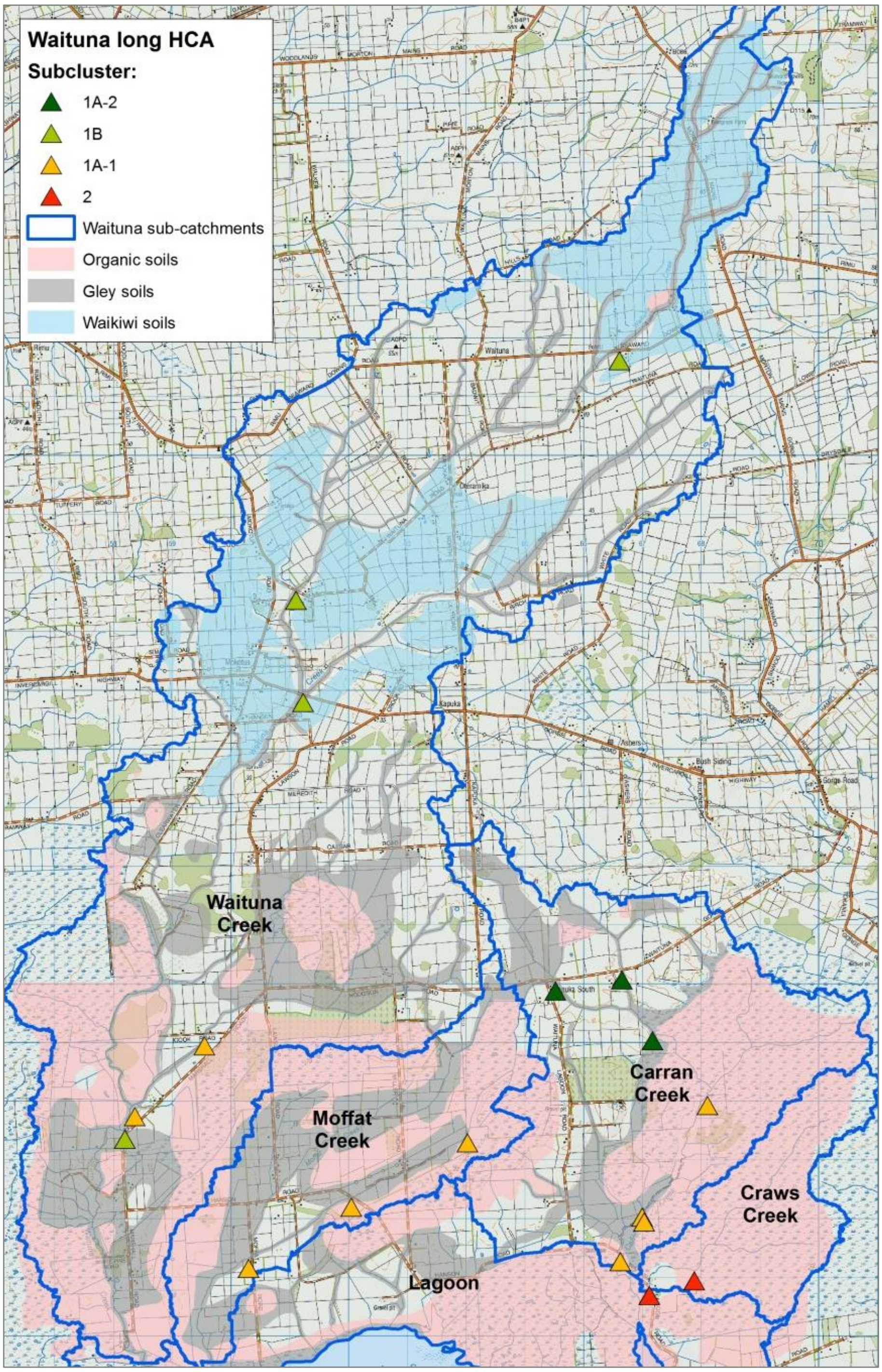

Figure 15 Surface water types derived by HCA (data courtesy of Clint Rissmann)

The mixing of groundwater discharge through gley soils with water sourced from organic soils may explain the distinction between Type 1A-1 water with the highly reduced Type 2 water of Craws Creek, which is expected to have a negligible contribution from groundwater discharge.

5.3 MODES OF NUTRIENT TRANSPORT

Figure 5 and Figure 16 show the spatial distribution of soils highlighted in Table 1 as being prone to nitrate leaching. Mean surface water and groundwater nitrate-nitrogen concentrations are also shown for the available record of each site. The spatial pattern of elevated groundwater nitrate concentrations closely follows the spatial distribution of soils that are identified as being more susceptible to nitrate leaching. In the Mokotua area nitrate concentrations exceed 2 mg/l beneath or down-gradient of Waikiwi soils. Two isolated instances of elevated mean nitrate occur close to Waituna Lagoon, and these bores are overlain by Orikaka pan podzols. The bores with elevated nitrate also tend to have low bicarbonate concentrations and low pH, which is typical of recently recharged groundwater in gravel aquifers.

5.4 GEOCHEMICAL CONTROLS ON INPUTS

Stream sampling shows that nitrate nitrogen concentrations increase with flow in all of the Waituna sub-catchments (NIWA, 2012). There are three interpretations of the source for this nitrate at higher flow:

1. **Groundwater pathway**: Rainfall is being infiltrated to groundwater beneath well-drained soils, thereby increasing the instream nitrate concentration by an increase in nitrate-enriched base-flow.
2. **Refused recharge**: Soil moisture exceeds field capacity, but either high water table or low hydraulic conductivity in limiting horizons in the soil/sub-soil opposes infiltration to the shallow aquifer and the excess diverts into the creek network by lateral drainage.
3. **Artificial drainage pathway**: For poorly-drained soils nitrate is being flushed from tile drains into the main stream channels in response to rainfall events.

A key question to resolve is whether the early storm response is a dilutive effect, followed by nitrate-rich groundwater discharge, or whether artificial drainage is rich in nitrate and is being diluted by base-flow. This is the critical question for controlling land use activities, since it determines whether to focus on freely draining or poorly draining soils. At this stage we are unclear on which of these processes is the dominant driver of nitrate concentrations in the streams.

To assist in understanding the system's response to rainfall events requires high resolution nitrate data from the stream, coupled with either stream flow or stage data at carefully selected locations in the creek. A small record of continuous data has been reported by Diffuse Sources (NIWA, 2012) for a storm event in May 2011. The record was collected in Waituna Creek at Marshall Road. This is not an ideal site for resolving catchment dynamics since the site integrates many types of potential flow paths rather than targeting specific pathway processes. However the results from that event do indicate that nitrate concentrations are higher on the falling limb of the hydrograph. This pattern is consistent with an early dilutive runoff contribution followed by nitrate-enriched groundwater discharge.

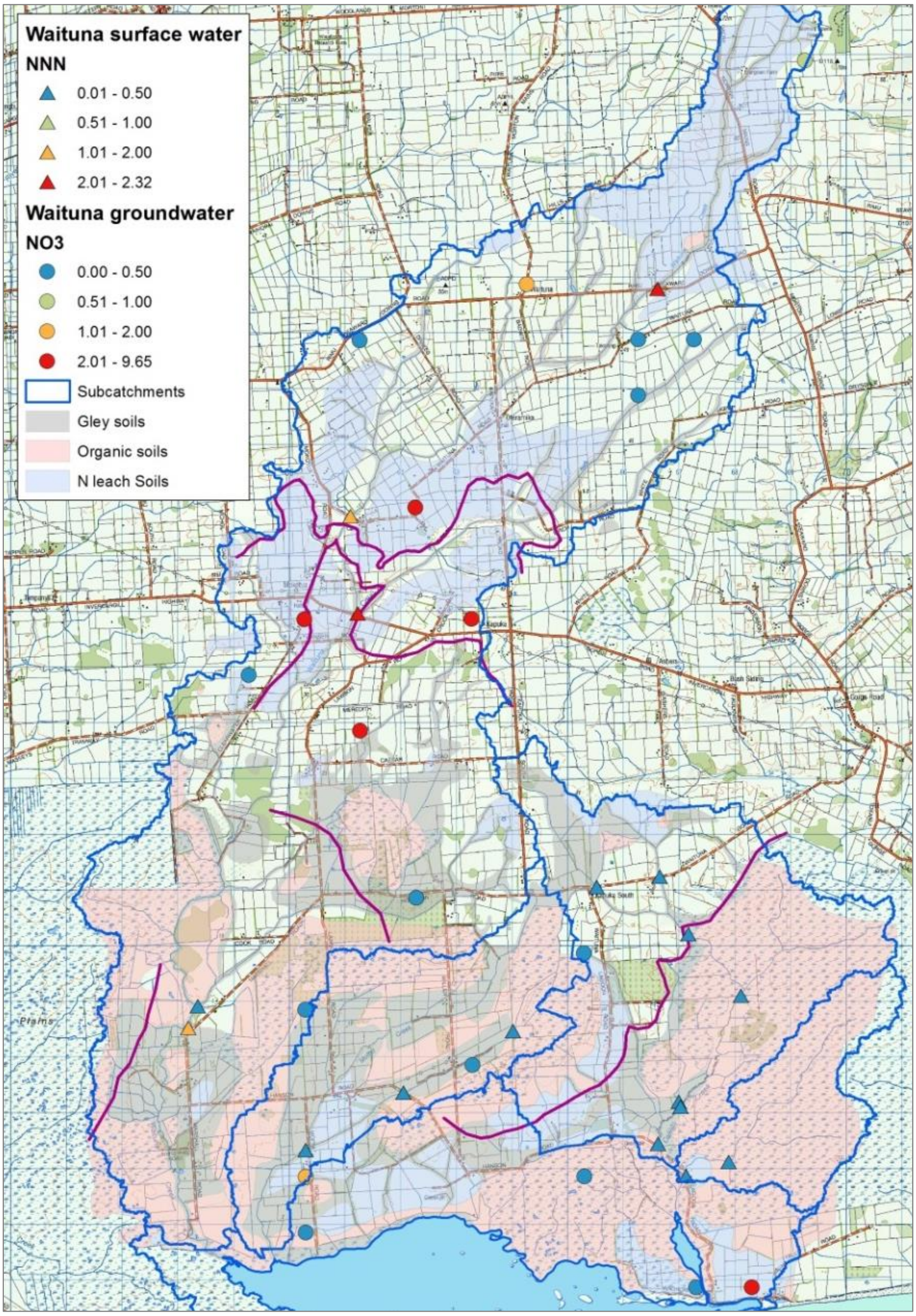

Figure 16 Map of imperfectly drained soils (gley and organic), and soils considered prone to nitrate nitrogen leaching ('N leach'), alongside classed creek and aquifer nitrate results[3]

[3] NNN = Nitrate Nitrite Nitrogen in gN/m^3, NO_3 = Nitrate Nitrogen in gN/m^3

6 SYSTEM NITROGEN MASS BALANCE

6.1 NODAL MASS LOADS

Since most of the nitrate to Waituna Lagoon is sourced from Waituna Creek, this section will focus on Nitrate-Nitrite Nitrogen (NNN) concentrations and flows within this sub-catchment. The focus of sampling for NNN in the Waituna catchment has been Waituna Creek at Moffat Road. A large number of samples have also been taken in the lower Moffat and Carran Creek sub-catchments (Table 6). The Moffat and Carran Creek systems have been interpreted to be geochemically reduced for most of the year, which is reflected in lower NNN concentrations than Waituna Creek.

Table 6 Summary averages & range in gN/m^{3}of NNN for the Waituna catchment

Site	Start	End	Samples	Mean	Max	Min
Waituna Creek at Marshall Road	20-Jul-95	1-Jul-15	362	1.7	4.8	0.0
Moffat Creek at Moffat Road	13-Aug-01	8-Jun-15	271	0.7	3.3	0.0
Carran Creek at Waituna Lagoon Road	13-Aug-01	8-Jun-15	260	0.7	2.5	0.0
Carran Creek Trib (Craws) at Waituna Lagoon Road	13-Aug-01	9-Jun-14	233	0.0	0.1	0.0
Waituna Creek at Waituna Road	13-Aug-01	9-Jun-14	190	2.0	5.6	0.2
Waituna Creek at White Pine Road	11-Apr-11	13-May-13	76	2.2	4.4	0.0
Waituna Creek at Rimu-Seaward Downs Road	8-Dec-11	9-Jun-15	58	2.2	5.5	0.1

There have been sufficient samples taken from Waituna Creek at Rimu-Seaward Downs Road, Waituna Road, and Marshall Road for a preliminary determination of nitrate source dynamics to be made. A time series for these three sites (Figure 17) indicates decreasing NNN concentrations downstream towards Marshall Road during autumn and winter.

From this temporal-spatial pattern we can conclude that nitrate is being rapidly transferred into the creek network in the upper catchment during winter. During summer, residual nitrate is entering the stream as base-flow lower in the catchment. Conversely, samples during 2013-2014 at Rimu-Seaward Downs Road and Waituna Road show that nitrate concentrations fall below 1 mg/l each summer. The reason for this is that nitrate retained in the groundwater reservoir is being depleted via stream discharge, and there is very little new nitrate being leached into the system at this time of year.

There is some evidence for distinct shifts in relative NNN concentrations between Waituna Creek sampling sites in the temporal cross-over from summer to winter to spring. While the apparent flushing out of accumulated NNN concentrations from groundwater into surface water is a relatively subtle manifestation in terms of concentration patterns, the shift is more discernible in nitrogen loads presented further on.

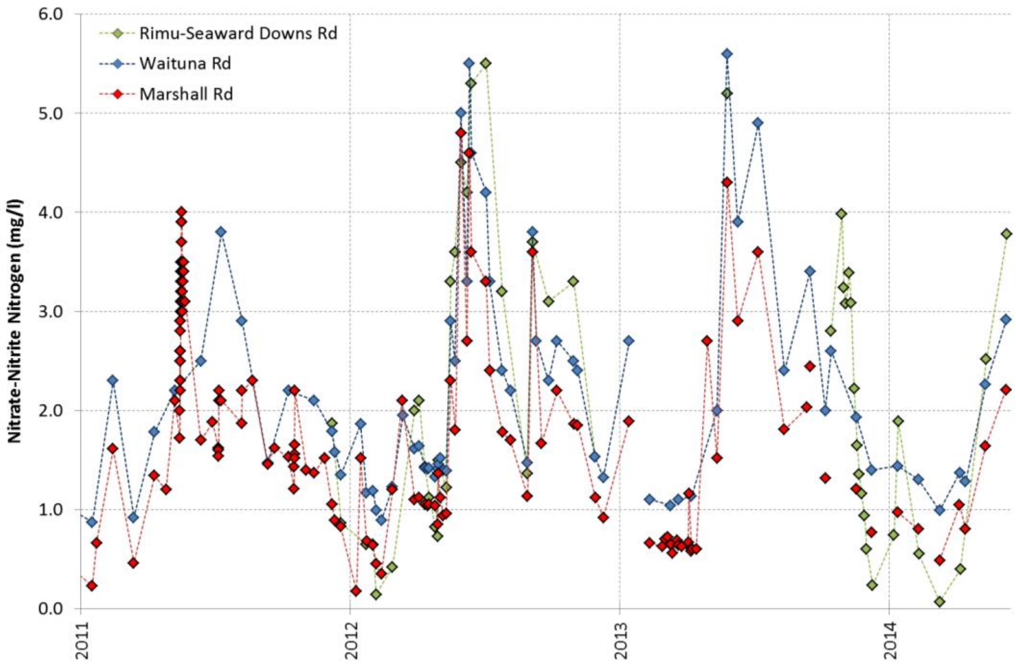

Figure 17 NNN concentrations from 2011 to 2013 within Waituna Creek

As outlined in section 5.1, a more detailed study of catchment water quality was undertaken in 2012, for an Environment Southland project called the 'Surface Water Quality Study'. This study involved the collection of water quality samples and flow gauging values at strategic points in the Waituna catchment on an approximately monthly basis with the aim of understanding water quality changes at a finer scale. Figure 18 shows the relationship between NNN values and gauged flow at the five Waituna Creek sites included in the Surface Water Quality Study. This cross-plot reveals a linear relationship at the upper three sites. There appears to be a log relationship at SE tributary and Marshall Road, suggesting that there is a substantial dilution of stream nitrate concentrations by lower nitrate concentration water in the lower catchment.

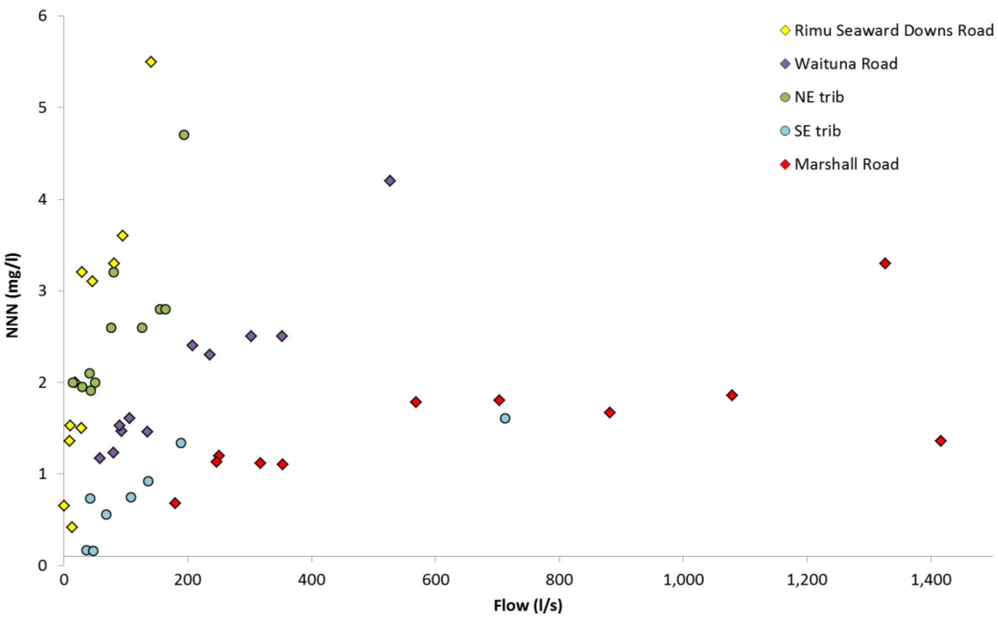

Figure 18 Waituna Creek NNN concentrations vs flow for the 2012 Surface Water Quality Study

There is a clear positive correlation relationship between nitrate and flow at all sites. In general, the highest NNN concentrations are observed in the upper part of the catchment, and there is increasing dilution downstream. Hierarchical cluster analysis indicates that the SE tributary has a reduced redox status, which is consistent with the predominance of gley soils in this catchment. Accordingly, this tributary shows NNN concentrations that are typically less than 1 gN/m^3, although concentrations do increase at higher flows. These higher concentrations suggest that some bypassing of the reduction process is occurring during flow events, either by rapid soil drainage or via artificial drains.

Figure 19 shows the same NNN data as a time series with flow at Marshall Road, but in this version, plotted alongside creek flow. For this graph, samples from a site at (30m upstream of) the Invercargill-Gorge Road Highway crossing of Waituna Creek are available and have been included. This site was not part of the Surface Water Quality Study and has no flow data associated with it, but it has been included in Figure 19 to expand the dataset. We consider the Highway site to be pivotal to understanding processes in the catchment. Concurrent flow gaugings made in late 2011 indicate that the catchment flow yield almost doubles between Waituna Road and the Highway (Environment Southland, 2012). This suggests that the escarpment above the highway is a major area of groundwater discharge, at least during spring time.

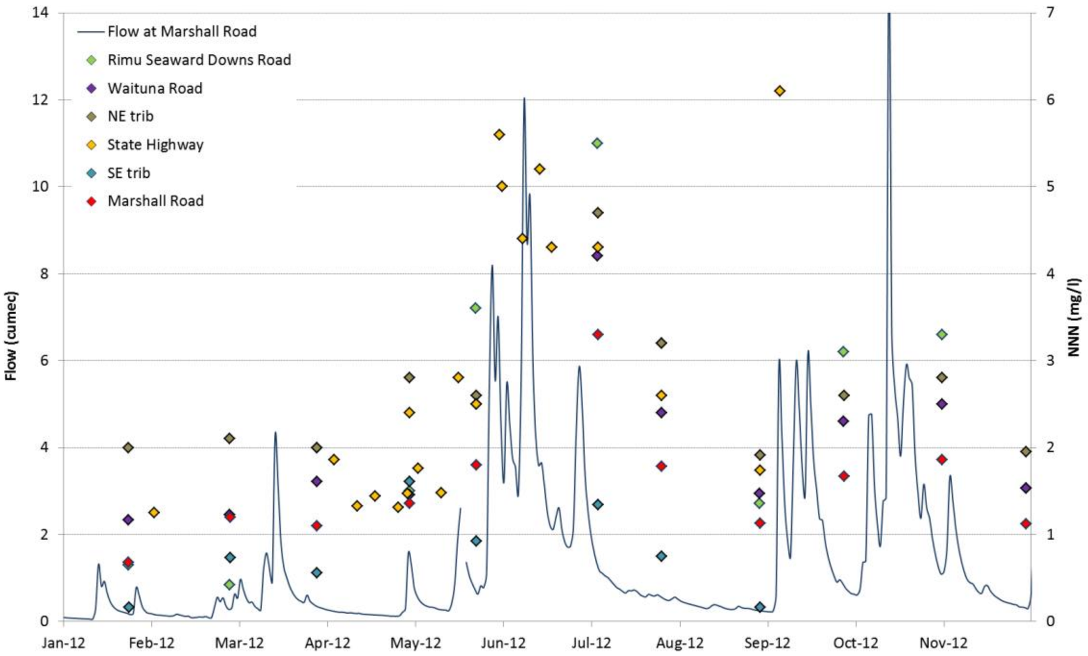

Figure 19 Time series for NNN concentration and flow at Marshall Road during the 2012 Surface Water Quality Study

Figure 19 also shows that nitrate concentrations are highest in the NE (Jordan) tributary during summer to autumn. The highest nitrate concentrations are seen at the Highway site during winter flow events. Nitrate concentrations at the Highway site tend to be slightly higher than those at Waituna Road, although the absolute difference is very small. The increase in flow at the Highway implies that the mass discharge of nitrate from the escarpment area is potentially very large. Furthermore, it implies that the main nitrate travel path is via groundwater discharge along the escarpment rather than tile drains. In conclusion, the concentration data indicate that the key nitrate pathway is infiltration to groundwater via the well-drained Waikiwi soils, and subsequent discharge as base-flow to the stream.

While Figure 18 and Figure 19 allow us to understand the variation of nitrate concentrations down the catchment, they don't indicate the relative amount of nitrate (in terms of mass) that is exported from different source areas. To do this we need to multiply the concentrations by the stream flow to derive a mass flux of nitrate. Figure 20 shows the resulting mass flux and stream flow as a time series[4]. This graph shows that most nitrogen discharge occurs above Marshall and Waituna Roads, although the relative input does change over time throughout the catchment.

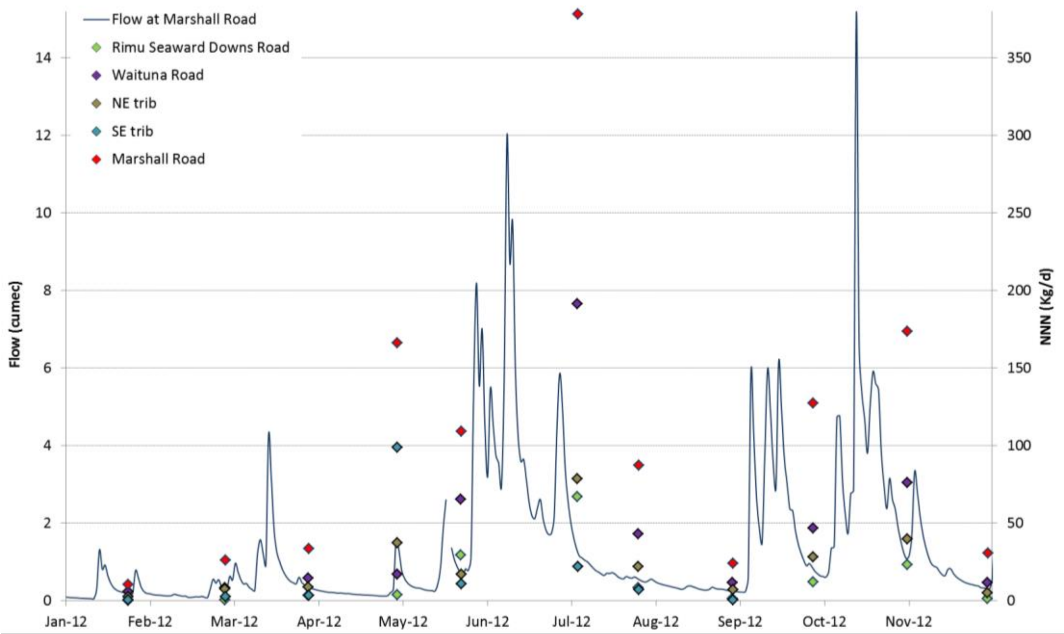

Figure 20 Time series for NNN mass flux and flow at Marshall Road during the 2012 Surface Water Quality Study

Very little nitrogen discharge is occurring during the summer and autumn period at each site, and the NNN discharge is less than 40kgN/d in the period from December to April. The most likely explanation for this is the high daily PET values during the summer, resulting in more cycling of nitrogen in the soil and less soil drainage containing nitrogen through the soil. The soil moisture store is also low at the end of summer, which suggests that the accrual of nitrate in the soil is not mobilized until the soil field capacity is again reached during first large rainfall event in late autumn or early winter. Soil drainage will initially occur within the brown soils and podzols, which have PAW values less than 200mm, particularly the Waikiwi soils which are well-drained and likely to be most responsive to rainfall.

Our concept of the rise and fall in creek nitrogen mass transport includes a marked increase in creek nitrogen concentrations from May to July as shallow groundwater nitrogen is flushed into surface water. The primary influence on the transport of nitrate mass in the stream is the concentration peak, with the rise

[4]Note that we don't have flow data for the Invercargill-Gorge Road Highway site

in creek discharge being secondary. While this seasonal pattern for nitrogen export is clear from the surface water monitoring results, it is more ambiguous in the groundwater record. The plot of groundwater NNN concentrations at the best available groundwater monitoring site, F47/0252[5] at Mokotua settlement, is shown in Figure 21 together with stream flow.

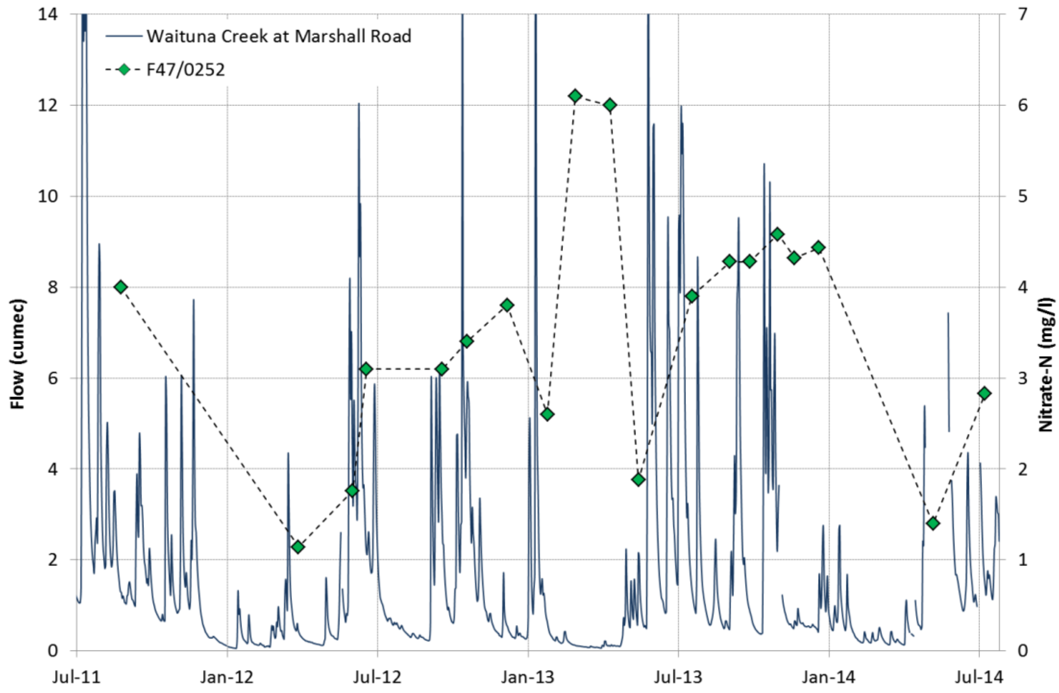

Figure 21 Time series for flow at Marshall Road and Groundwater nitrate-N concentrations

We consider that PET and the water content of agricultural soil through the year is one of the most important factors in the timing of nitrate-laden soil drainage. The distinct drop in PET as the season passes April results in a pronounced increase in soil moisture content to the point where it exceeds field capacity in response to rainfall events. This initiates the transport of nitrogen through the soil profile and into the shallow aquifer, and ultimately the creek network. This change between the winter and spring transfer will be discussed further in Section 6.3.

6.2 ROUTING, ATTENUATION & TRANSFORMATIONS

An assessment of the redox state of groundwater in the Waituna catchment has been made using existing data from the Environment Southland well database. The method for redox assignment follows that of McMahon and Chappelle (2008), and we have applied a simple oxidized, reducing, or mixed (ambiguous) classification. The thresholds for reducing conditions are DO < 0.5 mg/l, Mn > 0.05 mg/l and NO_3-N < 0.5 mg/l. A sample is assigned as reduced or oxidized if two or more parameters are present and are in agreement. In each case samples from the shallow (<50 m depth) aquifer are assessed.

[5] Monitoring bore F47/0252 is 7 m depth, and is located on the Invercargill-Gorge Road Highway about 40 m from Waituna Creek.

Figure 22 shows the results of the redox assignment. Areas of organic soils are consistently reflected in reducing groundwater conditions beneath them. An exception is the far eastern edge of the lagoon, which may have a sandy rather than peaty substrate.

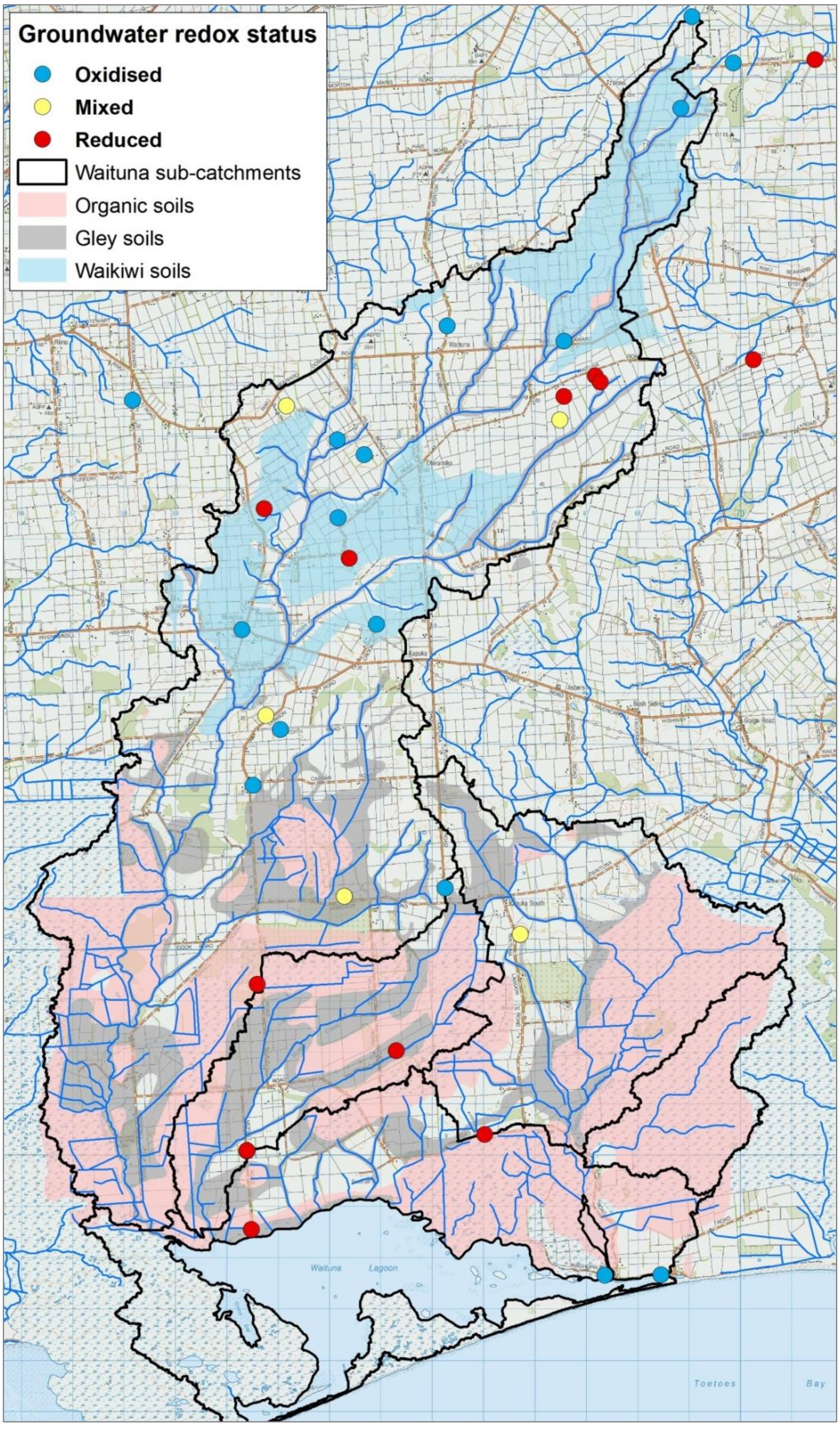

Figure 22 Shallow groundwater redox assignment for the Waituna catchment

Redox predictions associated with gley soils tend to show mixed results, suggesting that the redox state could change depending on groundwater levels or the associated proportion of fresh, oxidized recharge. The redox state of the springs discharging from gley soils south of the Invercargill-Gorge Road Highway also indicate reduced conditions, These creek water samples also have a high organic carbon concentrations, so there is a possibility these waters have become reduced during transport in the stream.

Predictions made from samples in the mid-Quaternary gravels (mQa) typically of the upper Waituna Creek catchment, where brown soils or podzols predominate, show that the groundwater is typically oxidized, but not always so. There is clearly a region of reducing conditions at the top of the NE (Jordan) tributary sub-catchment, and there are a couple of samples in the Mokotua area that show reducing conditions in an otherwise oxidized environment.

The predicted redox state in the mid-Quaternary gravels is difficult to comprehend because there is no clear spatial pattern. The results do suggest that the redox state is related to the overlying soil. Two possibilities for the reduced groundwater samples located beneath Waikiwi soils are that the samples are derived from flow paths that have passed beneath brown soils, or that have received a significant contribution from the underlying Gore Lignite Measures. However, we can't discount the possibility that the observed pattern reflects that the redox state changes over the course of the year in response to land surface recharge events, something that is less likely to be picked up by infrequent groundwater monitoring.

6.3 WAITUNA CREEK CATCHMENT BALANCE

An assessment of the nitrate flux for the Surface Water Quality Study data can be made by accumulating the nitrate mass downstream. To do this we have used the sampled nitrate concentrations from the Surface Water Quality Study to estimate the nitrate flux at key nodes along Waituna Creek.

The sampling sites we have used for this assessment are mapped on Figure 23. While we don't have nitrate concentrations at each of the key nodes in the main stem of Waituna Creek, the following exercise does give an indication of where the main nitrate load originates from at different times of the year. The results have been plotted as a linear graph in Figure 24, and as a semi-log graph in Figure 25.

The majority of samples have been collected during flow recession conditions, and they show a consistent pattern, which is particularly evident in the semi-log graph (Figure 25). The main departure from this trend occurred on 30 April 2012 when the Marshall Road hydrograph was on a rising limb. The trend for this sample is interpreted to be influenced by the time the samples were taken during the onset of a rainfall event, and is therefore not representative of the prevalent system hydrology.

The estimated median mass flux of nitrogen at Marshall Road is 50 kgN/d. For most of the year, the mass flux is less than 40 kgN/d, and it increases immensely during high flow events. The highest mass fluxes by far are recorded at the onset of winter (e.g. 4 July 2012) following nitrate being leached through the soil. The rise in nitrate in the creek in response to the 4 July and 31 October events is very rapid, indicating that tile drains may provide a rapid conduit, and/or the response through the shallow groundwater system is also very dynamic.

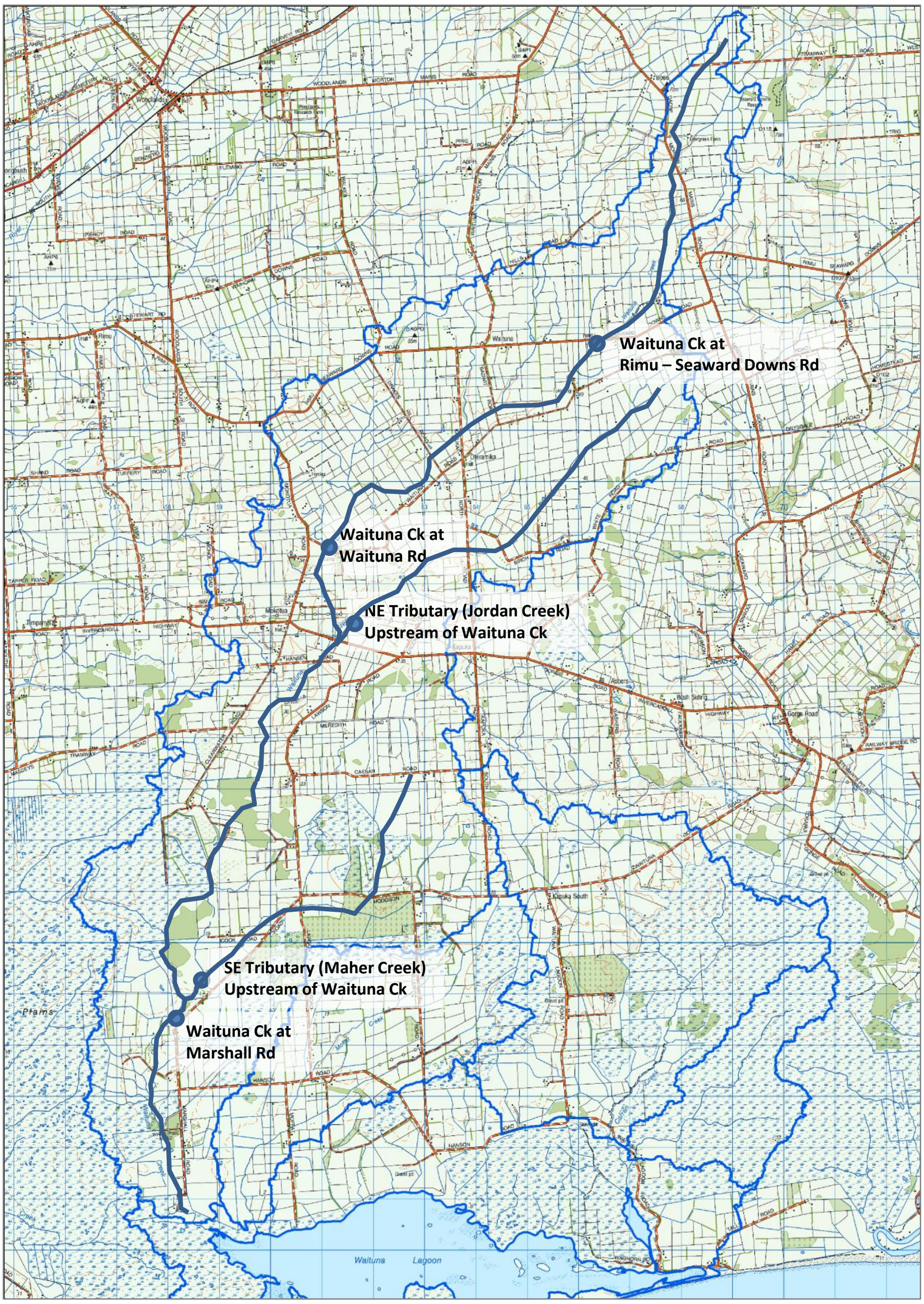

Figure 23 Location of Waituna Creek sampling points

The two graphs show that all times of the year, most of the nitrate mass is sourced upstream of the NE (Jordan) tributary confluence. There is very little additional nitrate contributed from below the NE (Jordan) tributary. As we have outlined earlier, we know that a large mass of nitrate accrues to the creek in the escarpment area between the Highway and the NE tributary because there is both an increase in nitrate concentration and a large increase in flow across this area. This implies that there must be a significant amount of denitrification or stripping by macrophytes or algal mats occurring within the stream between the Highway and Marshall Road.

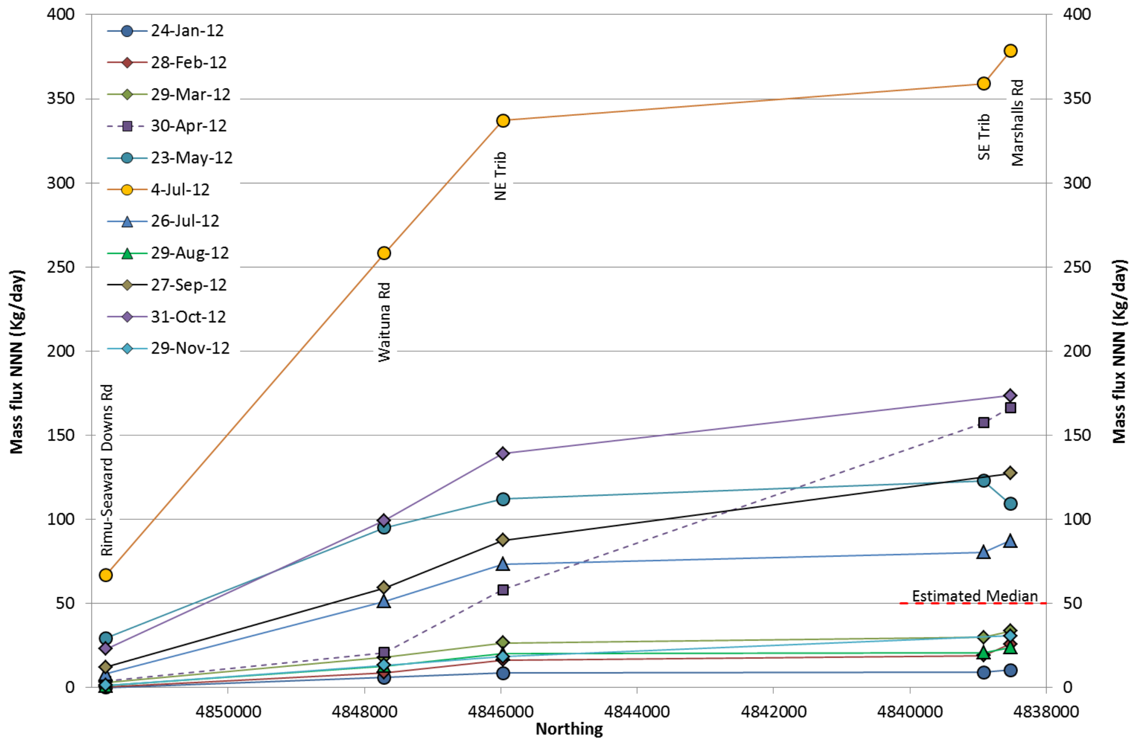

Figure 24 Estimated cumulative nitrate mass flux in Waituna Creek (linear)

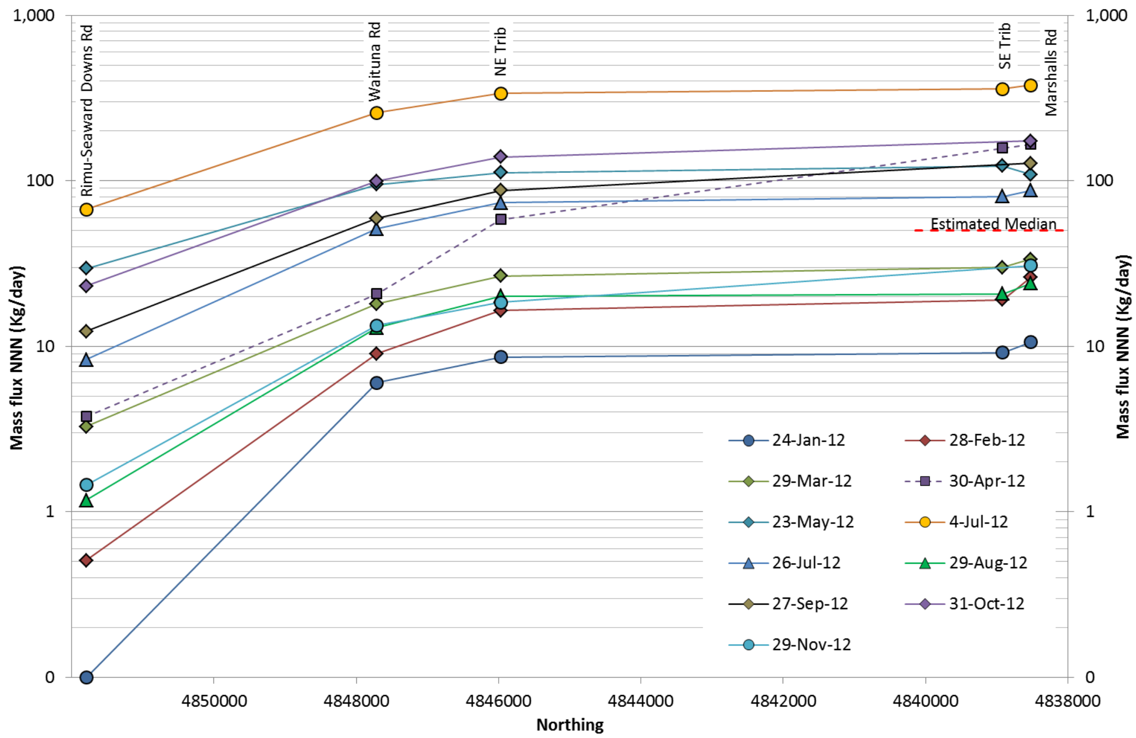

Figure 25 Estimated cumulative nitrate mass flux in Waituna Creek (semi-log)

6.4 DYNAMIC MASS BALANCES

The data have shown that the export of nitrate in the catchment is strongly influenced by high flow (or rainfall) events in the catchment. Since these events are brief, it would be helpful to estimate the mass nitrate flux that occurs during these events relative to the export that occurs during long-term groundwater discharge[6]. To solve this we have derived a relationship between nitrate concentration and flow at Marshall Road (Figure 26). Samples taken on the rising limb of the hydrograph have been removed. These samples can be recognised by high flow and relatively low nitrate concentration, as identified by the 30 April 2012 sample. The removal of these samples produces an exponential relationship with an r^2 of 0.91.

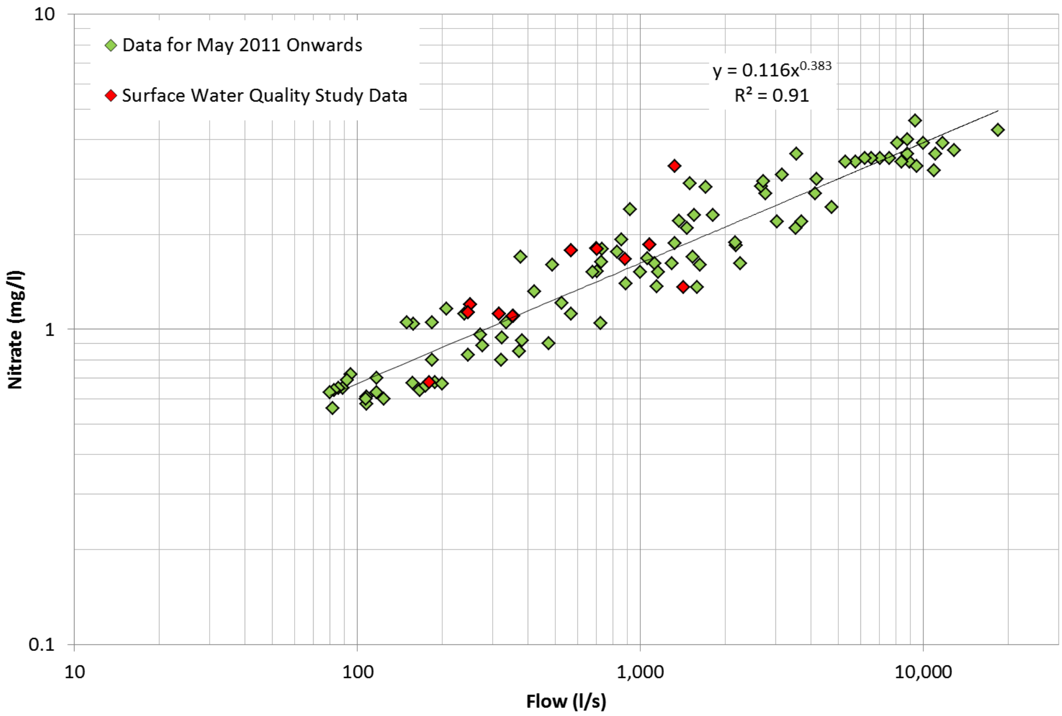

Figure 26 Relationship between nitrate concentration and flow at Marshall Road

The relationship in Figure 26 has been used to develop an estimated probability distribution for daily flow and nitrate mass discharge from the Waituna catchment for a three year period starting 1 August 2012. The results are shown as an exceedance probability plot in Figure 27. The mean and median flows are 1,661 l/s and 801 l/s, and the respective values for nitrate discharge are 360 KgN/d and 103 KgN/d. The slope of nitrate mass discharge steepens during high flow events, which produces mean values that are much higher than the median. The relationship predicts that over a tonne of nitrate mass is exported daily from the catchment 10% of the time, when the high flow events occur.

[6]Base-flow approximating low flows in Waituna Creek at Marshall Road equals 237 mm per annum or 0.81 m^3/s in accordance with Rissmann et al. (2012), Table 1.

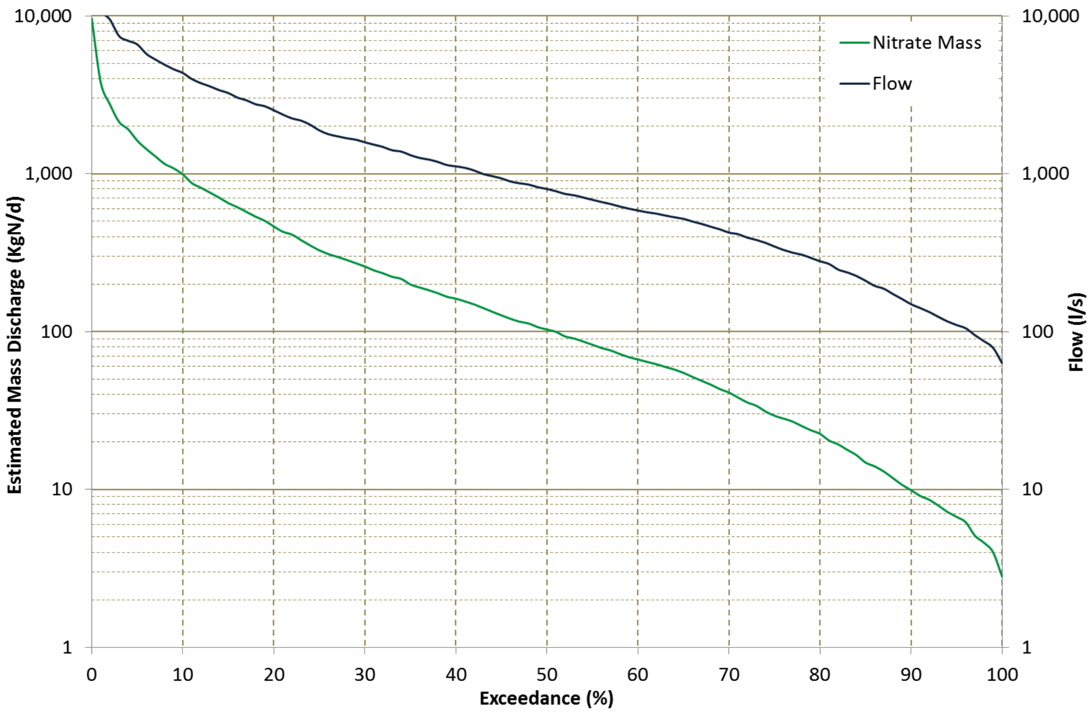

Figure 27 Exceedance plot for nitrate nitrogen mass discharge and flow in Waituna Creek at Marshall Road

Diffuse Sources & NIWA (2012) estimate a mean annual nitrate discharge of 108 tonnes (296 KgN/d) for Waituna Creek at Marshall Road, for the period 1995 to 2011. Our calculated mean annual nitrate discharge for 2011 to 2015 is 131 tonnes, or 360 KgN/d. This is equivalent to an average leaching rate after instream attenuation of approximately 8.1 to 12.7 KgN/ha/y for the entire 10,600 ha Waituna at Marshall Road catchment. The Surface Water Quality Study data suggests that 55 to 85 % of this load is being discharged between Waituna Road and Marshall Road crossings of Waituna Creek, which is an identified discharge zone for the catchment.

The Waikiwi soils between Waituna Road and Marshall Road cover an area of 1,420 ha. If we assume that all of the nitrate contribution to Waituna Creek came from this zone, the leaching rate would be equivalent to 42 to 64 kgN/ha/y. Given the large contrast in soil class drainage properties between Waikiwi soils on one hand, and Woodland and Mokotua soils on the other, we consider that it is reasonable to suppose that a large majority of nitrate in soil drainage is through the Waikiwi soil profile. Using this reasoning, the nitrate nitrogen loss estimate of 42 to 64 kgN/ha/y would hold. The lower end of the range is comparable to the range 'nitrogen loss to water' estimates produced from recent dairy conversions in the Waituna Creek catchment in the last 1 to 2 years (e.g. Milk Power Limited application number APL-20147087).

7 SYSTEM PHOSPHORUS MASS BALANCE

Currently, the most accurate estimates of surface water borne phosphorus mass loads are derived from the work of Diffuse Sources & NIWA (2012) using the least squares regression method and data in the period from 2001 to 2011. Table 7 summarises the calculated mass loads of Dissolved Reactive Phosphorus (DRP) and Total Phosphorus (TP) for the three flow and water quality monitoring points maintained by Environment Southland immediately upstream of the respective outfalls to the Waituna Lagoon. The combined surface water phosphorus loads of DRP and TP are taken as the sum of the main catchment creek loads.

Table 7 Summary of calculated phosphorus mass loads in the Waituna catchment

Site	DRP (tP/yr)	TP (tP/yr)
Waituna Creek at Marshall Road	1.5	6.0
Moffat Creek at Moffat Road	0.9	1.7
Carran Creek 1km U/S Waituna Lagoon Road	0.6	2.0
Combined catchment (sum of above)	3.1	9.7

Source: Diffuse Sources & NIWA (2012)

The calculated mass loads presented above are based on monthly or bi-monthly sampling with only one sample acknowledged to be taken during flooding. Lagoon Technical Group (2011) considered the low representation of flooded creek samples, plus the under-representation of suspended or particulate phosphorus leads to under-estimate of catchment phosphorus load accruing to the Waituna Lagoon. The Lagoon Technical Group also considered that comparing the first five years of the sampling period with the later five years indicated an increase in total phosphorus load of 12% per annum. This increase was not considered to be statistically significant by the Lagoon Technical Group (2011).

A catchment land-use based estimate of phosphorus load between 1995 and 2009 indicated a considerable increase in the land area extent of more intensive agriculture. A consequent rise in the land losses of total phosphorus was observed from 9.7 tP/yr in 1995 to 21 tP/yr in 2009 (Lagoon Technical Group, 2012 using nutrient loss data from Monaghan et al, 2010).

The land-use phosphorus load of 21 tP/yr estimated for 2009 in Lagoon Technical Group (2011) is not reflected in the total catchment load of 9.7 tP/yr calculated from creek sampling and flow measurement from 2001 to 2011 by Diffuse Sources & NIWA (2012). The difference in total phosphorus accounted for by the two methods could result from the following chief causes:

- Uncertainty in the land-use based phosphorus losses used,

- Time lags in the soil and sub-surface vectors of phosphorus transport (e.g. through shallow groundwater as DRP) delaying the expression of rising phosphorus load from agricultural land,
- Under-recording of creek phosphorus load due to entrainment in particulate form, including attached to suspended solids,
- Additional phosphorus joining creek flow between the lowest sampling / gauging site on catchment creeks and the lagoon, and
- Biological removal of phosphorus by macrophytes, periphyton or riparian vegetation between the sites that phosphorus leaves agricultural land and the sampling / gauging sites on catchment creeks and the lagoon.

The differences in estimated and calculated mass loads for phosphorus, and the attenuation processes that we can assume are active in reducing phosphorus loads within the soil, groundwater and surface water systems impair our ability to definitively account for the mass loads moving through the Waituna catchment. However, the Lagoon Technical Group (2011) made a case that in order to prevent Waituna Lagoon developing an undesirable state with turbid, murky water dominated by algal slime, that phosphorus loads should be reduced by up to 75% to bring lagoon trophic state in line with New South Wales coastal lagoon guidelines.

8 CATCHMENT INFLOWS, LAND-WATER QUALITY INFLUENCES & RESPONSES

8.1 REVIEW OF PREVIOUS CONCEPTS

The Mokotua Infiltration Zone (MIZ) is a concept introduced by Environment Southland (Rissmann et al., 2012) to account for rapid through-flow, negligible soil and groundwater nitrate attenuation, and minimal groundwater residence times. The MIZ was interpreted by Environment Southland to represent the Waituna catchment upstream of Marshall Road and downstream to Mokotua with the Caesar Road transition at its centre (see Figure 28). It is difficult to know what is intended by the definition of an MIZ, since use of the word "infiltration" implies infiltration of nitrate through the soil, whereas other descriptions (e.g. Rissmann et al., 2012) imply rapid, near-surface groundwater circulation.

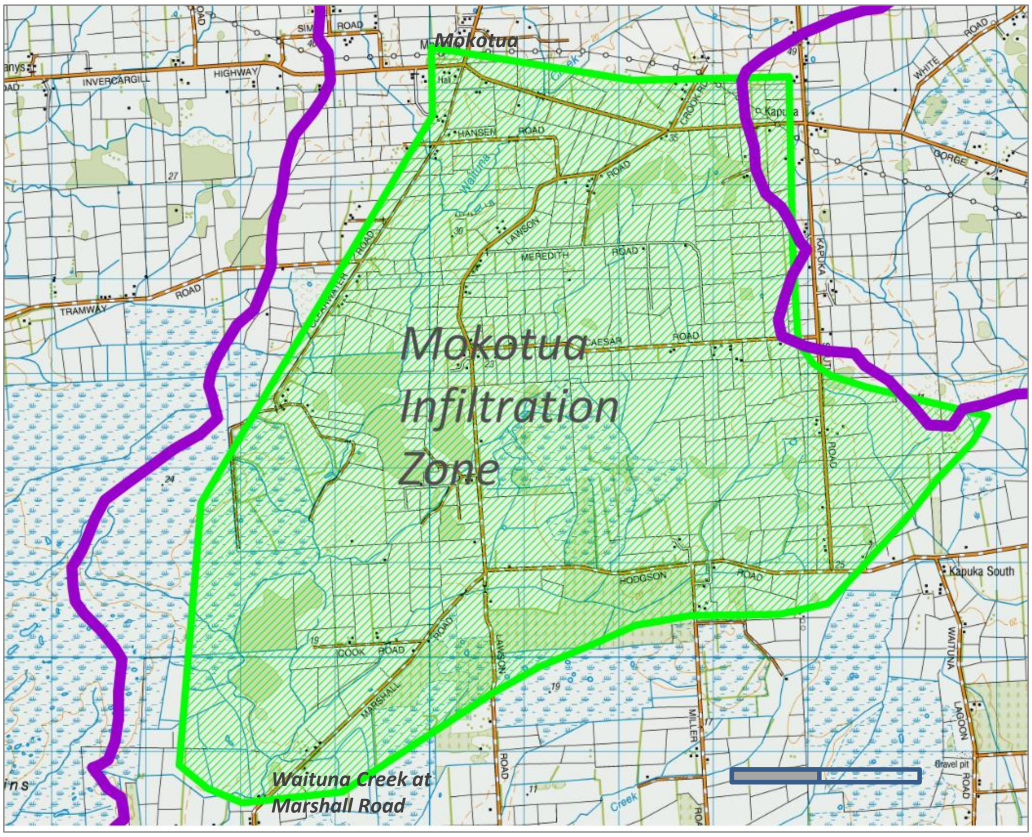

Figure 28 Outline of the Mokotua Infiltration Zone inferred from Rissmann et al. (2012)

To some extent we agree with the area of the MIZ as it identifies the main capture area for groundwater seepage to the surface water network within the Waituna catchment. However, the main area of nitrate infiltration to groundwater does not occur over this same area. The well-drained Waikiwi soils are only found in the extreme northern part of the proposed MIZ, and extend northwards beyond the MIZ boundary.

The Mokotua area envisaged in the MIZ would be more appropriately named the "Mokotua *Discharge* Zone" to acknowledge that this is the area where oxic, high nitrate, and sometimes reduced, low nitrate water is discharged via groundwater or drainage networks into Waituna Creek and tributaries. An infiltration zone would be more appropriately represented by the distribution of Waikiwi soils. Thus, there is a need to distinguish between source and receptor areas. The previous MIZ as outlined in the Environment Southland groundwater technical report (Rissmann et al, 2012) implied dual source-receptor zone of nitrogen infiltration and discharge. We are of the view that infiltration zone and discharge zone are distinct, and also not as strongly tied to the presence of the Q5 paleo shore line (see sections 2.7 and 2.8).

The capture area for recharge to Waituna Creek requires further work to determine the degree to which artificial drainage in the imperfectly drained Woodland and Mokotua soils provides nitrate-rich inflow. An additional question to be explored is whether groundwater emerging as springs along the paleo shoreline to the north of Caesar Road becomes reduced as it passes through the anoxic gley soils.

8.2 TIME LAGS IN GROUNDWATER – SURFACE WATER

Previous examination of time lags relevant to nutrient transport in the Waituna catchment, include two exercises in eigenvector hydrological modelling, which both suggested brief “residence times”. The eigen-vector modelling of the Waihopai catchment surface flows (LVL & MWH, 2003), which was considered to be representative of the Waituna catchment, indicated the following:

- 80% of stream flow has a hydraulic residence time of 5 days,
- The remaining 20% of discharge has a residence time of 120 days.

A Waituna-specific eigenvector model investigation using creek flows and groundwater level data (LVL, 2012) arrived at a similar conclusion with respect to hydraulic residence time in the range of 8 to 13 days.

In considering these estimates it is important to acknowledge two matters:

- The time lags are estimated by model calibration, so the numbers are inferred rather than measured.
- The hydraulic (or hydrodynamic) residence time refers to the time taken for a hydraulic impulse (such as recharge) to have full effect rather than residence time of a pore volume of water.

We consider that the hydrodynamic residence times referred to above are a significant under-estimate of the residence time or time lag for a pulse of nitrate nitrogen laden water to move from the point of infiltration to the point(s) of discharge into a creek in the Waituna catchment.

The Surface Water Quality Study data of 2012 when calculated nitrate-nitrite nitrogen loads and flow are plotted against time (see Figure 20), reveal evidence for mobilization of nitrogen that had accumulated over the summer and eventual exhaustion of the built-up nitrogen store. We consider that nitrate nitrogen in this context is conservative and moves in the subsurface at about the same rate as pore water. This implies that the pore volume residence time for transit of the saturated zone, hyporheic zone and creek water column to the point of water quality measurement is in the order of a few months once the PET drops sufficiently to mobilise the soil-moisture pulse in late autumn to early winter.

The inference of short residence time in the order of a month or two should not come as a surprise to us in view of the relatively low retention brown soils in the upper catchment, thin unsaturated zone overlying the water table and parallel shallow transfer pathways for soil drainage (e.g. tile drains). This is an important conclusion to be able to make, since it suggests a nutrient transport process that resets the stored nitrogen each winter to spring period. The implication arising is that accumulation of nitrogen loads would not extend appreciably from one year to the next. In the context of the Waituna Lagoon eutrophication issues, management solutions that operate on nitrogen load reduction would have effect in a single seasonal cycle rather than taking many years to take effect.

8.3 CATCHMENT BOUNDARIES

One of the questions for review asked whether the surface water catchment boundaries drawn on the basis of terrain were completely appropriate to delineating the full Waituna catchment for nutrient mass loads, including sub-surface pathways. The catchment boundaries of a creek system such as the Waituna catchment are potentially more diffuse than other catchments for the following reasons:

- The first order streams are usually channelized drains that are frequently re-graded to flow against terrain slope for the convenience of the drainage manager. This breaks the linkage between terrain and catchment flow divides.
- Some parts of the catchment are drained more by the shallow groundwater system than the surface water network. This blurs the margins of the catchment where shallow groundwater gradients underflow surface water flow divides.
- The Kapuka Creek catchment to the north of Waituna Gorge Road has a surface water network which mostly drains to the Mataura River. Our interpretation of a northeast trending fault between Waituna Lagoon Road and the Gorge Road platform suggests that the contact between Quaternary gravels and Tertiary sediments dips in a northwest direction. The implication for this is that groundwater in this catchment is more likely to flow in a southwest direction into the headwaters of Carran Creek towards the Mataura catchment.
- The lower catchment has significant areas of peatland and fens that are shared with peatlands and fens of the Awarua Wetland complex or the lower Mataura River at Toetoes Bay. Drawing catchment boundaries through adjoining peatlands and fens is hampered by indistinct flow pattern within them. Boundaries are less static and will tend to shift in response to differentials in water levels.

For the purposes of this discussion, the blurring of catchment boundaries by groundwater flow is more significant to discussion of nitrogen transport through the sub-surface to the Waituna Lagoon. Previous discussion of dynamic nitrate nitrite nitrogen accumulation and transfer in the upper Waituna catchment shallow aquifer (see section 6.4) considered Waikiwi soils to be the primary source area for the nitrogen.

We observe that a considerable area of Waikiwi soils under agricultural land uses lies on the northern flank of the Waituna Creek catchment in the neighbouring Waihopai catchment. The direction of regional groundwater flow is in a southerly direction towards the coast. Figure 29 shows that there is a large extent of Waikiwi soils located immediately up-gradient of the Waituna catchment. A potential groundwater gradient thus exists for nitrate nitrogen bearing shallow groundwater to flow south and cross the surface water catchment boundary. Such under-flowing of the surface water boundary by shallow groundwater would have the effect of increasing the nitrogen loading of the Waituna catchment more than would otherwise be expected.

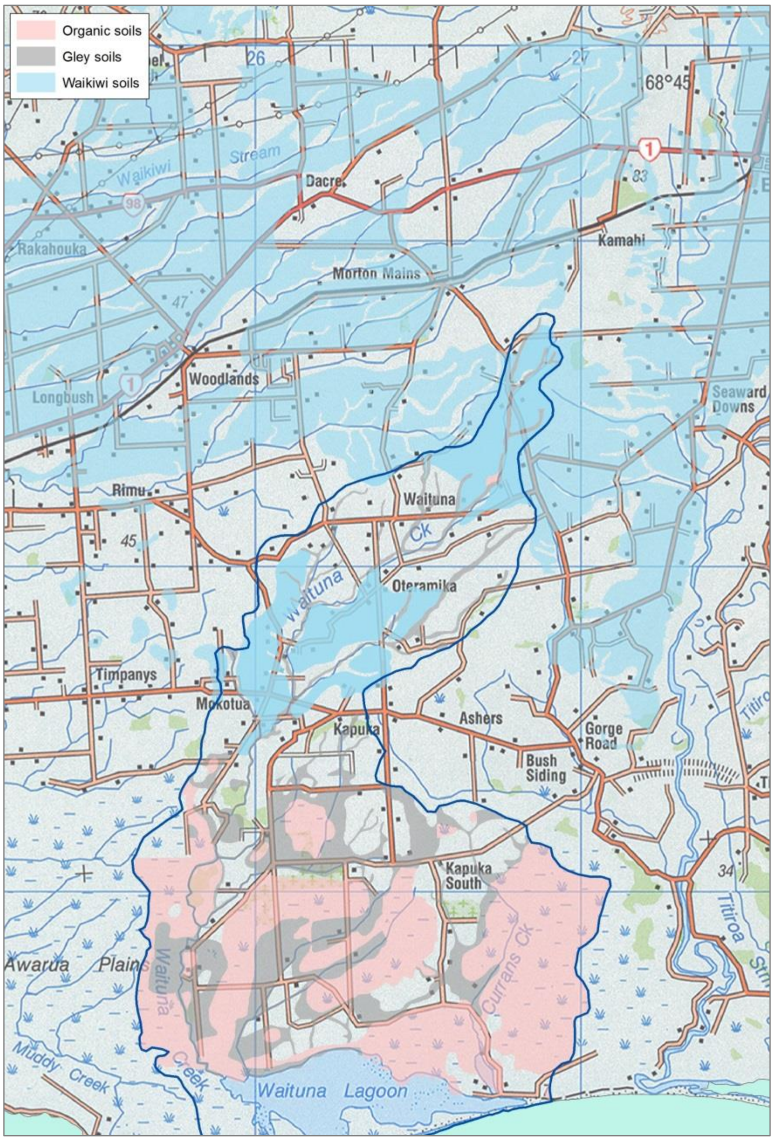

Figure 29 Map showing the wider extent of Waikiwi soils across the Waituna catchment

There is considerable uncertainty as to the extent of Waikiwi soils located in the Waihopai catchment that would affect the nitrogen loading in the Waituna catchment. We would expect that the shallow aquifer on the Waihopai side of the surface catchment boundary would have a groundwater flow divide. The position of this divide is not possible to definitively define on data currently available. A simultaneous high definition shallow aquifer bore water levelling survey of the upper Waihopai and Waituna catchments would be the sole means of estimating the range of positions for the groundwater divide. The quantity of additional loading accruing may prove to be small as a proportion of Waikiwi soils within the Waituna catchment proper, the main purpose of obtaining a more precise determination would be to attribute land-use derived nutrient loadings under any future limit setting process.

8.4 PHYSIOGRAPHIC ZONES

Environment Southland has been developing an integral map of the region's earth and water parameters relevant to rural water quality and groundwater vulnerability called physiographic zonation. The basis of this zonation process has been to integrate aspects of topography, soil cover, geology and surface hydrology that have the most relevant bearing on the tendency of land uses to affect water quality. The primary water quality detriments considered in physiographic mapping are the rural contaminants.

- Nitrogen (total nitrogen, nitrate nitrogen or ammoniacal nitrogen),
- Phosphorus,
- Suspended sediment / turbidity,
- Microbes such as faecal indicator bacteria.

The physiographic mapping process considered soil physio-chemical properties; the age and hydrogeological properties of the superficial geological formations; the geochemical characteristics of sub-soil or shallow groundwater systems; and the influence of recharge processes, such as river recharge from the major rivers containing alpine waters. The zonation maps were compared with the results of water chemical analysis obtained through groundwater and surface water monitoring as a means of calibrating the map zonation process. The physiographic zone classifications chosen to be representative of Southland region, include ubiquitous zones such as Hill Country and Riverine; but also highly specialised zones such as Old Mataura and Central Plains.

None of the specialised zone classifications fall within the Waituna catchment as Figure 30 illustrates. Instead, the Oxidising (soils & aquifers), Gleyed, Lignite – Marine Terraces and Peatlands physiographic zones typify the Waituna Creek, Moffat Creek and Carran Creek catchments. In comparing the physiographic zonation with this review of contaminant transfer modes in the Waituna catchment, the following similarities can be noted -

- Oxidising zonation directly correlates with the location of Waikiwi soils;
- Gleyed zonation incorporates the slow draining brown/minerals soils of the upper Waituna Creek catchment and the very shallow water table podzol soil classes further downstream in mid-catchment;
- Lignite & Marine Terraces correlate with both the strips of emergent lignite measures and inferred Q5a marine terrace strandlines;
- Peat Wetlands falls within the areas of raised bog, marshlands, swamplands and fens in the lower catchment.

As outlined and discussed herein, the oxidised geochemistry and permeable soil properties of the Waikiwi soil classes, plus underlying aquifer are consistent with the nitrate leaching characteristics envisaged in the regional-scale oxidising soils and aquifers zone assigned in physiographic mapping. Similarly, the heavier mineral and podzol soils have much less of a role as a gateway for nitrate to the groundwater system and waterways, and thus merit being grouped with gleyed zonation. The de-nitrified soils and shallow aquifer conditions of the peatlands are more active in phosphorus mobilisation and not a sphere for nitrate transport due to the reducing geochemical conditions predominating within them.

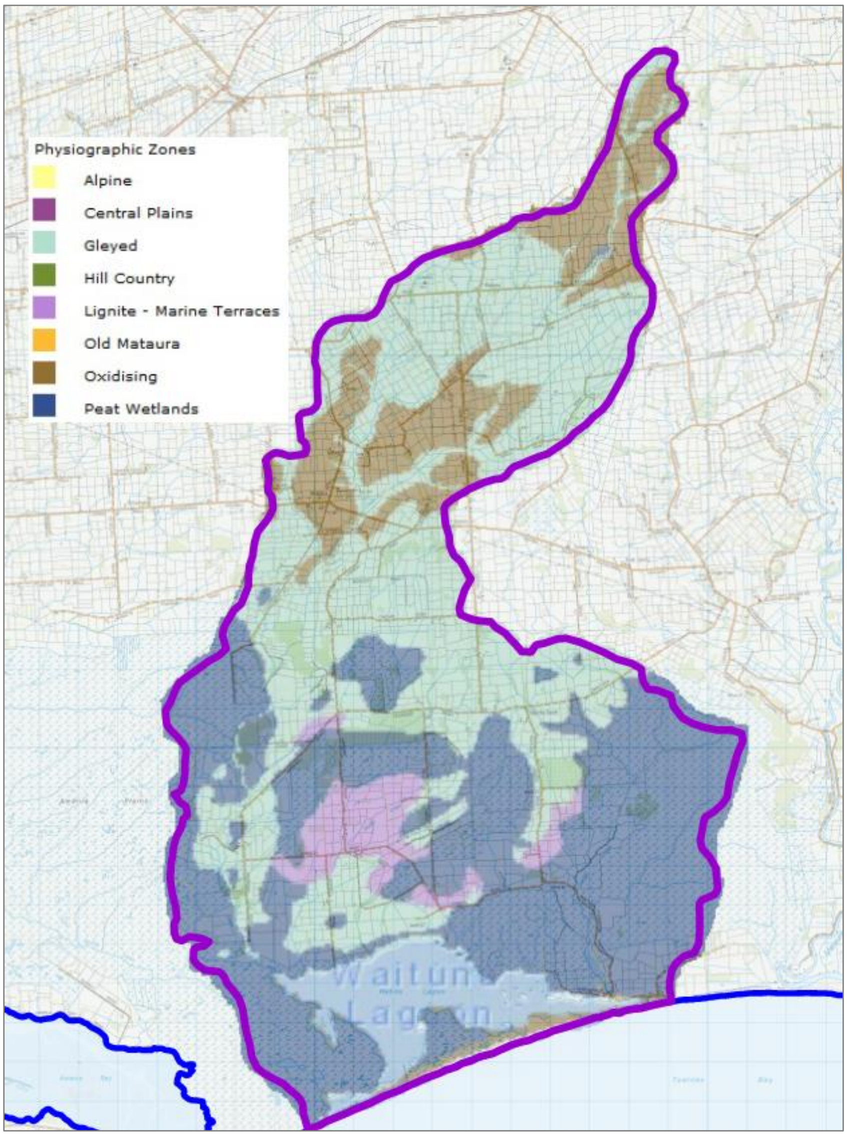

Figure 30 Environment Southland mapping of physiograpic zones within Waituna catchment

Accordingly, the soil-based aspects of catchment contaminant mobility are recognized in regional-scale physiographic zone mapping of the Waituna catchment. Environment Southland considers the 'Oxidised Soils and Aquifers' physiographic zone to be defined by the Waikiwi soil series and particularly prone to nitrate accumulation. Environment Southland considers the 'Peat Wetlands' physiographic zone to be defined by organic soils and generally reduced shallow aquifers with denitrification of oxidised nitrate and enhanced mobility for phosphorus or microbes. Other aspects of contaminant mobility such as the location of significant seepage into catchment creeks cannot be included in regional-scale physiographic mapping, but we consider them to have a significant role on nitrogen transfer to the lagoon.

9 DISCUSSION & CONCLUSIONS

9.1 DYNAMIC NUTRIENT ACCOUNTING REQUIRED

The Waituna catchment displays strong elements of temporal dynamism in its nutrient transfer mechanisms due to moderately retentive soil, thin unsaturated zone and winter-spring flushing of groundwater into creek base-flow. We have found that up to 90% of the nitrate mass discharged *via* Waituna Creek from the upper catchment to the lagoon is discharged in response to rainfall events during late autumn to early winter. The first leaching events of the year occur when PET falls to nominal levels and shallow groundwater down-gradient of Waikiwi soil areas is flushed into creek base-flow.

The dominant source of nitrate discharge is the Waituna Creek catchment upstream of the Invercargill-Gorge Road Highway. The main source of groundwater borne nitrate is therefore spatially removed from the Waituna Lagoon, and connected by base-flow within Waituna Creek, which provides a conduit for the delivery of nitrate through the otherwise post-oxic environment of the lower catchment. Direct groundwater seepage into the lagoon, whether from shallow aquifer or deep Gore Lignite Measures Aquifer seepage, is substantially more likely to have gone through a complete denitrification process that removes much of the nitrogen mass load.

9.2 NATURE OF NITROGEN MOBILISATION & MANAGEMENT

The Waituna catchment is predominantly recharged by rainfall, has a thin groundwater resource, and the majority of nitrate mass load is discharged during storm events *via* Waituna Creek. These characteristics make the Waituna Creek catchment a suitable subject system for dynamic nutrient flux accounting. Accordingly, a good estimate of both nitrate loads on land and mass discharge in the stream can be obtained by continuous monitoring of flow and concentration at strategic locations in the catchment.

Current national policy (Ministry for the Environment, 2014) aims to control the effect of nitrate concentrations in rivers by maintaining median nitrate concentrations below in-stream toxicity thresholds. The National Objectives Framework (NOF, Ministry for the Environment, 2012) nonetheless recognised the special nutrient accumulation circumstances of coastal lakes and ICOLLs (seasonally stratified and brackish lakes). From this we consider the use of median concentrations rather than cumulative loads would be inadequate for protecting the wetland because the recharging catchment is highly dynamic.

The wetland is also often closed to the sea so it is more sensitive to the delivery of nitrate mass rather than concentration. Likewise, the use of a long-term ‘losses to water’ estimation tool like Overseer® is less than adequate for managing diffuse discharges. To protect the lagoon and wetlands requires a focus on reducing the stored mass of nitrate held within the key contributing soils during summer and autumn. The objective is to reduce the mass of nitrate leached during the critical flushing events that occur during late autumn to early winter. This may involve improved land management practices to reduce leaching over the summer to autumn period, or perhaps the retirement of land with high risk soils in the upper catchment.

9.3 CARRAN CREEK

It had been noted in the discussion of the Surface Water Quality Study that the headwaters of Carran Creek had a few anomalous characteristics. In terms of hydrogeological analysis, the Carran Creek catchment is likely to have a larger groundwater catchment than is evident from the surface water drainage network. The Kapuka catchment to the north of Waituna Gorge Road has a surface water network which mostly drains to the Mataura River, so it is tempting to conclude that groundwater drains in a similar direction. However, our interpretation of a northeast trending fault between Waituna Lagoon Road and the Gorge Road platform suggests that the contact between Quaternary gravels and Tertiary sediments dips in a northwest direction. The implication for this is that the gravels are thinnest in the Carran Creek catchment. It also implies that groundwater to the north, in the vicinity of the Kapuka and Ashers settlements is likely to flow in a south-west direction into the headwaters of Carran Creek.

There is some additional empirical evidence that supports the idea of a Carran Creek groundwater capture area that extends into the Kapuka catchment. Firstly, the results of a hierarchical cluster analysis show that surface water samples from Carran Creek have a composition that is distinct from water in the rest of the Waituna catchment. These samples are identified as having a chemistry influenced by recharge through mineral soils and water-rock interaction in a gravel aquifer. This chemistry is consistent with the soils found in the upper Carran Creek, which is dominated by Asherspodzols, but also the Kapuka and Ashers area, which is predominantly Mokotua brown soils. Both of these soil types have imperfect drainage and low nitrate leaching vulnerability.

Secondly, stream flow in the upper part of Carran Creek at Kapuka South has a relatively large specific discharge compared to other Waituna sub-catchments, including Waituna Creek for much of the year. This supports the possibility of a substantial inflow of groundwater from outside of the surface water catchment.

10 RECOMMENDATIONS

10.1 CONTINUOUS NITROGEN MONITORING

Based on the information available, we think it is likely that the Waikiwi soils contribute much of the nitrogen load to the surface water network. However, we cannot discount the possibility of a significant contribution from tile drains over brown soils with impeded drainage. At this stage there is insufficient monitoring data in key areas to definitively identify nitrate source areas. One possible approach to determine the contribution for different sources areas requires high resolution monitoring of nitrate and flow at key locations. This type of monitoring could be done with optical nitrate nitrogen data-logging sensors. We recommend that paired flow and nitrate sensor monitoring be carried out during autumn and winter at Rimu-Seaward Downs Road, Waituna Road, and the (Invercargill-Gorge Road) Highway. High temporal resolution monitoring at these sites will capture data on the discharge dynamics during flow events from source areas dominated by Waikiwi and impeded brown soils.

10.2 SOIL CHARACTERISATION

We also recommend that further work be done to characterise the soils of the Waituna Creek catchment in more detail. We have used the S-Map database to guide our study. This database has been developed at a regional scale, and it may not be sufficiently accurate to adequately capture both the soil distribution and leaching characteristics at the scale of the Waituna catchment. One of the reasons for this conclusion is that the Waikiwi soils appear to be the main conduit for nitrate leaching due to their well-drained characteristics. Despite this, these soils have not been identified in the S-Map database as being vulnerable to nitrate leaching. This is inconsistent with the Topoclimate database, which identifies the Waikiwi soils as having a moderate nitrate leaching vulnerability. The Waituna catchment has a relative abundance of poorly-drained soils, which makes the catchment more vulnerable to leaching from soils that may not be considered to have a significant leaching risk elsewhere in the region. We also note that it may be difficult to distinguish Waikiwi soils from other brown soils in the region. The Topoclimate database and McIntosh (1992) both indicate that other brown soils in the area (e.g. Mokotua and Woodlands soils) are also formed in deep loess deposits. If land were to be retired from dairy farming, it would be critical to identify and map the soils that contribute the most nitrate leaching in the sub-catchment which contributes the most nitrate mass.

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