Tokanui Wastewater Treatment Plant: Assessment of the Physiographic Setting

Lisa Pearson and Clint Rissmann

Land and Water Science Report 2019/17
May 2019

Tokanui Wastewater Treatment Plant: Assessment of the Physiographic Setting

Prepared by
Pearson, L. and Clint Rissmann

Land and Water Science Ltd.
www.landwaterscience.co.nz
61c Leet Street
Invercargill, 9810
New Zealand

Corresponding Author
Dr Lisa Pearson
Contact number: 03 214 3003
Email: lisa@landwatersci.net

Document Information
Land and Water Science Report No: 2019/14
Draft Report Date: 29.03.2019
Final Report Date: 02.05.2019
Project Number: 19014

Reviewed By: Sue Bennett
Organisation: Stantec NZ
Position: Principal Environmental Scientist
Review Date: 01.05.2019

Document Status: Final

Citation Advice
Pearson, L., and Rissmann, C. (2018). Tokanui Wastewater Treatment Plant: Assessment of the Physiographic Setting. Land and Water Science Report 2019/17. p16.

Disclaimer: This report has been prepared by Land and Water Science Ltd. (Land and Water Science) exclusively for, and under contract to Stantec NZ on behalf of Southland District Council. Land and Water Science accepts no responsibility for any use of, or reliance on any contents of this report by any person or organisation other than Stantec and Southland District Council, on any ground, for any loss, damage, or expense arising from such use or reliance. Information presented in this report is available to Stantec NZ and Southland District Council for use from March 2018.

Table of Contents

List of Figures

1 Introduction

Southland District Council (SDC) are currently in the process of renewing their resource consent for the Tokanui Wastewater Treatment Plant (WWTP). Tokanui is a small rural town in southeast Southland servicing approximately 67 residential and commercial properties (Figure 1). The catchment area is approximately 6,717 ha. Stantec NZ (acting on behalf of SDC) has requested an assessment of the physiographic setting within a 2 km radius of the Tokanui WWTP oxidation ponds (Figure 1). The assessment does not attempt to assess the impacts of the disposal of treated wastewater.

The physiographic setting of the Tokanui WWTP described here is derived from recent high-resolution mapping and validation of the Southland region (Rissmann et al., 2019). Performance measures included cross-validated R^2 values of between 0.85 – 0.95 for median Total Nitrogen (TN), Total Oxidised Nitrogen (TON), Total Phosphorus (TP) and Dissolved Reactive Phosphorus (DRP) for regional surface waters. Total Suspended Sediment and E. coli returned cross-validated R^2 of 0.73 and 0.72 for median values. On the ground resolution is estimated at 100 x 100 m associated with the use of soil series as the fundamental unit of scale. Validation is relevant to stream drainage basins of an area >140 hectares with at least 5 years of monthly and event flow monitoring (Rissmann et al., 2019).

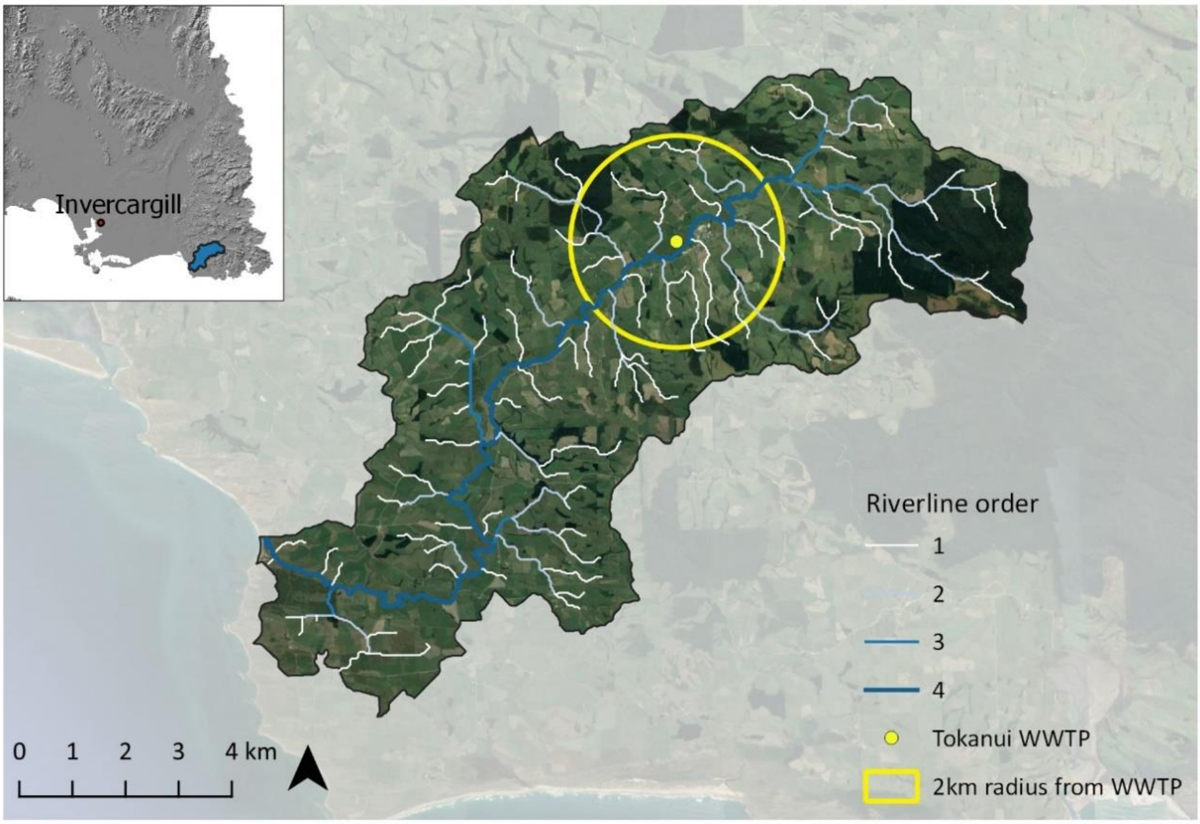

Figure 1: Location of the Tokanui catchment in Southland showing the WWTP (yellow dot) near the Tokanui river and the 2 km area of interest from the site. Catchment area and stream order from REC3.

2 Background to Physiographic Science

The key concept of the physiographic approach is that natural **gradients** in landscape features, which we term **attributes**, govern the variation in the key **processes** that determine water composition, water quality outcomes and risk (Rissmann et al., 2016; 2018; Pearson et al., 2018; Rissmann et al., 2019). The physiographic assessment uses a series of regional-scale geographical information system (GIS) layers to map the landscape controls over the composition and quality of surface and shallow groundwaters across the Southland region. The main landscape controls over water quality are hydrology and redox processes which can be explained through the combination of the following data layers:

- Hydrological process-attribute layers
    - Water source (e.g. alpine, hill, lowland) and the associated dilution potential
    - Water table depth – unsaturated zone thickness
    - Overland flow risk as a percent of annual rainfall
    - Deep drainage
    - Lateral flow through the soil zone
    - Artificial drainage – mainly mole-pipe
    - Natural bypass mediated by cracking soils
- Redox process-attribute layers
    - Soil zone reduction potential
    - Aquifer reduction potential

To best define the effective landscape properties of the region, attributes were selected from several national and regional GIS datasets. This included: topography, elevation, and altitude from an 8 m digital elevation model (DEM; Land Information New Zealand, 2012); geological attributes from the 1:250 000 geological map series (QMAP) covering Southland (Turnbull and Allibone, 2003), and the New Zealand Land Resource Inventory (NZLRI; 1:50 000; Newsome et al., 2008; Lynn et al. 2009); soil attributes from Topoclimate South (1:50 000; Topoclimate South, 2001) and Fundamental Soils Layer (1:50 000; Landcare Research, 2010), land cover from the Land Cover Database (LCDBv4.1; Landcare Research, 2015), and; land use from the Southland Land Use Map (Pearson and Couldrey, 2016). Regarding hydrological input data: catchment area was generated from the River Environment Classification (RECv3; Snelder and Briggs, 2002); riverlines from Topo (Land Information NZ, 2018) precipitation volume from the National Climate Database (Macara, 2013); $\delta^{18}O-H_2O$ of precipitation from the national isoscape model of Baisden et al. (2016), and; unconfined aquifer type (e.g. lowland, terrace, riparian) and extent from Environment Southland (unpublished).

3 Hydrological Process-Attribute Gradients

3.1 Water source and dilution potential

Water source identifies the origin of water in a stream or aquifer with water derived from alpine and hill country areas having both lower solute concentrations but also a larger volumetric mass flux due to elevated catchments with a large surface area and higher rainfall gradients than lowland derived waters. From this information the likely dilution potential of the receiving environment can be estimated. In this evaluation, areas with a mixed water source (i.e., alpine, hill, and lowland land surface recharge) have the highest dilution potential, whilst water recharged solely by local precipitation (lowland) have the lowest dilution potential.

The Tokanui river (stream order 4, drainage basin area of 6,717 ha) originates in the north east and discharges at the coast at the Tokanui estuary – Toetoes Bay (Figure 1). The underlying bedrock is sandstone with interbedded mudstones, shell bed, conglomerate and coal deposits, overlain by shallow unconsolidated aeolian (loess) and alluvial (gravels) sediments in close proximity to the Tokanui river (Turnbull and Allibone, 2003). Peat may also be present within the area of alluvial deposits; however, they are not specifically identified on the topographical (Topo50, Land Information NZ, 2018), geological (QMAP, Turnbull and Allibone, 2003), or soil maps (Landcare Research, 2010; Topoclimate South, 2001).

Areas of Bedrock hill country and Bedrock low relief have a moderate to low dilution potential, whilst areas of unconsolidated low relief have a low dilution potential as the water source to the catchment is land surface recharge from local precipitation (Figure 2).

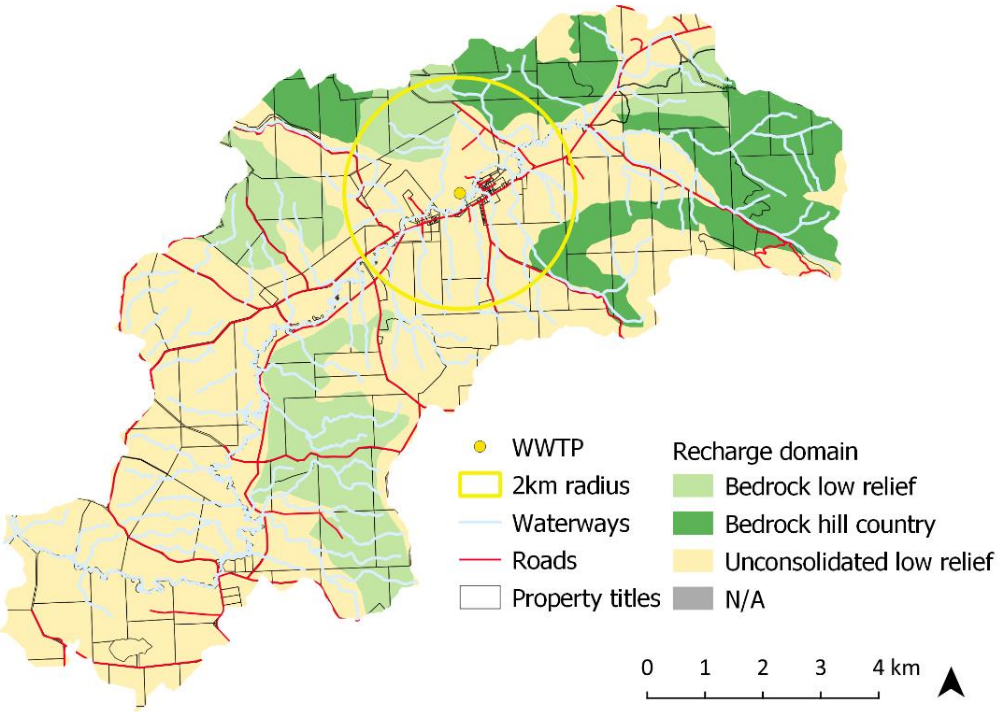

Figure 2: Water source and dilution potential for the area of interest around the Tokanui wastewater treatment plant (WWTP). The WWTP oxidation pond is shown in yellow in the centre of the 2km radius. Main highways are shown in red, with waterways in light blue.

3.1.1 Water table

Water table depth is used as a proxy to estimate unsaturated zone thickness which in conjunction with hydrological properties, such as unsaturated zone texture is critical for understanding the volume of material available for land treatment of treated wastewater.

The catchment is outside Environment Southland's aquifer management zones. However, it is likely shallow unconfined aquifers exist in the area identified as unconsolidated low relief (Figure 2). There are two bores in the 2 km radius of the WWTP oxidation ponds (Figure 3). Bore F47/0230 is approximately 840 m from the WWTP and has a static water level of 12 m below ground level (Environment Southland, unpublished data). Bore F47/0161 is approximately 420 m from the WWTP and 200 m from the Tokanui river. The static water level is 1.5 m below ground level (Environment Southland, unpublished data). Static water level is recorded at the time of drilling and does not represent seasonal variation within the aquifer. Static water level at the WWTP is likely to be less than 1.5 m given its proximity to the Tokanui river (approximately 30 m, Figure 3).

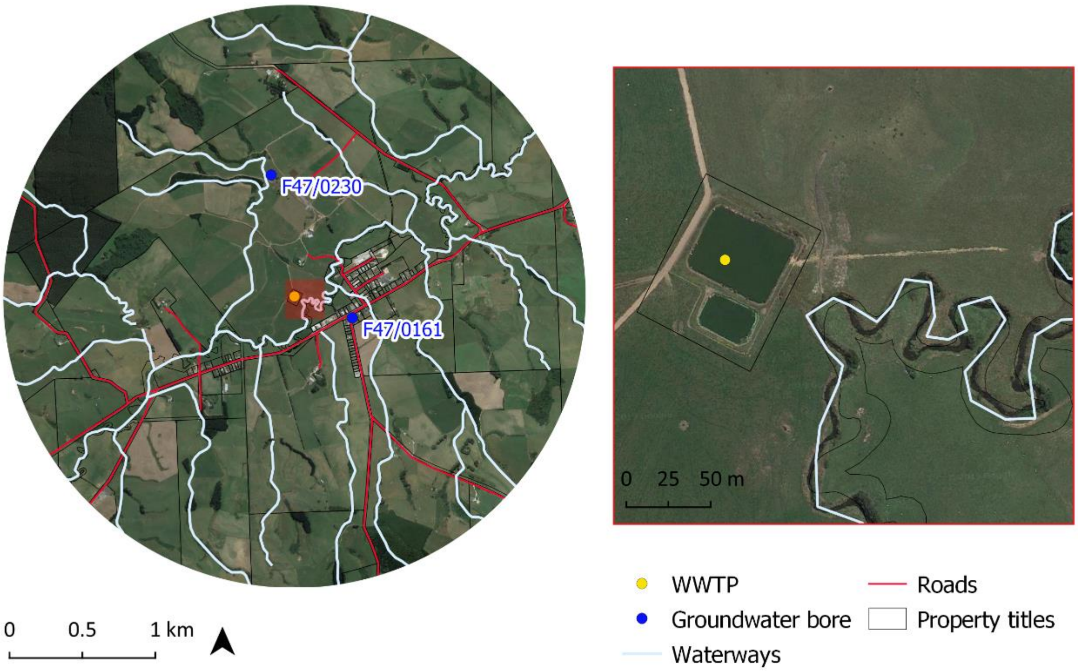

Figure 3: Bore location with static water level depth in the area of interest around the Tokanui WWTP (Data sourced from Environment Southland, obtained 14.11.2018). Wastewater treatment plant oxidation pond is shown in yellow in the centre of the 2km radius (left) with the red shading indicating the extent of the map on the left.

3.2 Overland flow

Overland flow risk was assessed by Pearson (2015a) by identifying areas where there is a higher likelihood of saturation excess overland flow occurring across the Southland region (Figure 4). Overland flow risk is increased in areas where soils have poor internal drainage and are structurally vulnerable to slaking and dispersion, or in areas where there is sufficient slope to generate runoff. The risk assessment is independent of land use management practices or vegetation cover, though it was noted that these factors do have a significant impact on overland flow occurrence (Pearson, 2015a).

Overland flow risk is low at the WWTP site with an estimated runoff risk of less than 2% which increases to 3.2% near the Tokanui river (Figure 4). This increase is due to the soils being slowly permeable and having imperfect to poor drainage in this area. However, it must be noted that the soil data sourced from Topoclimate South (2001) in the vicinity of the WWTP has multiple soil series identified. Whilst secondary soils are accounted for in the assessment by Pearson (2015a), more spatially accurate soil information is needed for a high resolution assessment of hydrological pathways at this site.

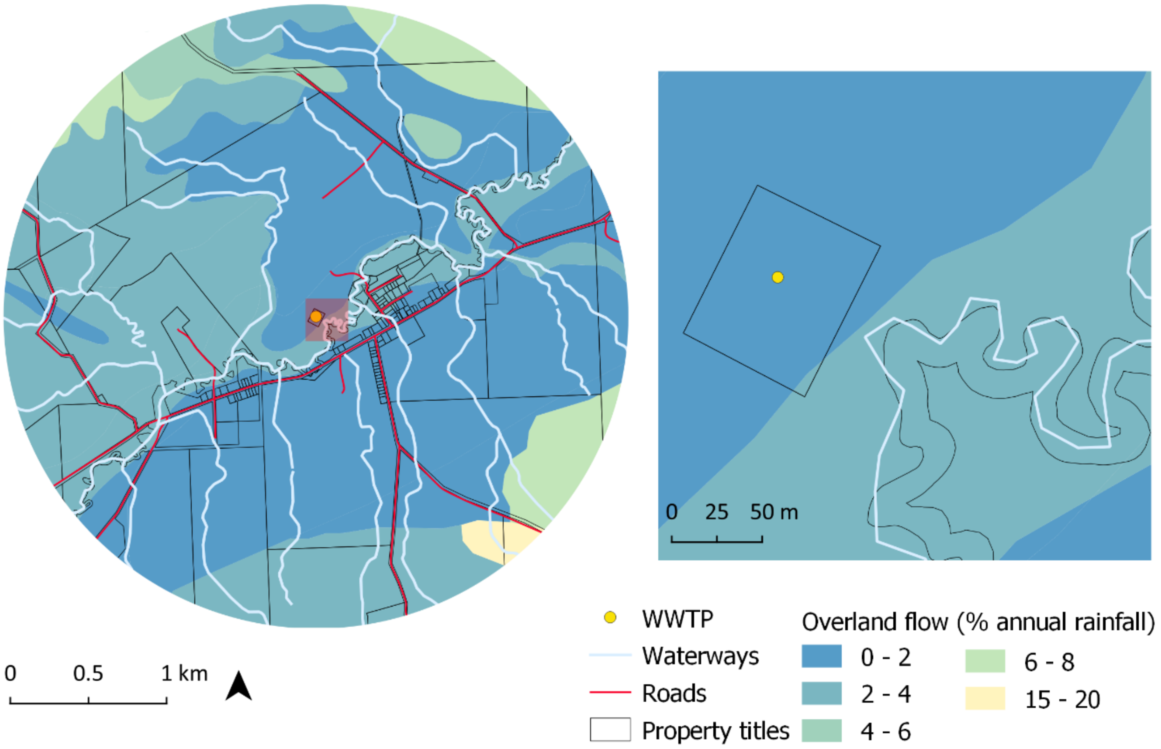

Figure 4: Overland flow risk expressed as a percentage of annual rainfall for the area of interest around the Tokanui WWTP oxidation ponds. Wastewater treatment plant is shown in yellow in the centre of the 2km radius (left) with the red shading indicating the extent of the map on the left.

3.3 Deep drainage

Deep drainage occurs from the percolation of rainfall through the soil zone to underlying aquifers. Deep drainage tends to be highly effective at excluding microbes and sediment and variably effective at retaining phosphorus, depending on the substrate texture, the abundance of the oxides and oxyhydroxides of iron and aluminium, and the thickness of the unsaturated zone. Deep drainage to an aquifer, therefore, delivers primarily nitrogen (nitrate) and/or dissolved reactive phosphorus depending on the composition of the soil and aquifer substrates.

A qualitative indication of water movement in the soil zone was estimated by partitioning water between deep drainage, lateral flow and artificial drainage guided by the quantitative assessment of rainfall recharge by Chanut (2014) and the artificial subsurface drainage classification of Pearson (2015b). Areas with high to very high artificial drainage densities are likely to have a low deep drainage contribution, whilst areas with low to no artificial drainage are likely to have a high deep drainage contribution (Figure 5).

Deep drainage is high at the WWTP site which becomes moderate near the Tokanui river as soils become imperfectly drained (Figure 5). The same limitations regarding the accuracy of mapping of secondary soils and the assignment of hydrological pathways are relevant here.

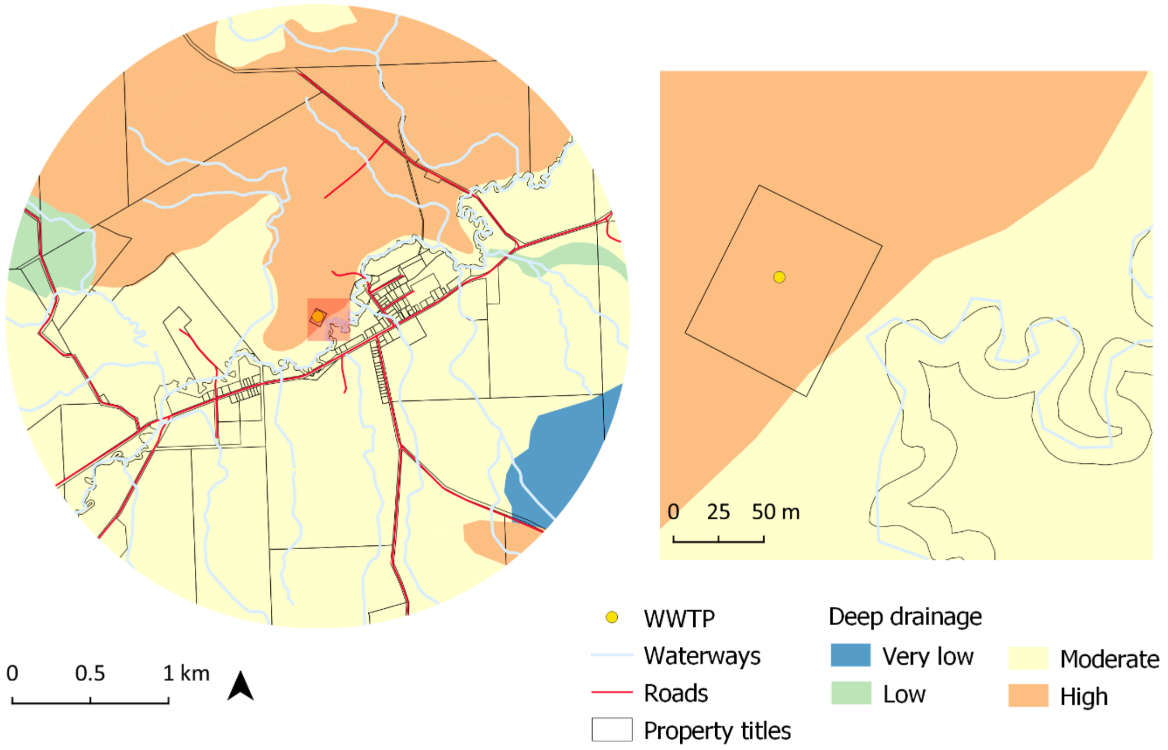

Figure 5: Deep drainage potential for the area of interest around the Tokanui WWTP oxidation ponds. Wastewater treatment plant is shown in yellow in the centre of the 2km radius (left) with the red shading indicating the extent of the map on the left.

3.4 Lateral Flow

Lateral soil flow occurs when water infiltrating through the soil intersects a layer with lower vertical permeability. Water flows along the contact between the higher and lower permeability layers (e.g. within a permeable topsoil overlying a slowly permeable subsoil). Water may accumulate to form a perched water table. Areas with a high potential for lateral flow were identified across Southland as:

- Hill country and alpine areas where thin sloping soils overlie slowly permeable bedrock, and
- Soils in lowland areas identified as having moderate to highly permeable topsoil overlying a slowly permeable subsoil. These soils were also assessed as having high to moderate artificial drainage if under agricultural land uses (Pearson, 2015b).

Therefore, the following assessment (section 3.4.1.) of artificial drainage is considered the most useful for assessing suitability for wastewater disposal in flat, lowland areas.

3.4.1 Artificial Drainage

Artificial subsurface drainage in Southland is typically a mole-pipe network, also known as tile drainage. Mole-pipe drains are usually comprised of an extensive fissure network that drains into mole channels, which are linked to a connector pipe or tile to remove the water (Pearson, 2015b). Most connector pipes in Southland are installed in contour patterns following the natural depressions (swales) of the landscape. Where artificial subsurface drainage exists, there is potential for contaminants to bypass the soil matrix allowing less time for absorption and retention of contaminants in the soil, especially nitrogen and phosphorus, sediment and faecal organisms (Monaghan and Smith, 2004; Houlbrooke and Monaghan, 2009). Avoiding areas of artificial subsurface drainage is important when seeking to maximise land based treatment of wastewater.

Pearson (2015b) developed a framework for estimating where artificial subsurface drainage systems are likely to be present in Southland (Figure 6). Soil permeability and drainage class attributes provided an indication of the density of drainage required to make the land suitable for agriculture. Artificial subsurface density classes ranged from none to very high and included categories for non-agricultural areas and the influence of slope on drainage type.

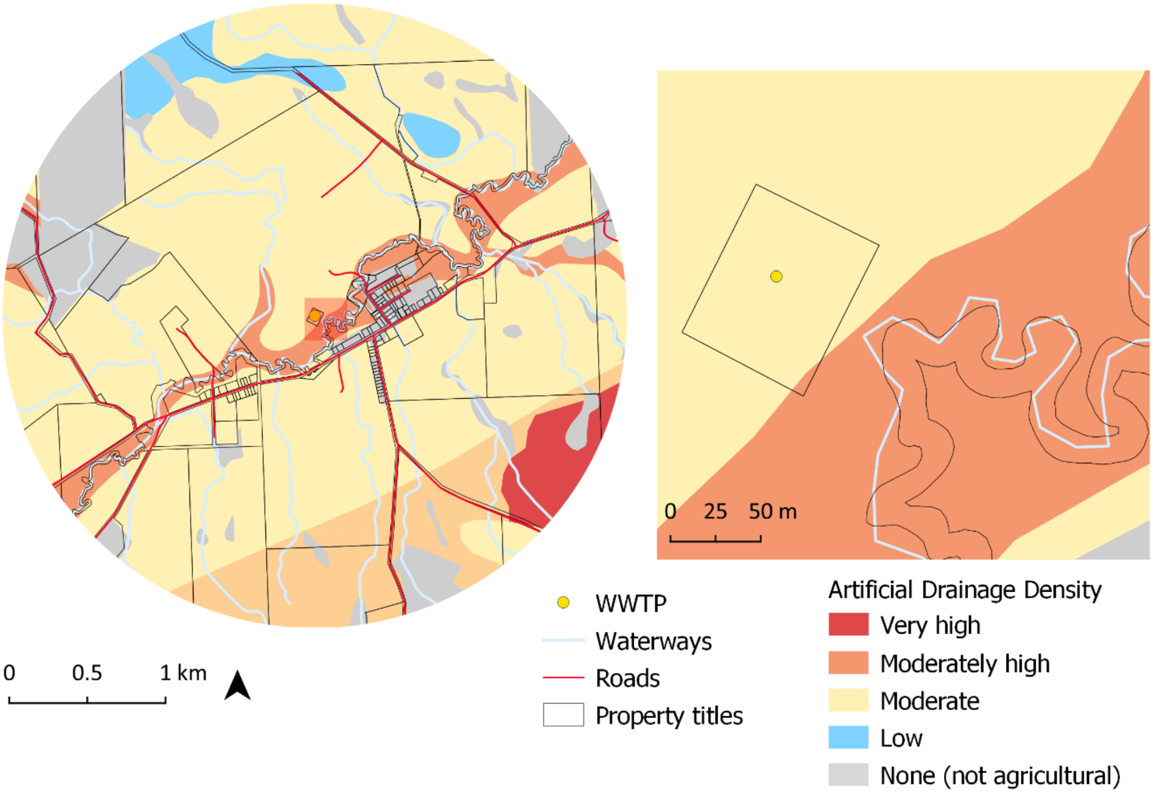

Figure 6: Estimated artificial drainage density for the area of interest around the Tokanui WWTP. Wastewater treatment plant is shown in yellow in the centre of the 2km radius (left) with the red shading indicating the extent of the map on the left.

3.5 Natural Macropore Bypass

Macropore bypass may be locally important with networks of cracks or soil pedogenic structures that propagate to depth (subsoil or underlying aquifer) and bypass much of the natural filtering or attenuative capacity of the soil zone. Macropore bypass may conduct large quantities of nutrients or microbial contaminants to underlying aquifers or mole-pipe drainage networks with little attenuation.

Natural macropore bypass was assessed for Southland during physiographic mapping (Rissmann et al., 2016). There are no areas identified as having natural macropore bypass due to soil moisture deficit in the area of interest around the Tokanui WWTP oxidation ponds.

4 Redox Process-Attribute Gradients

Redox is recognised as one of the most important processes controlling variation in water quality, (Moldan and Cerny, 1994; McMahon and Chapelle, 2008; Rissmann et al., 2011; 2016; Tratnyek et al., 2012). Redox processes in soil and shallow groundwater govern a multitude of parameters including but not limited to the concentration of the dissolved forms of nitrate and nitrite, oxygen, manganese, iron, sulphate, and heavy metals. Redox also indirectly controls the leachability and mobility of P species in soils, aquifers and subsequently surface waters.

The method used in the 'Physiographics of Southland' was revised by Rissmann et al. (2018) by classifying the soil (Landcare Research, 2010; Topoclimate South, 2001) and geological (Turnbull and Allibone, 2003) layers by their estimated reduction potential. The soil reduction potential (SRP) is primarily influenced by soil drainage class as organic carbon is seldom a limiting factor. Drainage class is typically assessed using the percentage of low chroma colours (indicative of waterlogging) and redoximorphic features (reduction of iron and manganese oxides) according to Milne et al. (1995). The soil reduction potential was therefore assigned a score of 1 to 5 (low to high) associated with the drainage class and carbon content of the soil. For mixed soil polygons, the SRP was proportionally weighted by the extent of the soil series within the polygon (Figure 7).

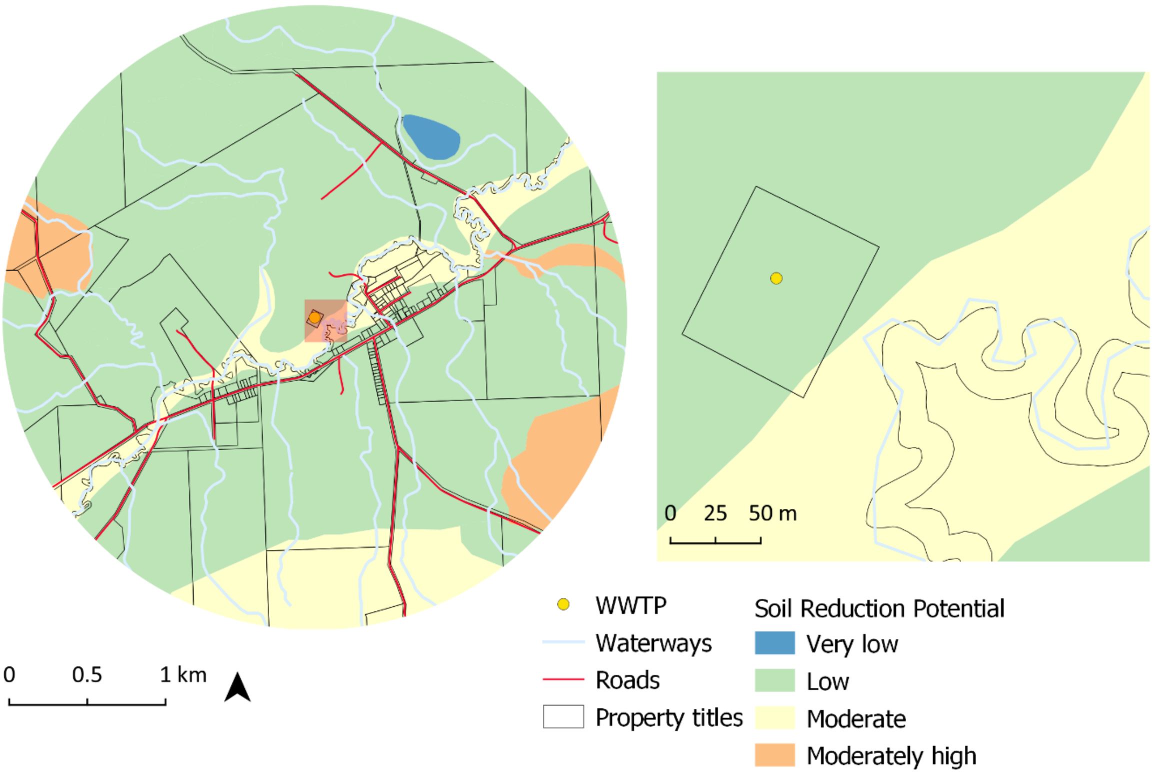

Figure 7: Estimated soil reduction potential for the area of interest around the Tokanui WWTP. Wastewater treatment plant is shown in yellow in the centre of the 2km radius (left) with the red shading indicating the extent of the map on the left.

The geological reduction potential (GRP) is strongly influenced by the abundance of electron donors which are commonly dominated by organic carbon (Rissmann, 2011). Aquifers hosted in materials containing a significant proportion of peat, lignite or other organic materials have an elevated organic carbon content and tend to be strongly reduced, whereas alluvial aquifers low in organic carbon are oxidising. The classification of GRP by Rissmann (2011) was modified in Rissmann et al. (2018) by extending the 3-class classification to a 5-class classification on the basis of significant differences in the organic carbon content of geological substrates. The geological composition was scored 1 to 5 (low to high) based on organic carbon of the substrate (Figure 8). Soil and aquifer reduction potential often accounts for a dominant fraction of the spatial variation in water quality outcomes in areas where water source is limited to local land surface recharge (Rissmann et al. 2018, 2019).

The geological substrate of the unconfined aquifer near the Tokanui WWTP oxidation ponds is gravel and sands with minor peat (QMAP; Turnbull and Allibone, 2003). As such, the alluvial aquifer component is designated as having a relatively low reduction potential. The redox potential of the unconfined aquifer at this location would benefit from additional sampling given the majority of wells within a 10 km radius of Tokanui are >40 m deep and as such unlikely to be representative of shallow near surface conditions.

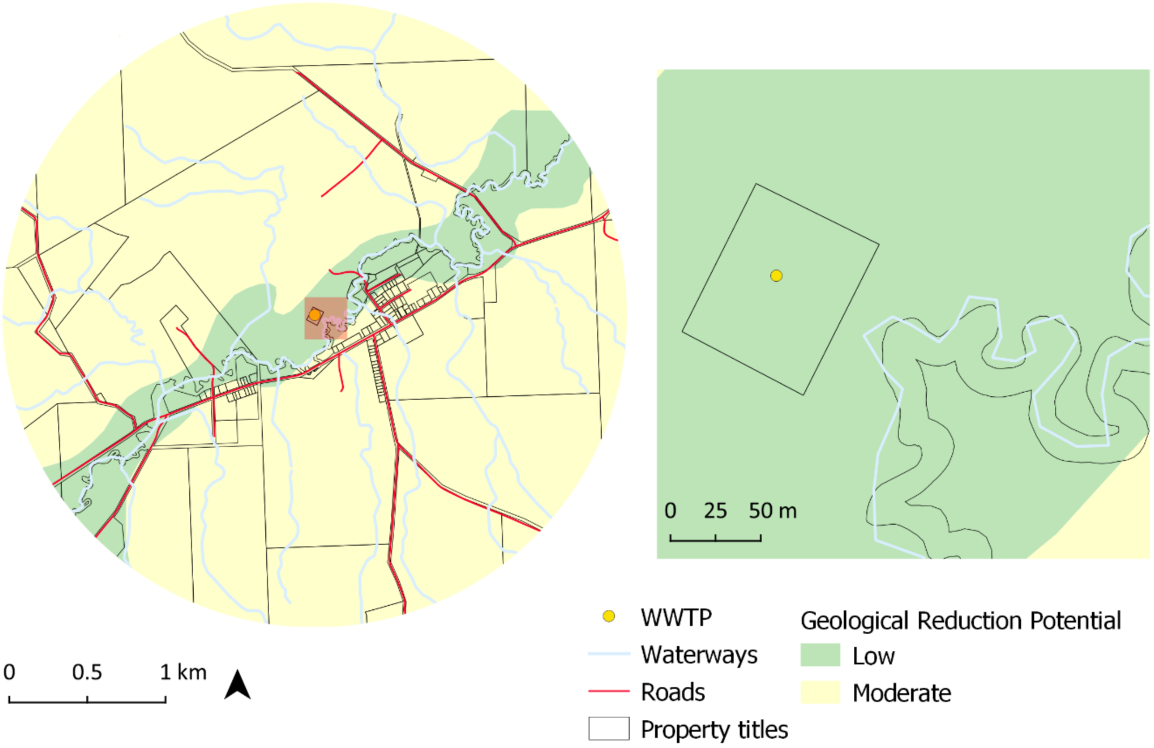

Figure 8. Estimated geological reduction potential for the area of interest around the Tokanui WWTP. Wastewater treatment plant is shown in yellow in the centre of the 2km radius (left) with the red shading indicating the extent of the map on the left.

5 Contaminant Risk Assessment

The characteristic attributes of the landscape define the inherent risk. Variation in the soil properties determines the pathway water takes with the type of water quality risk varying strongly with the hydrological pathway. For this assessment the primary and secondary pathways are assessed for each contaminant within the 2km radius of the WWTP oxidation ponds (Pearson et al., 2018). The need for a contaminant specific pathway assessment reflects the different properties (chemical and physical) of the soil and underlying geology, and as such, the resultant behaviour of water quality contaminants. The hydrological and redox process attribute gradients described above are subsequently combined in the physiographic assessment into susceptibility risk maps for the following environmental contaminants:

- Nitrogen
    - Nitrate Nitrite Nitrogen
    - Ammoniacal Nitrogen
    - Organic Nitrogen
- Phosphorus

  - Dissolved reactive phosphorus
  - Particulate phosphorus
- Sediment
- Microbes

5.1 Losses through the soil zone (deep drainage)

5.1.1 Nitrogen

Contaminants that are dissolved in water are predominantly leached from the soil zone by deep drainage. This pathway is the predominant mechanism for nitrate (NO_3^-) and nitrite (NO_2^-) nitrogen and in some settings dissolved reactive phosphorus (DRP, Figure 9 and 10).

Nitrate loss is highest in areas with a low reduction potential, specifically well drained soils with a high permeability (Figure 9). The risk to surface and shallow groundwater is low if these soils occur over a reducing aquifer, however the reduction potential of the aquifer near the Tokanui WWTP is high to low in close proximity to the Tokanui river (Figure 8).

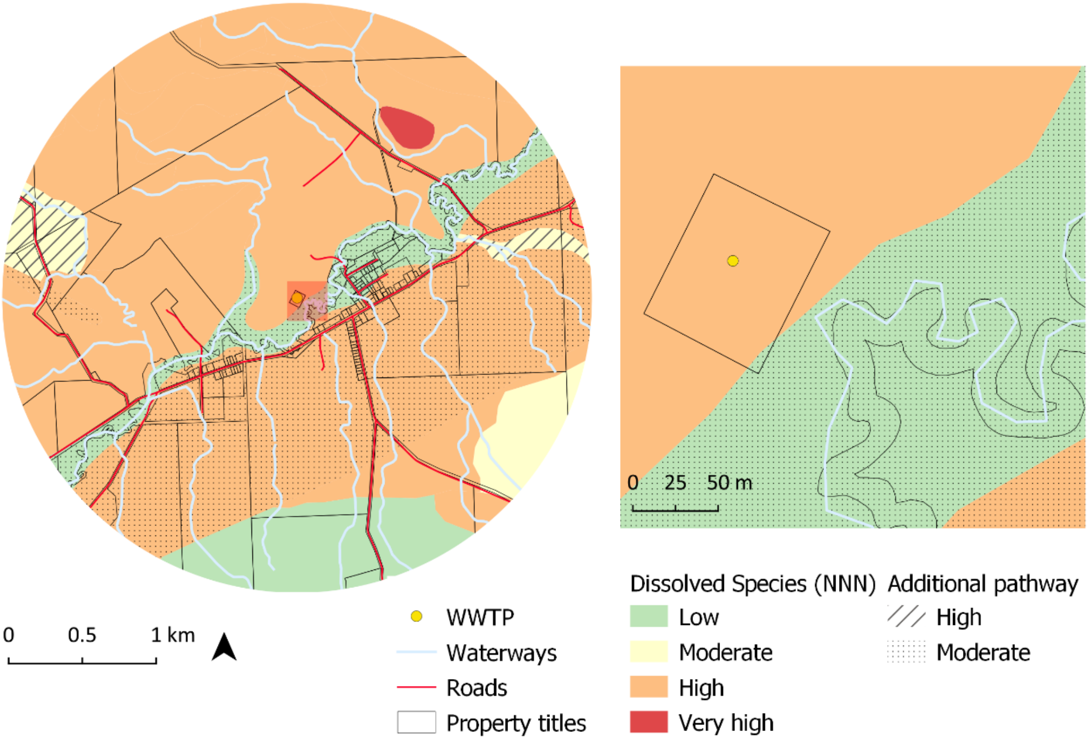

Figure 9: Inherent risk of nitrate and nitrite nitrogen (NNN) transported through the soil zone to the aquifer for the area of interest around the Tokanui WWTP. The additional pathway risk shows the surficial risk by artificial drainage and overland flow. The WWTP oxidation pond location is shown in yellow in the centre of the 2km radius (left) with the red shading indicating the extent of the map on the left.

The organic and ammoniacal forms of nitrogen (TKN) are commonly elevated in treated wastewater and are often strongly retained by the soil. The extent to which these reduced forms of nitrogen are converted to NO_3^- and NO_2^- is dependent on the redox potential of the soil (Figure 7). In poorly drained soils, with high reduction potential a greater proportion of wastewater nitrogen will be stored as ammoniacal and organic forms. These forms of nitrogen tend to be concentrated within the upper horizons of the soil making them more prone to mobilisation by overland flow and preferential subsurface drainage mediated by mole-pipe systems (Figure 10). Accordingly, shallow lateral soil zone flow (mediated by mole-pipe drainage) and especially overland flow are important pathways for organic and ammoniacal nitrogen delivery to streams. These forms of nitrogen are considered particularly important controls over instream eutrophication. Losses of organic and ammoniacal nitrogen from well drained and highly permeable soils are commonly negligible due to high rates of conversion to more mobile NO_3^- and NO_2^- and dominance by a deep drainage pathway.

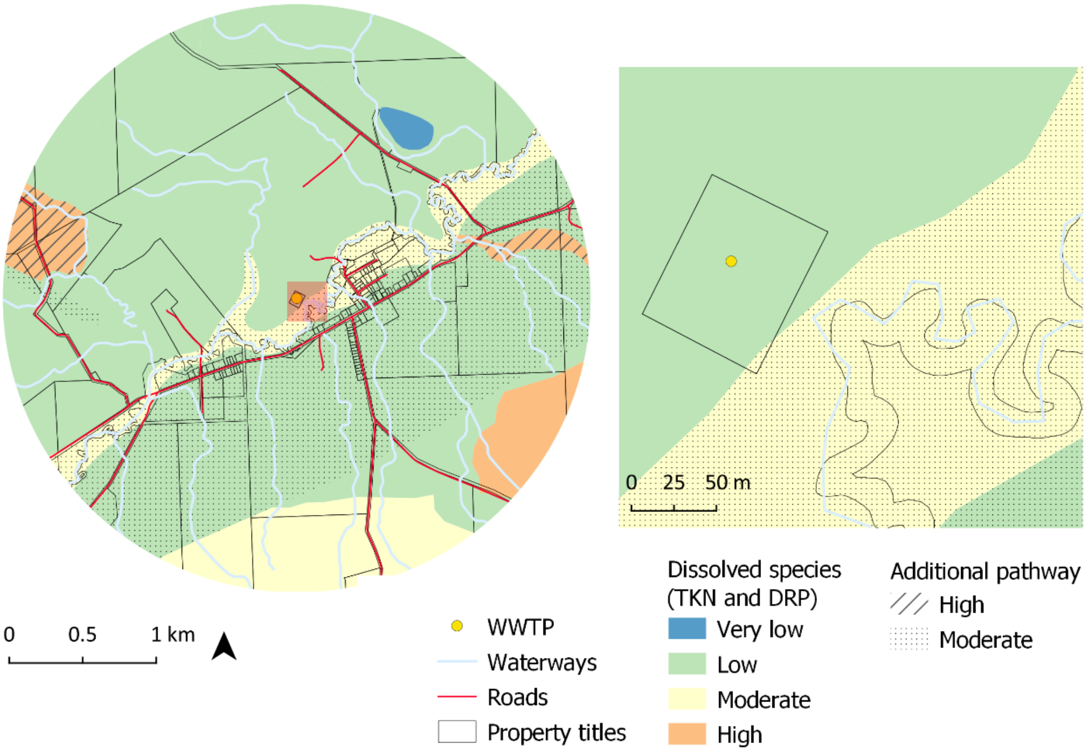

Figure 10: Inherent risk of dissolved reactive phosphorus and nitrogen as ammoniacal and organic forms which can be transported through the soil zone to the aquifer for the area of interest around the Tokanui WWTP. The additional pathway risk shows the surficial risk by artificial drainage and overland flow. The WWTP oxidation pond location is shown in yellow in the centre of the 2km radius (left) with the red shading indicating the extent of the map on the left.

5.1.2 Phosphorus

Particulate bound phosphorus is typically the dominant form of P in areas of developed land and behaves in a similar manner to organic and ammoniacal nitrogen (Figure 10; Rissmann et al., 2016; Rissmann et al., 2018). Particulate bound phosphorus is therefore prone to mobilisation by overland flow and to a lesser degree subsurface drainage mediated by mole-pipe networks (Section 5.2). For dissolved reactive phosphorus, redox plays an additional role over mobility and abundance, with increased yields from areas of reducing soils and aquifers, especially peat wetland areas. At the Tokanui WWTP oxidation pond site there is potential for minor peats to be found in close proximity to the Tokanui river. Higher-resolution soil maps are required to identify if these areas are present.

5.2 Surficial Runoff and Artificial Drainage

Sediment[1], particulate bound phosphorus, and microbes are deposited on and eroded from the land surface and are therefore transported predominantly by overland flow (or surficial runoff) (Figure

---

[1] Sediment is a general term used to describe the heterogeneous mix of organic and inorganic constituents (less than 0.2 mm in diameter) which may include organic carbon, clays (both poorly ordered and structured),

11). Wastewater discharged by irrigation results in the concentrations of contaminants reaching a maximum at or near the land surface, this risk is significantly lower for subsurface discharges. For this reason, overland flow commonly delivers the largest load of land use derived contaminants directly to stream (Smith and Monaghan, 2003; Goldsmith and Ryder, 2013; Orchiston et al., 2013; Curran Cournane et al., 2011; McKergow et al., 2007). The period with the highest risk for overland flow in Southland is between May and November (Smith and Monaghan, 2003; McDowell et al., 2005; Monaghan et al., 2016; Rissmann and Beyer, 2018). Artificial drainage also acts as a conduit for sediment, particulate phosphorus and microbes to surface water bodies (Monaghan and Smith, 2004; Houlbrooke and Monaghan, 2009). This contaminant pathway can be reduced by subsurface disposal fields and maintaining vegetation cover. In irrigated discharge systems, low rate or deferred discharges in times when the water table is elevated will also reduce the likelihood of surficial runoff.

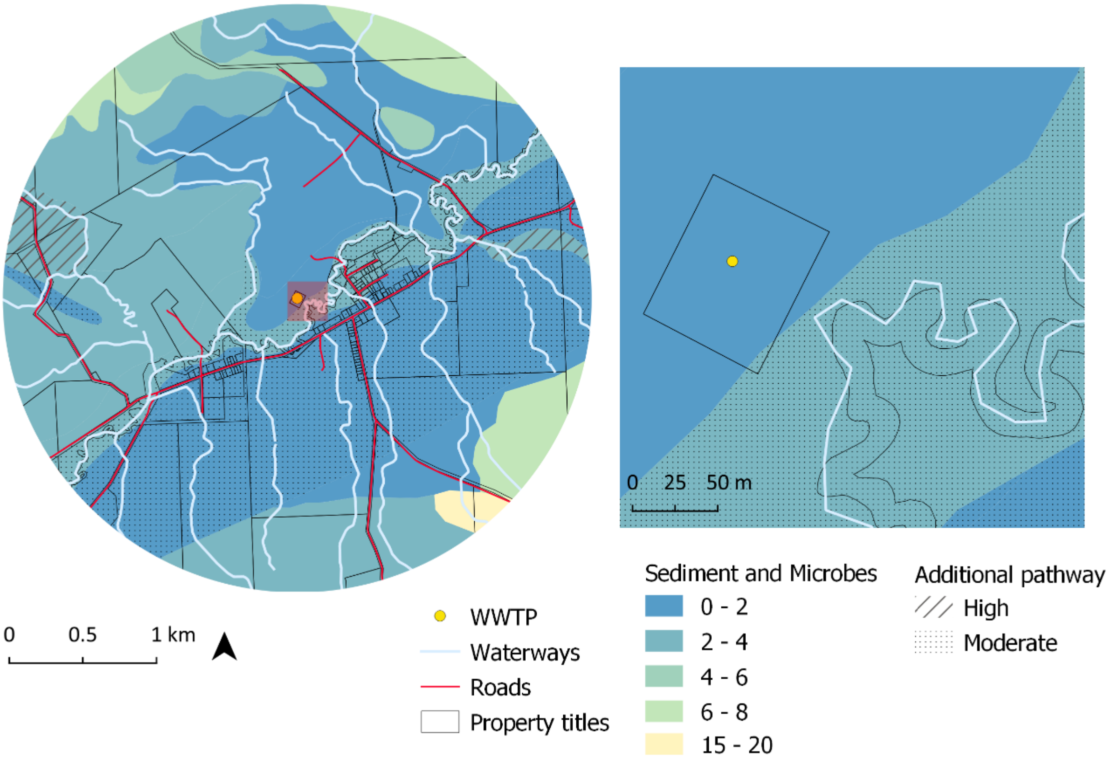

Figure 11: Inherent risk for sediment, particulate bound phosphorus and microbial loss by overland flow (surficial runoff) for the area of interest around the Tokanui WWTP. Risk of loss is increased by catchment modification through artificial drainage. The WWTP oxidation pond location is shown in yellow in the centre of the 2km radius (left) with the red shading indicating the extent of the map on the left.

6 Summary

Assessing water quality risk for the suitability of land disposal of treated wastewater includes consideration of the impact of wastewater on the receiving environment and human health. For any wastewater disposal scheme, it is important to contrast the water quality risks associated with overland flow vs. deep drainage through the unsaturated soil zone. If wastewater moves via deep drainage through a thick unsaturated zone formed in gravel, sand, silt and clay, the attenuation of sediments (organic and inorganic), metals, nutrients and microbes are likely to be high. The main risk

---

silt and sand, attached bacteria, viruses and both organic and inorganic ions and molecules - including N and P species.

to water quality from deep drainage is the leaching of nitrate to groundwater. In contrast, if overland flow to a waterway occurs, a larger range and a greater proportion of the wastewater contaminants may reach a water body. Consequently, there is less risk to water quality outcomes if treated wastewater infiltrates and percolates through a relatively thick unsaturated zone prior to reaching an aquifer versus direct discharge and little removal associated with overland flow.

The Tokanui WWTP oxidation ponds are located approximately 30 m from the Tokanui river. The greatest risk to water quality at the Tokanui WWTP oxidation ponds is associated with a shallow unsaturated zone, fluctuation of the local water table and a high degree of connectivity to the Tokanui river. The shallow water table (< 1.5 m below ground) is associated with a thin unsaturated zone and a lesser capacity to filter, store and attenuate wastewater derived contaminants. In this setting, the risk of ‘over loading’ the system with treated wastewater can lead to the breakthrough of wastewater derived contaminants to the local groundwater system and surface water bodies (Rissmann, 2017; Rissmann and Lovett, 2016 and references therein).

Therefore, the ideal landscape attributes for most wastewater disposal include a thick unsaturated zone (> 3 m) comprised of highly permeable and free draining materials of varying particle size (e.g. sand, silt and clay). The site should be flat (<4°) and should also have little connectivity to surface water bodies. The unsaturated zone and underlying aquifer should be well aerated to limit the transport of heavy metals and phosphorus species that are often elevated in wastewater (see Rissmann and Lovett, 2016 and references therein).

References

Baisden W.T., Keller, E.D., Van Hale, R., Frew, R.D. and Wassenaar, L.I. (2016) Precipitation isoscapes for New Zealand: enhanced temporal detail using precipitation-weighted daily climatology, Isotopes in Environmental and Health Studies, 52:4-5, 343-352, doi:10.1080/10256016.2016.1153472.

Chanut, P., Ledgard, G., Rissmann, C. and Wilson, S., (2014). Estimating Time Lags for Nitrate Response in Shallow Southland Groundwater. Environment Southland, Technical Report No. 2014-13. Invercargill, New Zealand. 51 p.

Curran Cournane, F., McDowell, R., Littlejohn, R., and Condron, L. (2011). Effects of cattle, sheep and deer grazing on soil physical quality and losses of phosphorus and suspended sediment losses in surface runoff. Agriculture, ecosystems and environment, 140(1): 264- 272.

Goldsmith, R., and Ryder, G. (2013). Factors affecting contaminant loss in overland flow. Ryder Consulting Limited. Technical Review for Environment Southland. Dunedin, New Zealand.

Houlbrooke, D. J., & Monaghan, R. M. (2009). The influence of soil drainage characteristics on contaminant leakage risk associated with the land application of farm dairy effluent. AgReserach report prepared for Environment Southland.

Landcare Research. (2010). Fundamental Soil Layer New Zealand Soil Classification. [vector polygon]. https://lris.scinfo.org.nz/layer/48079-fsl-new-zealand-soil-classification/.

Landcare Research. (2015). Land Cover Database version 4.1 Mainland New Zealand. [vector polygon]. https://lris.scinfo.org.nz/layer/48423-lcdb-v41-land-cover-database-version-41-mainland-new-zealand/.

Land Information New Zealand. (2018). New Zealand Topo50 Map. [TIFF] https://www.linz.govt.nz/land/maps/topographic-maps/topo50-maps

Land Information New Zealand. (2012). NZ 8m Digital Elevation Model. [raster]. https://data.linz.govt.nz/layer/51768-nz-8m-digital-elevation-model-2012/

Lynn I.H., Manderson, A.K., Page, M.J., Harmsworth, G.R., Eyles, G.O., Douglas, G.B., Mackay, A.D., Newsome, P.J.F. (2009). Land Use Capability survey handbook – a New Zealand handbook for the classification of land. AgResearch Hamilton; Manaaki Whenua Lincoln; GNS Science Lower Hutt, New Zealand.

Macara, G.R. (2013). The climate and weather of Southland. 2nd edition, NIWA Science and Technology Series, No.63. ISSN 1173-0382.

McDowell, R. W., Monaghan, R. M., and Wheeler, D. (2005). Modelling phosphorus losses from pastoral farming systems in New Zealand. New Zealand Journal of Agricultural Research, 48(1): 131-141.

McKergow, L. A., Tanner, C. C., Monaghan, R. M., and Anderson, G. (2007). Stocktake of diffuse pollution attenuation tools for New Zealand pastoral farming systems. NIWA Client Report HAM2007–161, Prepared for Pastoral, 21. Hamilton, New Zealand.

McMahon, P., and Chapelle, F. (2008). Redox processes and water quality of selected principal aquifer systems. Groundwater 46(2): 259-271.

Milne, J.D.G., Clayden, B., Singleton, P.L. and Wilson, A.D. (1995). Soil Description Handbook. Manaaki Whenua Press. Lincoln, Canterbury, New Zealand.

Moldan, B., and Cerny, J. (Eds.) (1994). Biogeochemistry of Small Catchments: A tool for Environmental Research. Published on behalf of the Scientific Committee on Problems of the

Environment (SCOPE) of the International Council of Scientific Unions (ICSU) and of the United Nations Environment Programme (UNEP). Wiley and Sons, England.

Monaghan, R. M., & Smith, L. C. (2004). Minimising surface water pollution resulting from farm-dairy effluent application to mole-pipe drained soils. II. The contribution of preferential flow of effluent to whole-farm pollutant losses in subsurface drainage from a West Otago dairy farm. New Zealand Journal of Agricultural Research, 47(4), 417-428.

Monaghan, R.M. (2016). Management practices and mitigation options for reducing contaminant losses from land to water. Research Report No. RE500/2016/036 prepared for Environment Southland. Mosgiel, New Zealand.

Newsome, P.F.J., Wilde, R.H., and Willoughby, E.J. (2008). Land Resource Information System Spatial Data Layers. Landcare Research, Palmerston North, New Zealand.

Orchiston, T. S., Monaghan, R., and Laurenson, S. (2013). Reducing overland flow and sediment losses from winter forage crop paddocks grazed by dairy cows. In: Accurate and efficient use of nutrients on farms. (Eds. L.D. Currie and C L. Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 26. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 7 pages.

Pearson, L. (2015a). Overland flow risk in Southland. Environment Southland. Technical Report No. 2015-06. Invercargill, New Zealand.

Pearson, L. (2015b). Artificial subsurface drainage in Southland. Environment Southland. Technical Report No. 2015-07. Invercargill, New Zealand.

Pearson, L., and Couldrey, M. (2016). Methodology for GIS-based land use maps for Southland. Environment Southland. Technical Report No. 2016-10. Invercargill, New Zealand.

Pearson, L., Rissmann, C. and Lindsay, J. (2018). Waituna Catchment: Physiographic Risk Assessment. Land and Water Science Report 2018/02. Prepared for Living Water. 45p.

Rissmann, C. (2011). Regional mapping of groundwater denitrification potential and aquifer sensitivity. Environment Southland Technical Report No. 2011-12. Invercargill, New Zealand.

Rissmann, C. and Lovett A. (2016). Hydrochemical analysis for the Otane Waste Water Treatment Plant, GNS Science Consultancy Report 2016/83. 32p.

Rissmann, C., Rodway, E., Beyer, M., Hodgetts, J., Pearson, L., Killick, M., Marapara, T.R., Akbaripasand, A., Hodson, R., Dare, J., Millar, R., Ellis, T., Lawton, M., Ward, N., Hughes, B., Wilson, K., McMecking, J., Horton, T., May, D., and Kees, L. (2016). Physiographics of Southland Part 1: Delineation of key drivers of regional hydrochemistry and water quality. Environment Southland Technical Report No. 2016/3. Invercargill, New Zealand.

Rissmann, C., Pearson, L., Lindsay, J. Marapara, M., and Badenhop, A. (2018). Waituna Catchment: Technical Information and Physiographic Application. Land and Water Science Report 2018/01. Prepared for Living Water, 134p.

Rissmann C.W.F., Pearson L.K., Beyer M., Couldrey M.A., Lindsay J.L., Martin, A.P., Baisden, W.T., Clough, T.J., Horton T.W., Webster-Brown, J.G. (in press). A hydrochemically guided landscape classification system for modelling spatial variation in multiple water quality indices: Process-attribute mapping. Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2019.03.492

Rissmann, C. and Beyer, M. (2018). Waituna Catchment: Temporal Variation. Land and Water Science Report 2018/09. Prepared for Living Water. 12p.

Smith, L. C., and Monaghan, R. M. (2003). Nitrogen and phosphorus losses in overland flow from a cattle-grazed pasture in Southland. New Zealand Journal of Agricultural Research, 46(3): 225-237.

Snelder, T.H., and Biggs, B.J.F. (2002). Multiscale river environment classification for water resources management. Journal of the American Water Resources Association. https://doi.org/10.1111/j.1752-1688.2002.tb04344.x.

TopoClimate South, (2001). Topoclimate South Soil Mapping Project. Electronic files held by Environment Southland. Copyright: Crops for Southland, Invercargill, New Zealand.

Tratnyek, P. G., Grundl, T. J., Haderlein, and S.B. Eds. (2012). Aquatic Redox Chemistry. American Chemical Society symposium series 1071; Oxford University Press, 20.

Turnbull, I.M. and Allibone, A.H. (compilers) (2003). Geology of the Murihiku area. Institute of Geological and Nuclear Sciences Limited. 1:250 000 geological map 20. 1 sheet and 74 p. Lower Hutt, New Zealand.