Rissmann, C., Pearson, L., Lindsay, J., Beyer, M., Marapara, T., Badenhop, A., and Martin, A. 2018. Integrated landscape mapping of water quality controls for farm planning – applying a high resolution physiographic approach to the Waituna Catchment, Southland. In: *Farm environmental planning – Science, policy and practice.* (Eds. L. D. Currie and C.L. Christensen). http:flrc.massey.ac.nz/publications.html. Occasional Report No. 31. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 19 pages.

INTEGRATED LANDSCAPE MAPPING OF WATER QUALITY CONTROLS FOR FARM PLANNING

- APPLYING A HIGH RESOLUTION PHYSIOGRAPHIC APPROACH TO THE WAITUNA CATCHMENT, SOUTHLAND

Clint Rissmann[1,2], Lisa Pearson[1], Jessie Lindsay[1], Monique Beyer[1], Tapuwa Marapara[1], Alexandra Badenhop[3], and Adam Martin[4]

[1]Land and Water Science Ltd., 61 Leet Street, Invercargill, New Zealand
[2]Waterways Centre for Freshwater Management, University of Canterbury and Lincoln University, Private Bag 4800, Christchurch, New Zealand
[3]e3Scientific Ltd., Arrow Lane, Arrowtown, New Zealand
[4]GNS Science, 764 Cumberland Street, Dunedin, New Zealand
Email: lisa@landwatersci.net

Abstract

Water quality outcomes can vary spatially across the landscape, even when there are similar land use pressures. These differences are often the result of natural spatial variation in the landscape, which alters the composition of the water through coupled physical, chemical and biological processes. Living Water (a Fonterra and Department of Conservation partnership) commissioned a high-resolution physiographic assessment of the Waituna Catchment, Southland, to support water quality and biodiversity investment decisions for the catchment.

The physiographic approach is an integrated or 'systems view', predicated upon the spatial coupling between landscape attributes and the key processes governing water quality outcomes in surface and shallow groundwater. For example, the relationship between soil drainage class (*attribute*) and redox (*process*) can be used to predict soil denitrification potential. Unlike other mapping and classification approaches, the physiographic approach incorporates water quality, hydrochemical and/or hydrological response signals into a spatial format to identify, select, combine and classify those landscape gradients that drive variation in water quality outcomes. The key process-attribute layers identified for the Waituna Catchment are hydrology and redox.

Areas characterised by similar process-attribute classes for both hydrology and redox are defined as Physiographic Units (PGU). Each PGU responds in a similar fashion at the process level to broadly equivalent land use pressures. Through classification of the catchment into PGUs we demonstrate that: (i) physiographic mapping can be used to estimate the steady-state water composition of surface water and shallow unconfined groundwater with a high degree of confidence, and; (ii) process-attribute gradients and resultant PGUs are a powerful tool for informing and optimising efforts to improve water quality – matching efforts to the process level controls over water quality at the land parcel scale.

A national physiographic classification (Physiographic Environments of New Zealand) is currently being created in conjunction with the Our Land and Water National Science Challenge and a range of stakeholders. A web-based interface for farmers and industry to access physiographic science is initially being developed in the Southland region as part of a

Ministry for Primary Industries, Sustainable Farming Fund grant. Development and design of the web-based interface is being guided by farmers, industry groups and Environment Southland farm extension staff.

Introduction

Water quality can vary spatially across the landscape, even when there are similar land uses or pressures in a catchment. These differences occur because of natural spatial variation in landscape attributes, which alters the composition of the water through coupled physical, chemical and biological processes. Previous research has noted that spatial variation in landscape attributes can account for more than twice the variability in water quality than land use alone (Johnson et al., 1997; Hale et al., 2004; King et al., 2005; Dow et al., 2006; Shiels, 2010; Becker et al., 2014). The role of landscape variability over water quality outcomes is especially true for countries such as New Zealand, which is often recognised as one of the most complex geological regions in the world (Johnson et al., 1997).

Until recently a systematic approach to mapping the integrated landscape controls over surface and shallow groundwater quality has been lacking. In this paper, a conceptual overview of the physiographic method for identifying and mapping the critical attributes of the landscape that control spatial variation in water quality outcomes is presented (Figure 1). The physiographic method provides a greater opportunity to target and implement mitigations that are environmentally and cost-effective, in addition to providing critical context to calibrate existing tools that seek to better understand and model land use losses, such as nutrients and sediment (SFF, 2017).

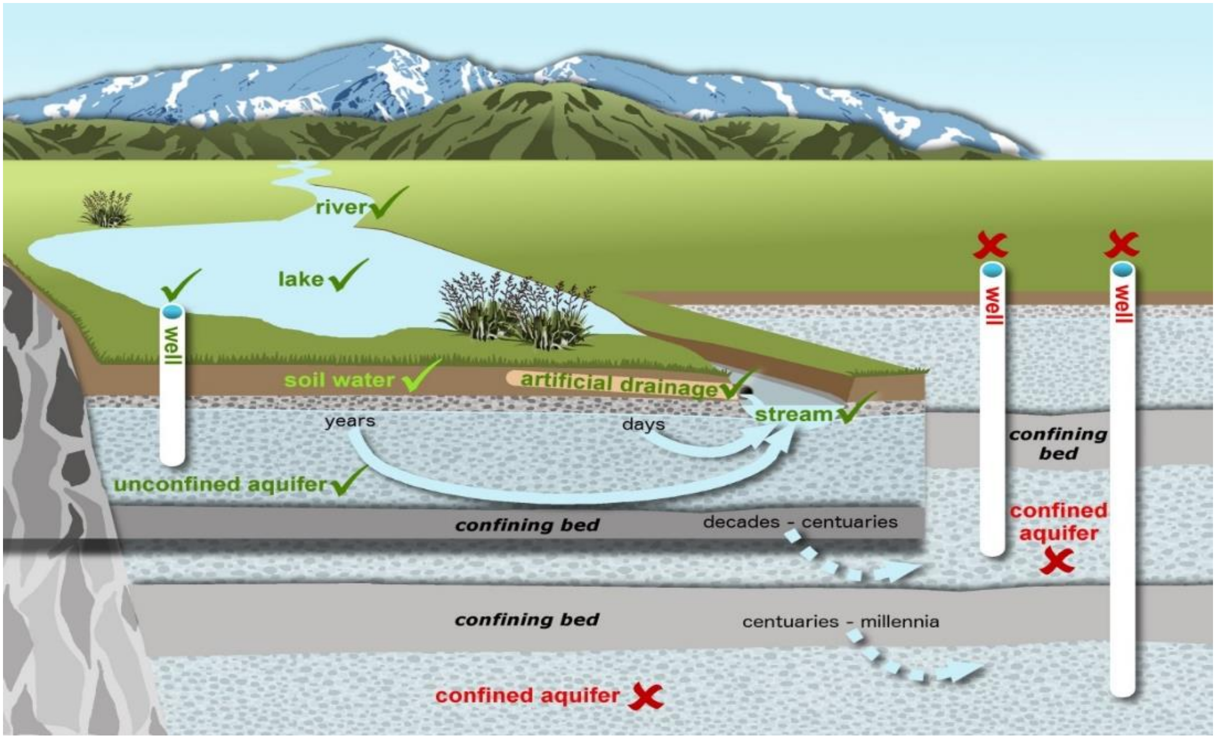

Figure 1: Illustration of the connectivity of near-surface water resources, including soil water, surface and shallow groundwater (Hughes et al., 2016). Green tick marks show the hydrologically connected settings included in the physiographic approach, whereas red crosses identify settings that are excluded.

To explain the physiographic approach, examples from the initial 'Physiographics of Southland' project are provided (Environment Southland, 2016; Rissmann et al., 2016; Hughes et al., 2016). In addition, selected outputs from the recent high resolution physiographic mapping for the Waituna Catchment, Southland, are presented. These outputs were prepared through the Living Water (Department of Conservation (DOC)-Fonterra Partnership), and Whakamana Te Waituna project partners (Iwi/hapū, Environment Southland, Southland District Council, DOC and Fonterra). Finally, it is proposed that the physiographic method has a natural home in supporting existing tools that seek to understand and minimise land use losses by providing critical context as to the role of the landscape over spatial variation in surface and shallow groundwater.

Physiographic Method

It is widely recognised in hydrochemical and geochemical literature that there are four key process families governing the composition of fresh water - atmospheric, hydrological, redox and weathering (Moldan & Černý, 1994; Clark & Fritz, 1997; Güler & Thyne, 2004; Kendall & McDonnell, 2008; Tratnyek et al., 2012). Of these process families, hydrological and redox processes are often considered the most significant in governing variation in water quality outcomes (Moldan & Černý, 1994; Langmuir, 1997; Wieder et al., 2004; Tratnyek et al., 2012; Eriksson, 2012). The fundamental premise of the physiographic approach is that spatial variation in water composition (quality and hydrochemistry) can be understood by identifying and mapping the spatial coupling between *process signals* in water and *landscape attributes*.

For example, spatial variation in the concentration of sodium (Na), chloride (Cl), and the stable isotopes of water ($\delta^{18}O/\delta^{2}H\text{-}H_2O$, V-SMOW) in precipitation (*atmospheric process signals*) are known to be governed by altitude and distance from the coast (*landscape attributes*) (Clark & Fritz, 1997; Langmuir, 1997; Wieder et al., 2004; Kendall & McDonnell, 2008); spatial variation in the Na, Cl and $\delta D/\delta^{18}O$ in surface and shallow groundwater (*hydrological process signals*) are known to vary according to water source and connectivity between recharge domains (*landscape attribute*) (Clark & Fritz, 1997; Kendall & McDonnell, 2008; Inamdar, 2011); spatial variation in groundwater pH and hence alkalinity (*weathering process signals*) are governed by the acid neutralising capacity (ANC) (*landscape attribute*) of soil and rock, as well as its degree of weathering (Wright, 1988; Moldan & Černý, 1994; Giller & Malmqvist, 2004; Lydersen et al., 2004), and; aquifer reduction potential (*redox process signals*) varies according to the abundance of electron donors within an aquifer (*attribute*) (Krantz and Powars, 2002; McMahon and Chapelle, 2008; Rissmann, 2011; Beyer et al., 2016; Wilson et al., 2018).

The signals in water are used to verify the effective properties of the landscape. This process is important for: (i) linking landscape compartments (i.e., land surface, soil, aquifer, surface waters); (ii) understanding the relative significance of each compartment over water composition, and; (iii) refining pre-existing maps of landscape attributes that may not have been mapped with water in mind, or do not contain the key attributes governing water quality outcomes.

With this integrated perspective in mind, the ultimate aim of the physiographic method is to produce a number of classed process-attribute GIS layers that depict the spatial coupling between process signals in water and landscape attribute gradients. The steps for physiographic mapping of the landscape are summarised in Figure 2.

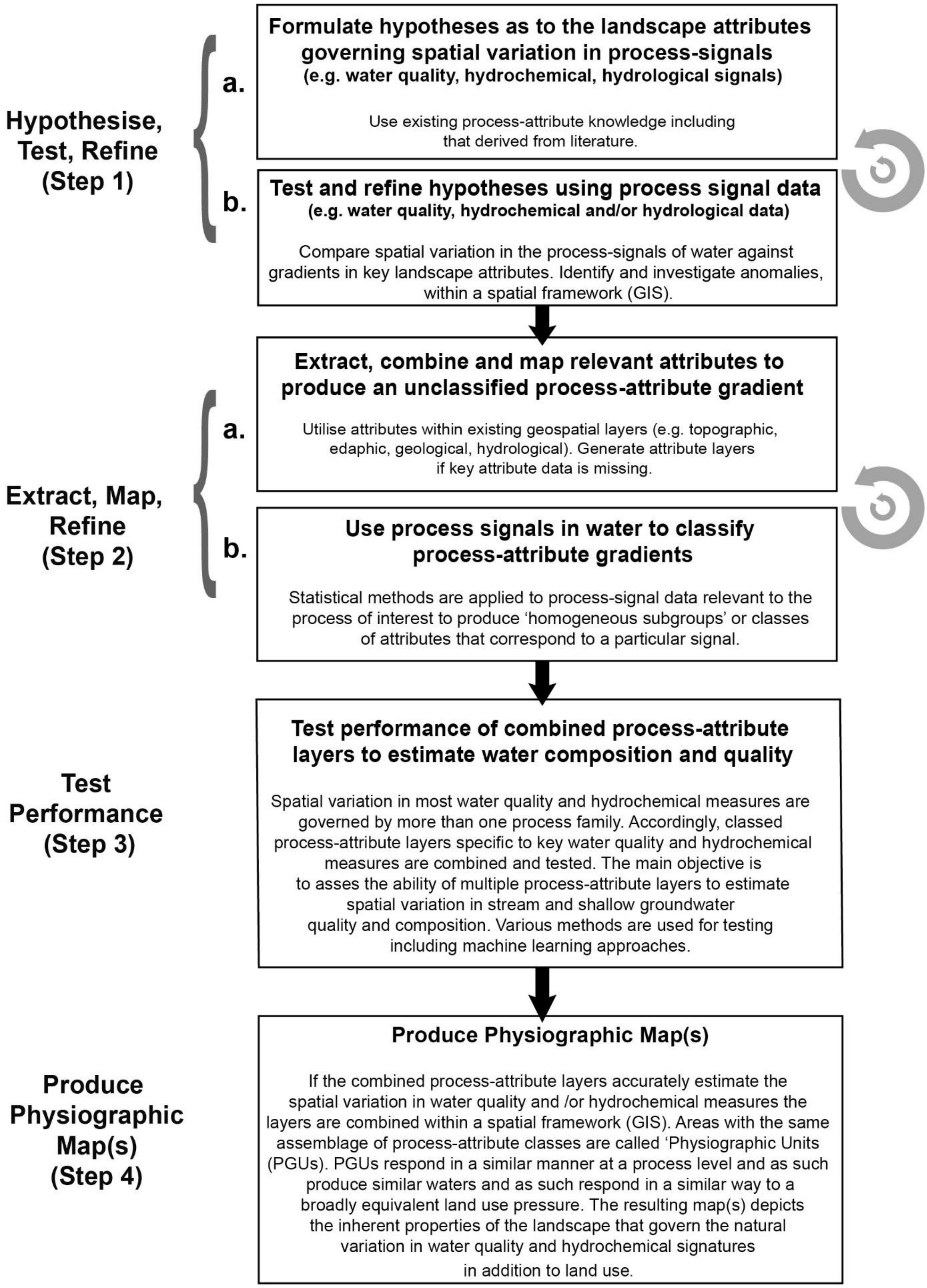

Figure 2. Summary of steps to develop the physiographic mapping method (Rissmann et al. in prep.).

Step 1: Hypothesise and Test

Firstly, hypotheses as to the likely landscape attributes governing spatial variation in a particular process signal are formulated (Step 1a). Hypotheses may be informed by international peer review literature, prior technical reporting and/or a working knowledge of a catchment, or regional scale landscape controls over variation in water composition. For example, the dissolved oxygen (DO) and nitrate (NO_3^-) concentration in surface waters are expected to vary according to the landscape attributes soil drainage class and the abundance of electron donors (mainly organic carbon) in soil and shallow aquifers (Rissmann, 2011; Beyer et al., 2016; Beyer and Rissmann, 2016).

Using the above example, the hypothesis is then tested by interrogating the relationship between field measures of DO and NO_3^- and soil drainage class, soil carbon content and the likely electron donor abundance of the shallow aquifer associated with a given surface and/or groundwater monitoring site and associated capture zone (Step 1b). The key question is whether in-stream or shallow groundwater process signals vary in the hypothesised manner within and between capture zones. Various hydrochemical, graphical and multivariate methods are used during this phase (Rissmann et al., 2016; 2018). Pre-existing geospatial layers (e.g. Digital Elevation Model (DEM), soil, geological) are used as the source of landscape attribute data.

During the hypothesis testing stage, a spatial disconnect between process signals and a key landscape attribute suggests decoupling of the hypothesised process-attribute relationship. For example, across a significant area of Southland a disconnect was observed between soils mapped as poorly drained (reducing) and the occurrence of elevated nitrate (>8.0 mg/L NO_3^- N) in shallow groundwaters beneath these soils (see Central Plains Physiographic Zone after Hughes et al., 2016). Elsewhere, aquifers underlying poorly drained soils showed little sign of anomalous NO_3^-, indicating considerable removal within the soil zone by reduction (Beyer et al., 2016). Further investigation into the nature of this anomaly indicated that these soils crack in response to soil moisture deficit, with autumn recharge of high NO_3^- waters bypassing the reducing soil zone and rapidly recharging the underlying strongly oxidising aquifer (Rissmann et al., 2016b; Hughes et al., 2016). Accordingly, where the correlation between a given process signal and geospatial representations of landscape attributes are anomalous further investigation as to the character of the attributes within an area may be necessary.

Step 2: Extract Landscape Attributes, Map and Classify

Once the hypotheses have been tested and subsequently refined to incorporate any anomalous signals, an unclassed process-attribute layer is produced by extracting the key landscape attributes that govern process signatures from pre-existing geospatial layers (Step 2a). For example, attribute data on soil chroma, redox segregations, organic carbon content and texture were extracted from pre-existing geospatial layers (e.g., NZLRI, regional soil layers, S-Map) and combined to produce an unclassified process-attribute layer that defines a soil zone reduction potential gradient for Southland (Killick et al., 2015; Beyer et al., 2016; Rissmann et al. in prep.). Similarly, data on the abundance of electron donors (i.e., organic carbon, glauconite and iron sulphides) associated with shallow aquifers were extracted and mapped from pre-existing geological (Q-Map (Turnbull & Allibone, 2003); Rock 2 in NZLRI (Lynn et al., 2009)) and petrochemical (Petlab; Strong et al., 2016)) data sets (Rissmann, 2011). Critically, the method utilises the smallest scale polygons associated with soil series mapping as the basis for delineating process-attribute gradients. At this stage additional information provided by regional or catchment scale surveys of attribute properties are incorporated (e.g. finer scale soil mapping, LiDAR, radiometric imagery (see Rissmann et al., 2017)).

Following the mapping of each process-attribute gradient, water signals are used to classify the attribute gradient into key classes that are associated with relatively homogenous process signals in water (Step 2b; Rissmann et al., 2016). The number of classes is finite and often correlated with the number of distinctly different attributes that make up an attribute gradient. For example, pH and alkalinity in Southland shallow groundwater was observed to vary strongly between six key rock/sediment classes, decreasing across the carbonate > ultra-mafic > mafic > intermediate > felsic > and carbonaceous continuum (Rissmann et al., 2018). Shallow aquifers associated with each of these rock/sediment categories showed statistically significant differences in pH and alkalinity as well as major ion abundances. The role of different rock, sediment and soil attributes over pH and alkalinity is well established in the international peer reviewed literature and has been used by many authors to spatially map the likely impact of acid rain over the pH and alkalinity of aquatic ecosystems across North America and Europe (Wright, 1988; Giller & Malmqvist, 2004; Lydersen et al., 2004). In another example, mapping of soil drainage class has historically been informed by soil redox indicators, soil colour (chroma) and the abundance of redox segregations (mottles) (Lynn et al., 2009). It is perhaps not surprising therefore, that the redox signatures in soil drainage waters are also correlated with soil drainage class (Beyer et al., 2016; Beyer and Rissmann, 2016; Rissmann et al., 2018). Many other such relationships exist and can be used to estimate the likely process signals in water and the number of classes within a region.

Therefore, although there is an obvious benefit in having a significant water sampling dataset it is not essential, as much can be inferred from knowledge of how landscape attributes influence different process signals in water. Mapping of 'likely' process-attribute classes can be used for targeted water quality sampling, minimising the number of samples that are required for validation. Further, as the approach is looking at process signals, not trend, historical water quality data is a valuable source of process signal information for the initial evaluation of process-attribute gradients and likely classes (see Rissmann et al., 2016).

Step 3: Test Performance

As the spatial variation of most water quality and hydrochemical measures is controlled by more than one process, the combination of classed process-attribute layers is necessary in order to best estimate spatial variation in water quality and/or hydrochemical measures (Rissmann et al., 2016; Snelder, 2016). For example, the concentration of NO_3^- in a stream may be controlled by both the overall redox setting in a capture zone and the degree of hydrological connection to low NO_3^- waters sourced from reducing parts of a catchment or a hydrologically connected recharge domain with naturally low NO_3^- (i.e. Alpine recharge domain).

Selection of the process-attribute layers to be combined will depend on the objectives of the study and the processes considered to exert the greatest control over spatial variability. For example, if understanding and estimating the spatial variation in nitrogen (N) and phosphorous (P) is the key objective, then the hydrological and redox process-attribute gradients should be combined. If the objective is to better understand and estimate spatial variation in the process level controls over water source and recharge mechanism, then the atmospheric and hydrological attribute-process layers should be combined. If the purpose is to better understand and estimate spatial variation in the process level controls over the major ion concentration, pH and alkalinity of water, then the atmospheric, hydrological, and weathering process-attribute layers should be combined. Finally, if the objective is to better understand and estimate both water quality and hydrochemical variation, then all four process attribute layers should be combined.

For the regional 'Physiographics of Southland' project, all four-classed process-attribute layers representing each key process family were combined, and both a simple hierarchal sorting (Rissmann et al., 2016) and a more sophisticated machine learning approach (Random Forest (RF) (Snelder, 2016) were applied. The two key questions formulated for testing were: (i) can the process-attribute classes within the capture zone of a monitoring point independently estimate spatial variation in water quality and hydrochemistry for surface and shallow groundwaters? and; (ii) do water quality and hydrochemical measures change in a manner consistent with the process level understanding used to develop the layers?

In the RF models of Snelder (2016), the classed process-attribute layers representing each key process family were used as predictor variables and the water quality and hydrochemistry as response variables. Snelder (2016) found the mapping accurately estimated spatial variation in surface water quality and hydrochemistry for most key measures. Further, the response characteristics evident in partial response plots derived from the RF modelling were consistent with the underlying process level understanding used to develop each layer. The performance of the physiographic approach to estimate groundwater signatures from bores across the region was less accurate (Snelder, 2016). However, mapping still readily identified and constrained all previously recognised groundwater NO_3^- and P hotspots, and correctly estimated water source and aquifer redox status (Rissmann et al., 2012; Rissmann, 2012; Rissmann et al., 2016). Furthermore, the strong performance for surface water suggested the approach could be used to accurately estimate the shallow groundwater contribution most relevant to the surface water network. This interpretation is consistent with established knowledge that the zone of water table fluctuation is often the key driver of the young groundwater exported to streams (Molenat et al., 2008; Inamdar, 2011). This issue occurs as groundwater wells are drilled for security of supply, not for targeting the shallow aquifer component most critical to stream. Accordingly, regional groundwater data sets may vary as to their representativeness, with well depth and the degree of confinement critical considerations.

For the 'Physiographics of Southland' project, estimation of the spatial variability in surface water sediment and *E. coli* was not as well constrained, although variation in these measures between monitoring sites with significantly different assemblages of process-attribute classes were statistically significant and as hypothesised (Hughes et al., 2016). In the Waituna case study provided here, additional effort was made to improve the spatial mapping of the landscape controls governing variation in steady-state sediment and *E. coli* measures, with some significant improvements (Rissmann et al., 2018). This was accomplished by mapping landscape gradients in percentage excess rainfall occurring as overland flow and artificial drainage density (Pearson, 2015a and b). These attributes were not initially included in the science component of the regional scale project. At regional scales, greater variability in the landscape attributes governing sediment loss to streams necessitates that additional attributes be considered (e.g. rock strength) (Rissmann et al., 2017).

The strong performance of the physiographic method to estimate spatial variation in water composition suggests the scale of geospatial layers used are appropriate. However, it is noted that most surface water monitoring networks are biased towards larger order streams and that some geospatial layers have limited resolution for drainage basins <8 km^2 (Rissmann et al., 2017). At this level of resolution, additional fine scale geospatial data may be required to improve mapping of process-attribute gradients, such as radiometric imagery (Rissmann et al., 2017).

Finally, if process-attribute mapping can be used to accurately estimate water quality and/or hydrochemical composition across monitoring sites, then it is assumed that it can be used for areas without monitoring data given similar land use intensities. This assumption is based upon the recognition that process-attribute gradients are just as relevant for areas without water quality data (as noted in Step 2).

Step 4: Produce Physiographic Map(s)

Following testing, process-attribute layers are combined to produce a "Physiographic Map". Areas with the same assemblage of attribute-process classes are identified as Physiographic Units (PGUs). Combining classed process-attribute layers to produce PGUs, essentially self-classifies at the process level, the landscape attributes that govern variation in shallow ground and surface water quality and/or hydrochemistry. Relevant here is that PGUs respond in a similar manner at the process level and as such also respond in a similar manner to a broadly equivalent land use pressure.

As with Step 3 above, the Physiographic Map that is produced will depend on the objectives of the study. If traditional water quality contaminants are the key focus, then the process-attribute layers representing the hydrological and redox process layers are combined and areas that share the same characteristics are identified. A more complex Physiographic Map is produced when all four process-attribute layers are combined. For the Southland region, *c.* 30 PGUs were identified based on the combination of regional hydrological and redox process-attribute layers. Several hundred (*c.* 300) PGUs were produced when all four process-attribute layers were combined. Ultimately, the number of PGUs is finite and dependent upon the inherent complexity of the landscape within a given catchment or region.

An example of an important PGU, within the intensively farmed lowland area of Southland, is that characterised by well-drained soils overlying oxidised aquifers that are recharged exclusively by local precipitation - with no flushing by alpine or hill country derived waters. This PGU is commonly associated with elevated groundwater NO_3^- concentrations and contributes NO_3^- rich waters to local streams as baseflow (Hughes et al., 2016). Another PGU that is also recharged exclusively by local precipitation is characterised by well drained soils that overly reducing aquifers. Nitrate leaching from these soils is rapidly removed in the underlying aquifer with little deleterious impact on hydrologically connected groundwater or surface water bodies (Hughes et al., 2016). Another important PGU is associated with well-drained gravel soils overlying strongly oxidising aquifers that are recharged by Alpine derived waters (Hughes et al., 2016). In this PGU, high NO_3^- concentrations in soil drainage water that reach the underlying aquifer are diluted to low levels by large volumes of low NO_3^- waters. More examples of Southland PGUs are presented in Hughes et al., 2016 and Rissmann et al., 2018.

In addition to accurately estimating spatial variation in water quality, the physiographic method has the advantage of being able to explain, at the process level, 'how' and 'why' water quality and composition vary despite similar levels of land use intensity (Hughes et al., 2016; Rissmann et al., 2016; Snelder et al., 2016). As such, the method adds value by providing the underlying context to questions of state and trend and when communicating with stakeholders the likely reason for variation in water quality outcomes between different catchments or farms (Hughes et al., 2016; Rissmann et al., 2018). For example, the question of *Why is* NO_3^- *increasing in this stream or aquifer but not in others?* For the same reasons, physiographic mapping can be used to provide context to other useful tools and numerical models commonly used to estimate land use losses and catchment loads (i.e. OVERSEER Nutrient Budgets, CLUES, LUCI, SPASMO etc.).

Waituna Case Study

Recent high resolution physiographic mapping undertaken in the Waituna Catchment, Southland, are provided to demonstrate (i) the key process-attribute layers, hydrology and redox, which govern spatial variation in water quality outcomes across the catchment, and; (ii) outline current investment in the use of physiographic mapping within the catchment.

The Waituna Catchment (*c.* 22,000 Ha) forms part of the Awarua-Waituna wetland complex, which has been recognised under the Ramsar Convention as a wetland of international importance since 1976. The Waituna Catchment drains into the Waituna Lagoon, a brackish intermittently closed and open lake (ICOL), within the Waituna Wetland Scientific Reserve. The Waituna Lagoon is fed by Waituna, Moffat, and Carran Creeks (Rissmann et al., 2012; Rekker and Wilson, 2016; Rissmann et al., 2018). Craws Creek, a tributary of Carran Creek, drains an area of undeveloped peat wetland, and provides a good reference catchment for comparison with agriculturally land developed within a wetland setting.

Environment Southland has undertaken water quality monitoring at 15 sites across the three subcatchments. Median data used for this analysis was calculated between the years 2012 and 2016. The number of samples for the sites vary between a maximum of 143 and a minimum of 12.

1. Hydrological Process-Attribute Layer

The hydrological process-attribute layer (H-PAL) for the Waituna Catchment was developed following the method described above (Steps 1-3) using pre-existing geospatial layers (i.e., DEM, artificial drainage network, soil and geological layers) and water quality data supplied by Environment Southland. Due to the small scale of the catchment and a desire for farm scale relevance, soil hydrological properties at the soil series level, including the subordinate soil series within a polygon, governing variation in drainage pathways were included. Specifically, the soils of the catchment were classified according to the likelihood of deep drainage (vertical percolation to depth through well drained soils) (Hughes et al., 2016), artificial subsurface and farm ditch drainage (mainly lateral flow) (Pearson, 2015b; Rissmann et al., 2018) and the percentage excess precipitation occurring as overland flow (OLF, Pearson 2015a). A water source and routing layer for the perennial stream network was also incorporated to provide constraint over the export of water from headwater areas to down gradient reaches of streams and ultimately the Waituna Lagoon (not shown here).

Following hypothesis testing and refinement (Step 1b), the key landscape attributes governing variation in hydrological flow pathways were extracted and mapped (Step 2a) and subsequently classified to produce the H-PAL (Step 2b) (Figure 3). During each of these steps the hydrological tracers, Na and Cl in conjunction with a small number of stable isotope measures ($\delta^{18}O/\delta^{2}H\text{-}H_2O$, V-SMOW) were used as key signals of water source and routing via the perennial stream network. Clarity, turbidity (NTUs), Total Suspended Sediment (TSS), Volatile Suspended Sediment (VSS) and Dissolved Organic Carbon (DOC) concentrations were used as key signals of hydrological pathway – mainly deep drainage, lateral soil zone flow and surficial OLF pathways.

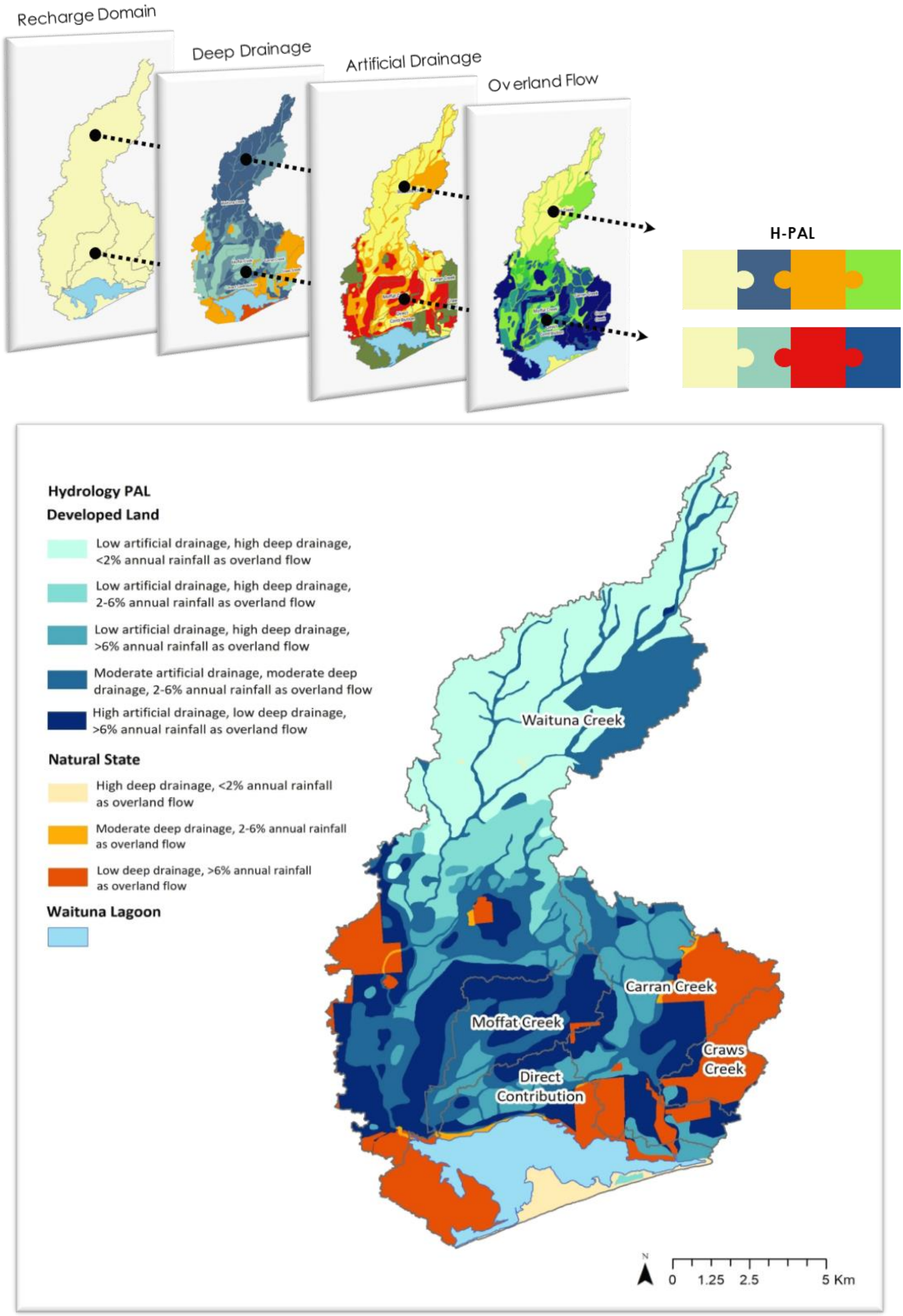

Figure 3. The H-PAL layer for the Waituna Catchment, depicting the combination of drainage pathways. The water source and routing layer is not depicted in this image due to complexity.

Graphical examples of the performance of the hydrological pathways within the H-PAL (Step 3), on its own, to estimate steady-state process signals for key water quality measures known to be influenced by water flow path are presented in Figure 4. The relationships for Total Suspended Sediment (TSS) and Volatile Suspended Sediment (VSS) showed similar magnitudes of correlation. The use of steady state values reduced the influence of flow with the magnitude of each process signal reflective of the relative proportion of artificial drainage and OLF within each capture zone. Quantitative multivariate methods were also applied but not discussed here.

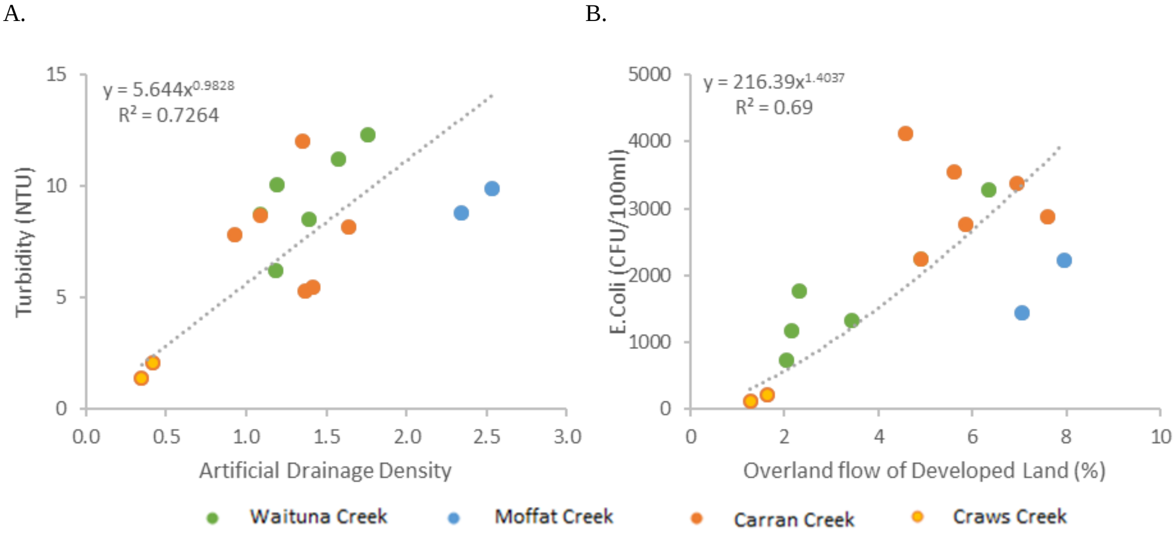

Figure 4. The relationship between the H-PAL scores for a capture zone and water quality metrics that are known to be influenced by flow pathway. A) shows median turbidity vs. artificial drainage density where 0 = none to little subsurface artificial drainage and 3 = a high proportion relatively. B) Mean E. coli vs. percentage rainfall as overland flow from developed land. Mean data for E. coli was calculated from 12 monthly samples in 2012.

The spatial relationships between H-PAL pathways and steady state water quality measures were improved when a coarse land use layer, incorporating conservation estate, reserves and pastoral land, was used to estimate and weight the proportion of agricultural land within the capture zone of the surface water site, reflecting the importance of land use loading (not shown; see Rissmann et al., 2018). Some additional minor improvements in accuracy were noted when the weathering process-attribute (W-PAL) and redox process-attribute (R-PAL) layers were combined with the H-PAL (not shown). The role of the W-PAL and R-PAL appear to reflect landscape influences over the susceptibility of different substrates to erosion and the binding of sediments by the oxides and oxyhydroxides of iron, respectively.

In order to provide a farm scale interface to the H-PAL and the final Physiographic Map, vector style land parcel and paddock scale flow paths and convergence zones were mapped (Marapara & Jackson, 2017). Zones of flow path convergence were integrated with pre-existing maps of the artificial drainage networks (obtained from Environment Southland, 2017), likely artificial drainage density (Pearson, 2015b) and spatial coordinates of mole-pipe drainage outfalls (sourced from DOC, and Environment Southland, 2017) before a significant effort to digitise open ditch drains and subsurface drainage (Figure 5). Flow path vector layers provide a high-resolution interface for property owners and farm extension experts seeking to better target the reduction of land use losses to surface waters at the land parcel and paddock scale and are designed to be used in conjunction the H-PAL and/or the final PGU layer.

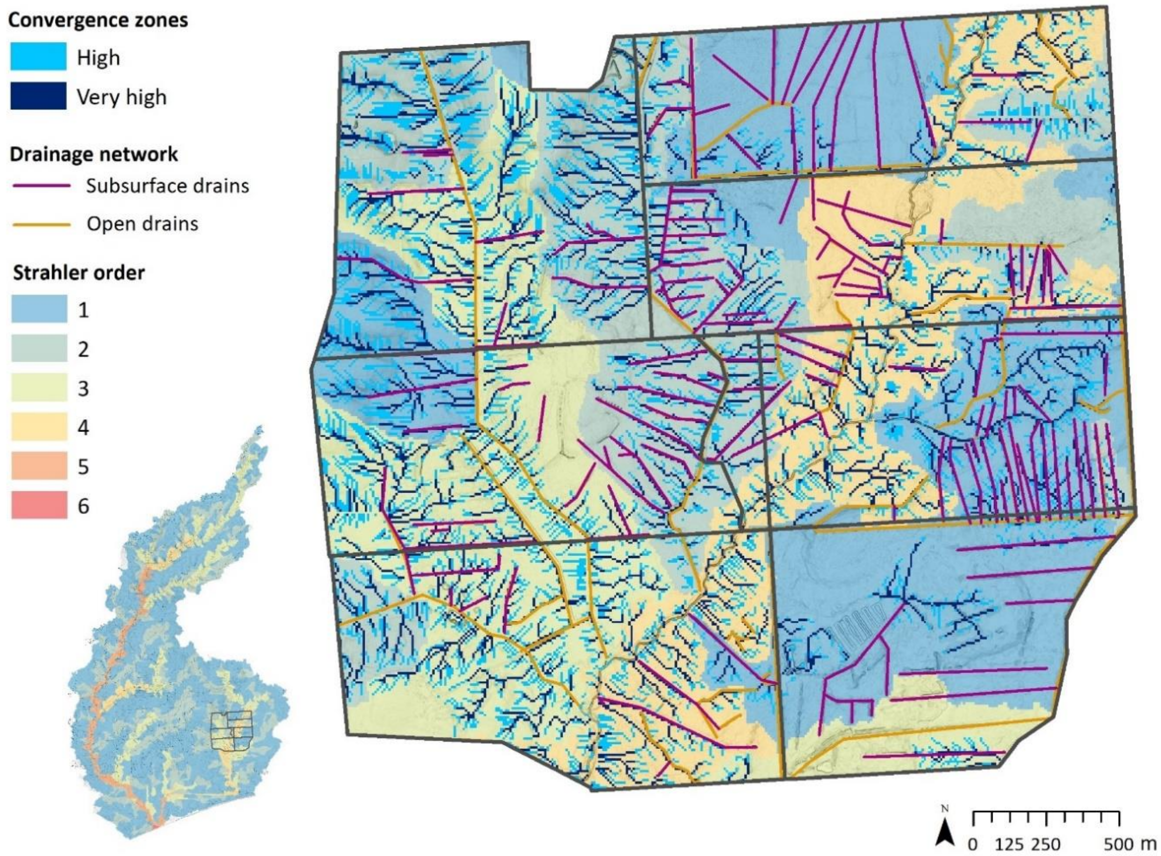

Figure 5. High resolution mapping of open and subsurface artificial drainage, flow path and flow convergence for land parcel and paddock scale interventions. Convergence zones (after Marapara and Jackson, 2017) depict those areas of the land parcel where water flux is 5 (high) to >20 (very high) times higher than precipitation volume. Strahler order pertains to convergent zones not the perennial stream network.

2. Redox Process-Attribute Layer

The redox process-attribute layer (R-PAL) for the Waituna Catchment is presented below in Figure 6. The layer was developed following the method described above utilising a range of soil and geological layers and leveraged off the existing regional scale redox layer produced for Environment Southland's Physiographics of Southland project (Rissmann et al. 2016, Rissmann et al. 2018). The regional layer found that in order to estimate spatial variation in shallow ground and surface water redox signatures, both the influence of soil zone and shallow aquifer redox conditions needed to be considered (Rissmann, 2011; Killick et al., 2015; Rissmann et al., 2016). A similar conclusion was reached by Wilson et al. (2018).

Refinement of the regional scale R-PAL for the Waituna Catchment included a new classification for estimating soil reduction potential utilising attributes of soil drainage and carbon content within the soil layer (Rissmann et al., 2018). It was evident during hypotheses testing (Step 1b) that these attributes exerted a key control over P mobility via the reductive dissolution of P-sorbing minerals, such as the oxides and oxyhydroxides of iron (see also McDowell & Monaghan, 2015). During the production of the R-PAL, DO, NO_3^-, manganese (Mn^{2+}), iron (Fe^{2+}), sulphate (SO_4^-) and dissolved organic carbon (DOC) were used as key signals of redox process. Following hypothesis testing and refinement (Step 1), the key soil and geological attributes were extracted and mapped (Step 2a) and subsequently classified to produce the R-PAL (Step 2b).

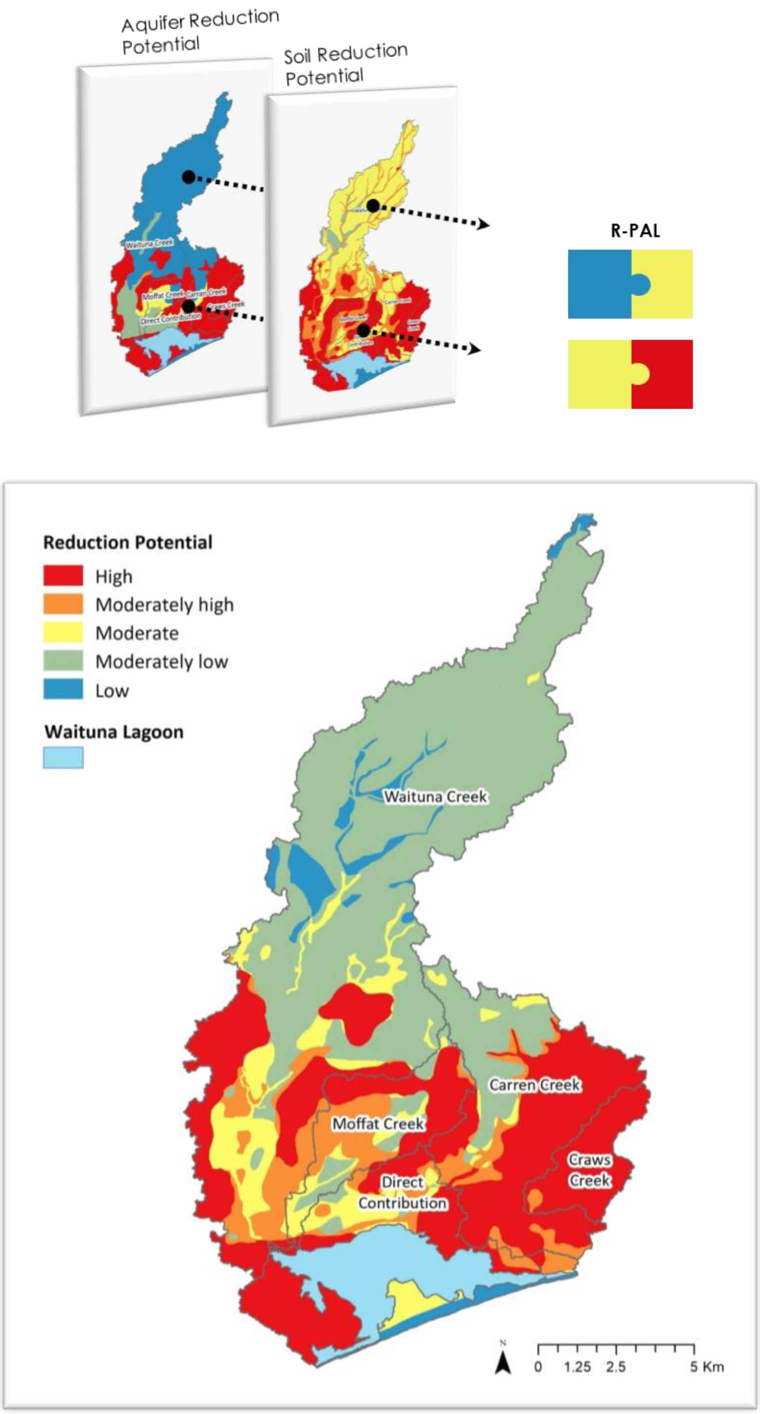

Figure 6. The R-PAL layer for the Waituna Catchment, depicting the two-classed aquifer (geological) and soil reduction potential layers and their subsequent combination to form the R-PAL.

Graphical examples of the performance of the R-PAL (Step 3), on its own, to estimate steady-state process signals for water quality measures known to be influenced by water flow path are presented in Figure 7. Quantitative multivariate methods were also applied but not discussed here due to complexity.

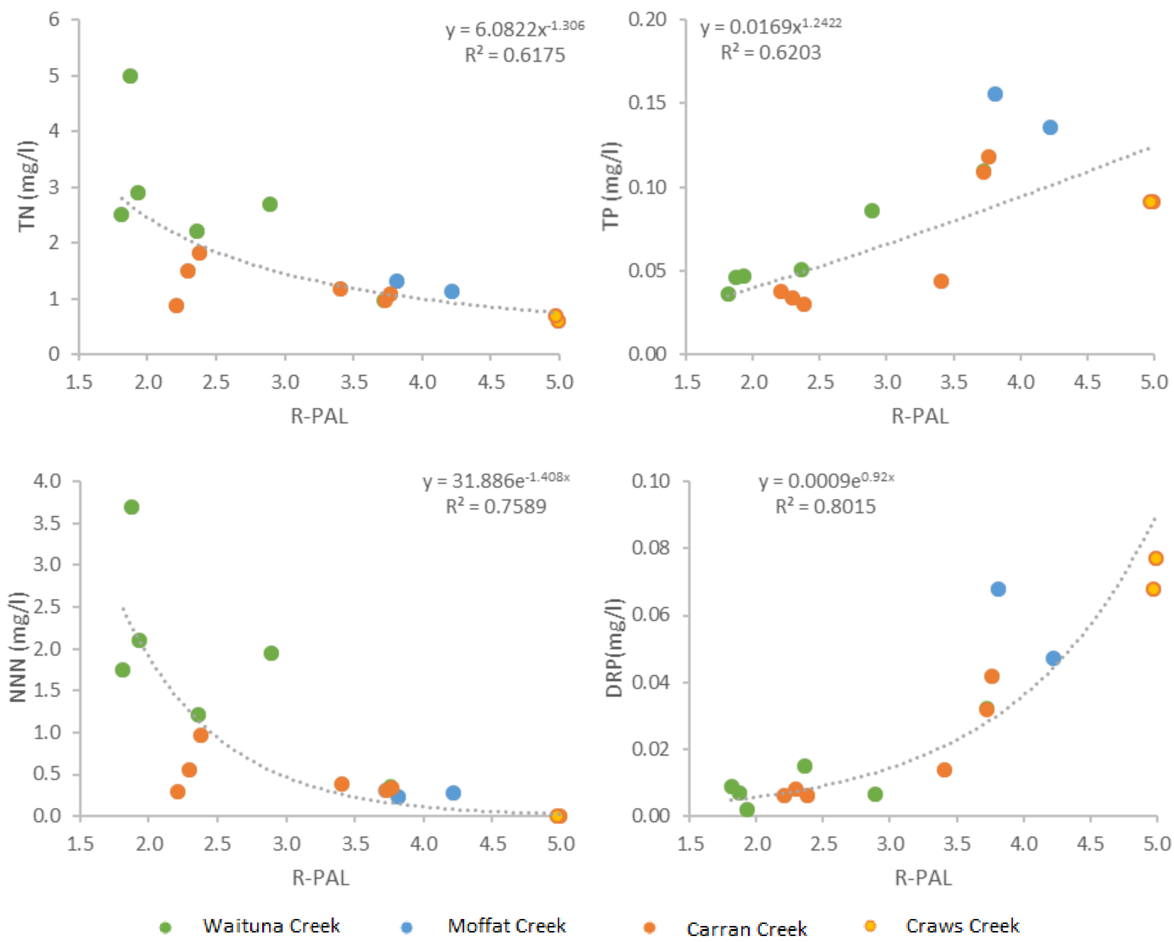

Figure 7. The relationship between the R-PAL scores for a capture zone and total nitrogen (TN), total phosphorus (TP), oxidised nitrogen (nitrate and nitrite, NNN), and dissolved reactive phosphorus (DRP). These water quality metrics are known to be influenced by redox processes. Where an R-PAL value for a surface water capture zone of 1.5 indicates a relatively low reduction potential (relatively well drained soils and oxidising aquifers) and a score of 5.0 indicates a strong soil and aquifer reduction potential (mainly peat soil and aquifers). The relationship between the R-PAL and P species reflects both the reductive dissolution (a redox process) of the oxides and oxyhydroxides of Fe^{2+} and Mn^{2+} that govern P mobility and as a result P-retention. The relationships for DO, DOC, and Fe^{2+} show similar magnitude correlations.

Better control over the spatial variation in redox sensitive water quality measures occurs when the water source and routing layer within the H-PAL is combined with the R-PAL (Rissmann et al., 2018). This reflects the role of the perennial stream network over the transport and of waters of different redox status to lower reaches and is especially relevant for the longer run Waituna and Carran Creek sub-catchments, where oxidised drainage from the northern portions of these catchments is transported to lower reaches.

3. Physiographic Map

The combination of the hydrological and redox process-attribute layers to produce a physiographic map of the Waituna Catchment is presented in Figure 8 (Step 4). In this version the R-PAL is represented by the soil and geological properties separately, to allow for a temporal assessment for the catchment to be developed at a later date. The atmospheric (A-PAL) and weathering (W-PAL) process-attribute layers are not included given the main objective was to estimate and explain the landscape controls over spatial variation in water quality measures (i.e. N, P, sediment (S) and microbial (M)). The water source and routing layer and the land parcel and paddock scale pathway vector mapping are not included due to the clutter at catchment scale. However, these layers and in particular the land parcel and paddock scale vector mapping are critical aspects of the work when seeking to assess land parcel and paddock scale controls over water quality outcomes. In total there were 19 PGU's defined by combing the H-PAL and R-PAL, each of which are characterised by a unique combination of landscape attributes that mediate land use pressure in a different manner and/or degree.

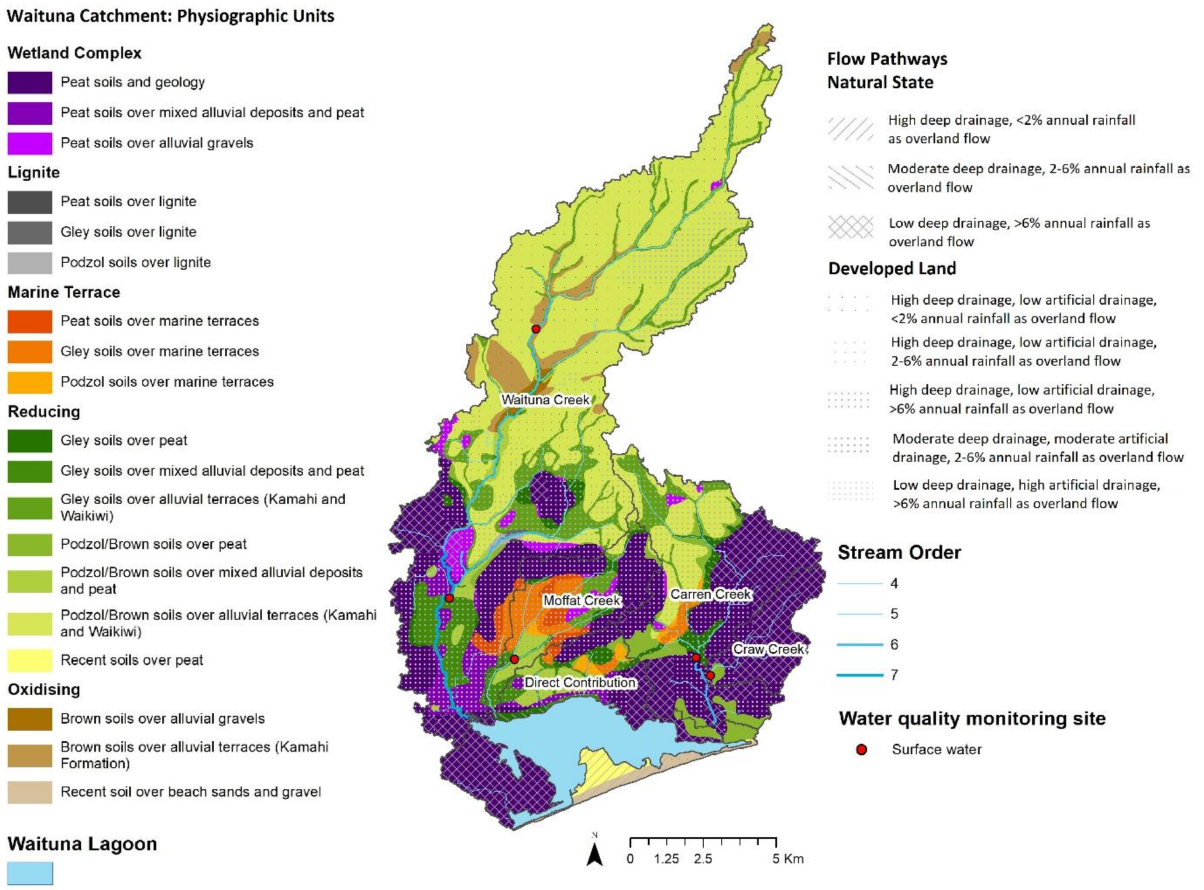

Figure 8. Physiographic map of the Waituna Catchment, based on combination of hydrological and redox process-attribute layers (Rissmann et al., 2018). Finer scale water source and routing network and land parcel and paddock scale flow paths are not shown but are critical components when evaluating controls at the farm scale.

4. How is this information being used?

The outputs of physiographic mapping for the Waituna Catchment are currently being used to provide a strategic platform for a range of critical management and investment decisions. Specifically, 'Living Water' and 'Whakamana Te Waituna' partners (Environment Southland, Southland District Council, local iwi/hapū, Dairy NZ, Fonterra and the Department of Conservation) are utilising the work *"…to figure out what to do where and provide a platform* *to prioritise nutrient and sediment mitigation tools over the catchment. This will help ensure we invest the right solutions in the right place.*" The physiographic information is also considered "*vital for demonstrating the scalability of alternative drainage system design and contaminant management to reduce the impacts of ground and surface water contaminants on Waituna Lagoon and its tributaries.*"

Currently, Fonterra farm extension advisors are using the method to tailor their evolved Sustainable Dairying Programme (Tiaki). Specifically, calibrating farm extension initiatives to the physiographic setting, in order to implement the most effective and least cost steps towards minimising environmental contamination from farms.

Overall, the uptake of physiographic science has been driven by interest in the application of a targeted approach to managing water quality outcomes, one that seeks to maximise effectiveness and minimise the cost for both the rural community and the ecological wellbeing of the Waituna Catchment and Lagoon.

Future work

A national physiographic classification (Physiographic Environments of New Zealand) is currently being created in conjunction with the Our Land and Water National Science Challenge and a range of stakeholders. To make physiographic science more accessible, a web-based interface for farmers and industry is initially being developed in the Southland region as part of a Ministry for Primary Industries, Sustainable Farming Fund grant (SFF,2017). Development and design of the web-based interface is being guided by farmers, industry groups and Environment Southland farm extension staff.

Acknowledgements

The authors acknowledge funding from the Living Water partnership and acknowledge the partners of the Whakamana Te Waituna project. The authors acknowledge staff at Environment Southland who provided access to key data and provided helpful feedback. Funding from the National Science Challenge, Our Land and Water has helped advance the physiographic method. Thank you to Abigail Lovett and Professor Tim Clough for their comments on this paper and Matt Couldrey for editing. Finally, we thank the farmers of the Waituna Catchment for their input and keen support of this work.

References

Becker, J. C., Rodibaugh, K. J., Labay, B. J., Bonner, T. H., Zhang, Y., and Nowlin, W. H. (2014). Physiographic gradients determine nutrient concentrations more than land use in a Gulf Slope (USA) river system. Freshwater Science, v.33(3), p.731–744.

Beyer, M., and Rissmann, C. (2016). Tile drain and soil water sample assessment: relationships between soil denitrification potential and redox processes. Lower Hutt, N.Z.: GNS Science. GNS Science report 2016/60 ii.

Beyer, M., Rissmann, C., Rodway, E., Killick, M., and Pearson, L. (2016). Technical Chapter 6: Influence of Soil and Geological Composition over Redox conditions for Southland groundwater and surface waters. Environment Southland. Technical Report. No: 2016/3.

Clark, I. D., and Fritz, P. (1997). Environmental Isotopes in Hydrogeology. Taylor and Francis.

Dinka, M. O., Loiskandl, W., and Ndambuki, J. M. (2015). Hydrochemical characterization of various surface water and groundwater resources available in Matahara areas, Fantalle Woreda of Oromiya region. Journal of Hydrology: Regional Studies, v.3, p.444-456.

Dow, C. L., Arscott, D. B., and Newbold, J. D. (2006). Relating major ions and nutrients to watershed conditions across a mixed-use, water-supply watershed. Journal of the North American Benthological Society, v.25(4), p.887–911.

Drever, J. I. (1997). The geochemistry of natural waters, surface and ground water environments third edition. Prentice Hall.

Eriksson, E. (2012). Principles and Applications of Hydrochemistry. Springer. p175.

Giller, P. S., and Malmqvist, B. (2004). Biology of Habitats: The Biology of Streams and Rivers. Oxford University Press.

Güler, C., and Thyne, G. D. (2004). Delineation of hydrochemical facies distribution in a regional groundwater system by means of fuzzy c-means clustering. Water Resources, v.40, p.1–11.

Hale, S. S., Paul, J. F., and Heltshe, J. F. (2004). Watershed landscape indicators of estuarine benthic condition. Estuaries, v.27(2), p.283–295.

Hughes, B., Wilson, K., Rissmann, C., and Rodway, E. (2016). Physiographics of Southland:Development and application of a classification system for managing land use effects on water quality in Southland (Technical Report. No 2016/11). Invercargill, New Zealand: Environment Southland.

Inamdar S. (2011). The Use of Geochemical Mixing Models to Derive Runoff Sources and Hydrologic Flow Paths. In: Levia D., Carlyle-Moses D., Tanaka T. (eds) Forest Hydrology and Biogeochemistry. Ecological Studies (Analysis and Synthesis), v.216. Springer, Dordrecht

Jiang, Y., Wu, Y., Groves, C., Yuan, D., and Kambesis, P. (2009). Natural and anthropogenic factors affecting the groundwater quality in the Nandong karst underground river system in Yunan, China. Journal of Contaminant Hydrology, v.109, p.49-61.

Johnson, L., Richards, C., Host, G., and Arthur, J. (1997). Landscape influences on water chemistry in Midwestern stream ecosystems. Freshwater Biology, v.37(1), p.193–208.

Kendall C., and McDonnell, J. J. (2008). Isotope Tracers in Catchment Hydrology. Elsevier Science B.V., Amsterdam. p.41-86.

Killick, M., Stenger, R., and Rissmann, C. (2015). Estimating soil zone denitrification for Southland. Technical Report. Invercargill, New Zealand: Environment Southland.

King, R. S., Baker, M. E., Whigham, D.F., Weller, D.E., Jordan, T.E., Kazyak, P.F., and Hurd, M.K. (2005). Spatial considerations for linking watershed land cover to ecological indicators in streams. Ecological Applications, v.15, p.137–53.

Krantz, D. E., and Powars, D. S. (2002). Hydrogeologic setting and potential for denitrification in groundwater, Coastal Plain of Southern Maryland: U.S. Geological Survey Water-Resources Investigations Report 00-4051.

Langmuir, D. (1997). Aqueous Environmental Chemistry. Prentice Hall. p.600.

Lydersen, E., Larssen, T., and Fjeld, E. (2004). The influence of total organic carbon (TOC) on the relationship between acid neutralizing capacity (ANC) and fish status in Norwegian lakes. The Science of the total environment, v.326(1-3), p.63-9

Lynn, I. H., Manderson, A. K., Page, M. J., Harmsworth, G. R., Eyles, G. O., Douglas, G. B., Mackay, A. D., and Newsome, P. J. F. (2009). Land Use Capability Survey Handbook – a New Zealand handbook for the classification of land 3rd edition. Hamilton, AgResearch; Lincoln, Landcare Research; Lower Hutt, GNS Science. 163p.

Marapara, T., and Jackson, B. (2017). Synthesising water convergent zones for optimised farm contaminant mitigation. Wellington, New Zealand: Victoria University.

McDowell, R. W., and Monaghan, R. M. (2015). Extreme Phosphorus Losses in Drainage from Grazed Dairy Pastures on Marginal Land. Journal of Environment Quality, v.44(2), p.545.

McMahon, P. B., and Chapelle, F. H. (2008). Redox Processes and Water Quality of Selected Principal Aquifer Systems. Ground Water, v.46(2), p.259-271

Moldan, B., and Černý, J. V. (1994). Biogeochemistry of small catchments: a tool for environmental research. Prague, Czech Republic: Scientific Committee on Problems of the Environment (SCOPE) of the International Council of Scientific Unions (ICSU) and of the United Nations Environment Programme (UNEP).

Molenat, J., Gascuel-Odoux, C., Ruiz, L., and Gruau, G. (2008). Role of water table dynamics onstream nitrate export and concentration in agricultural headwater catchment (France). Journal of Hydrology, v.348(3-4), p.363-378.

Pearson, L. (2015a). Overland flow risk in Southland. Technical Report No. 2015/06. Invercargill, New Zealand: Environment Southland. 19p

Pearson, L. (2015b). Artificial subsurface drainage in Southland. Technical Report No. 2015/07. Invercargill, New Zealand: Environment Southland. 18p

Rekker, J., and Wilson, S. (2016). Waituna Catchment: Water Quality Review. Report 1051-3-R1. Lincoln Agritech Ltd. report prepared for Environment Southland. Lincoln, Christchurch, New Zealand.

Rissmann, C. (2011). Regional Mapping of Groundwater Denitrification Potential and Aquifer Sensitivity. Technical Report. No: 2011/12. Invercargill, New Zealand: Environment Southland. 40p

Rissmann, C., Wilson, K., and Hughes, B. (2012). Waituna Catchment Groundwater Resource. Technical Report No. 2012/04. Invercargill, New Zealand: Environment Southland.

Rissmann, C. (2012). The Extent of Nitrate in Southland Groundwaters Regional 5 Year Median (2007 - 2012 (June)).

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. Technical Report No. 2016/3. Invercargill, New Zealand: Environment Southland.

Rissmann, C., Beyer, M., Rodway, E., Hodson, R., Ward, N., Ellis, T., Hodgetts, J., Pearson, L., Killick, M., Marapara, T., Akbaripasand, A., Dare, J., Kees, L, Snelder, T., Moriarty, E., Almond, P., and Webster-Brown, J. (2016b). Shrink-swell (cracking) soils as important conduits of ground and surface water microbial contamination? NZ Freshwater conference, Invercargill, New Zealand.

Rissmann, C., Marapara, T., Bloomberg, S., Lindsay, J., and Pearson, L. (2017). Evaluation of geospatial datasets and recognition of landscape gradients specific to water quality. e3Scientific Technical Report prepared for Northland Regional Council. 108p

Rissmann, C., Pearson, L., Lindsay, J., Badenhop, A., and Marapara, T. (2018). Waituna Catchment: Technical Information and Methodology. e3Scientific Technical Report prepared for Living Water.

Shiels, D. R. (2010). Implementing landscape indices to predict stream water quality in an agricultural setting: An assessment of the Lake and River Enhancement (LARE) protocol in the Mississinewa River watershed, East-Central Indiana. Ecological Indicators, v.10(6), p.1102–1110.

Snelder, T. (2016). Performance testing of the Physiographics of Southland using random forest (RF) models. Water Land People report prepared for Environment Southland.

Snelder, T., Hughes, B., Wilson, K., and Dey, K. (2016). Physiographic Zones for the Southland Region: Classification system validation and testing report. Water Land People report prepared for Environment Southland. 60p

Strong, D. T., Turnbull, R. E., Haubrock, S., and Mortimer, N. (2016). Petlab: New Zealand's national rock catalogue and geoanalytical database. New Zealand Journal of Geology and Geophysics, v.59(3), p.475–481

Sustainable Farming Fund (application) (2017). Farmer interface for PhysiographicEnvironments. Prepared for Ministry for Primary Industries by e3Scientific Ltd, Invercargill. 20p

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: scale 1:250,000. Lower Hutt: Institute of Geological and Nuclear Sciences Limited. Institute of Geological and Nuclear Sciences 1:250,000 geological map 20. 74 p. + 1 folded map

Wieder, R.K., Novak, M., and Vile, A. (Eds.). (2004). Biogeochemical Investigations of Terrestrial, Freshwater, and Wetland Ecosystems across the Globe. Kluwer Academic Publishers, New York. p.748.

Wilson, S. R., Close, M. E., and Abraham, P. (2018). Applying linear discriminant analysis to predict groundwater redox conditions conducive to denitrification. Christchurch, New Zealand. Journal of Hydrology, v.556, p.611-624.

Woodward, S. J. R., Stenger, R., and Bidwell, V. (2011). Using a simple 2D steady-state saturated flow and reactive transport model to elucidate denitrification patterns in a hillslope aquifer.

Wright, R. F. (1988). Influence of Acid Rain on Weathering Rates. *In:* A. Lerman, and M. Meybeck, Physical and Chemical Weathering in Geochemical Cycles p.181-196. Oslo, Norway: Kluwer Academic Publishers.