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CRITICAL PATHWAYS PROGRAMME: UNRAVELLING SUB-CATCHMENT SCALE NITROGEN DELIVERY TO WATERWAYS

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Abstract

To be effective and efficient, decision making on land use, land management, mitigation measures, as well as policy, need to be based on a clear understanding of cause-effect relationships. Present practice is to link activities on the land and water quality outcomes at spatial scales of 100s to 1000s of km^2. However, such large catchments are inevitably heterogeneous. Consequently, it is exceptionally difficult to link an observed contaminant flux at the catchment outlet to the many past and present activities within the large catchment that collectively have caused it. The need to focus on the sub-catchment scale (10s of km^2), i.e. the local streams that feed the large rivers that are typically being monitored has therefore recently been emphasised internationally.

To unravel sub-catchment scale nitrogen delivery to waterways, we are introducing an innovative multi-scale measurement, data analysis and modelling approach that allows to coherently link transect, sub-catchment and catchment scale hydrogeophysical information. Three key innovations will collectively enable us to achieve this. Firstly, we will introduce a novel geophysical measurement suite (airborne and ground-based) to gain information on structural, hydrological, and chemical characteristics controlling N transport and attenuation, particularly in the shallow subsurface zone (top 20m). Secondly, innovative Environmental Data Analytics (EDA) techniques will be used to integrate the information from the 'Big Data' created by the new geophysical measurements. Thirdly, we will use the hydrogeophysical units, identified by EDA together with Lidar to conceptualise and develop a numerical structure for catchment-scale flow models. To simulate the sub-catchment scale flow, transport, and attenuation, we will nest finer resolution models within the coarser catchment models using information gathered at the sub-catchment scale.

Two intensively farmed catchments with contrasting hydrological and biogeochemical conditions provide our case studies. The Waiotapu Stream catchment ($\approx$ 312 km^2) on the North Island's Central Plateau represents a baseflow-dominated upland catchment with a

large groundwater reservoir in young volcanic deposits. In contrast, the Piako River headwater catchment is a lowland catchment (≈ 104 km^2) in the upper Hauraki Plains with aquifer deposits of lower transmissivity and a high quickflow fraction in the flow hydrograph.

Introduction

To enable effective and efficient decision making on land use, land management, mitigation measures, as well as related policy, a clear understanding of cause-effect relationships is needed. The source – transfer – receptor chain concept has internationally been proven useful to elucidate these relationships and has been successfully applied in Aotearoa - New Zealand, e.g. in the Groundwater Assimilative Capacity and Transfer Pathways research programmes.

The '*source load*' (= loss from root zone) is in NZ often estimated by the nutrient budgeting model OVERSEER. The '*delivered load*', i.e. the load that is observed at the receptor (= monitoring site at catchment outlet) is often smaller than the '*source load*'. There are two main reasons for this. Firstly, where the transfer pathways are long and significant storage capacity exists in the subsurface environment, the transfer can take many years (lag time). In this case, the currently observed '*delivered load*' may reflect the lower land use intensity in the catchment decades ago. Secondly, attenuation processes, in the case of nitrogen largely denitrification, can reduce the contaminant load between source and receptor. While long lag times only result in a delayed delivery of the source load, denitrification irreversibly reduces the load that is delivered.

However, in the large and heterogeneous catchments usually being monitored in NZ (100s – 1000s of km^2), it is very difficult to link a delivered load measured in a river (Fig. 1) to the many past and present activities that collectively have caused it. The need to understand and model the dynamic water and contaminant fluxes at the sub-catchment scale (10s of km^2) has therefore not only been recognised in our previous research, but also internationally (McGuire et al., 2014; McDowell et al., 2017; Abbott et al., 2018; Bol et al., 2018).

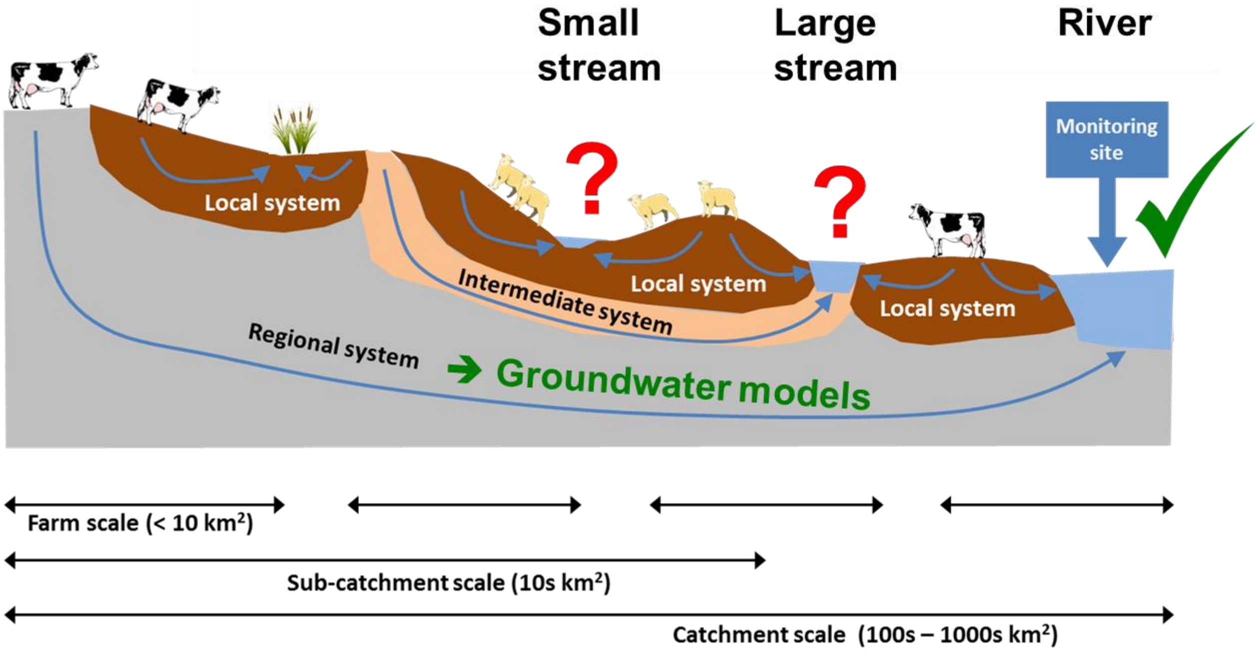

Fig. 1: Approximate relationships between flow systems and spatial scales.

Accordingly, the Critical Pathways Programme (CPP) focuses on unravelling the sub-catchment scale nitrogen delivery to waterways, i.e. into the many streams that feed the typically monitored rivers (Fig. 1). To achieve this, we need to develop the capability to elucidate the relatively shallow and relatively short pathways operating in many landscapes at the sub-catchment scale and to represent them in water flow and contaminant transfer models.

Methods

Our understanding of physical and chemical characteristics that determine transport and transformation processes between source and receptor is currently largely based on point-scale information (e.g. from soil pits, bore logs, aquifer tests). Accordingly, there is substantial uncertainty about these characteristics along pathways through catchments (e.g. Woodward et al., 2016), which geophysical methods can help to reduce (Binley et al., 2015). Moreover, geospatial datasets are available for most of NZ for the soil zone (e.g. S-map down to ≈ 1m) and for the underlying geology (QMAP). However, there is a scarcity of reliable geospatial information on the characteristics of the critical zone in-between (Fig. 2), which often consists of superficial heterogeneous deposits (sometimes called regolith). Analogously, the groundwater models that are often used in resource management focus particularly on the deeper groundwater pathways operating at the regional scale and are therefore not well suited to describe the dynamic behaviour of the shallower sub-catchment scale water flows and contaminant transfers (Fig. 1).

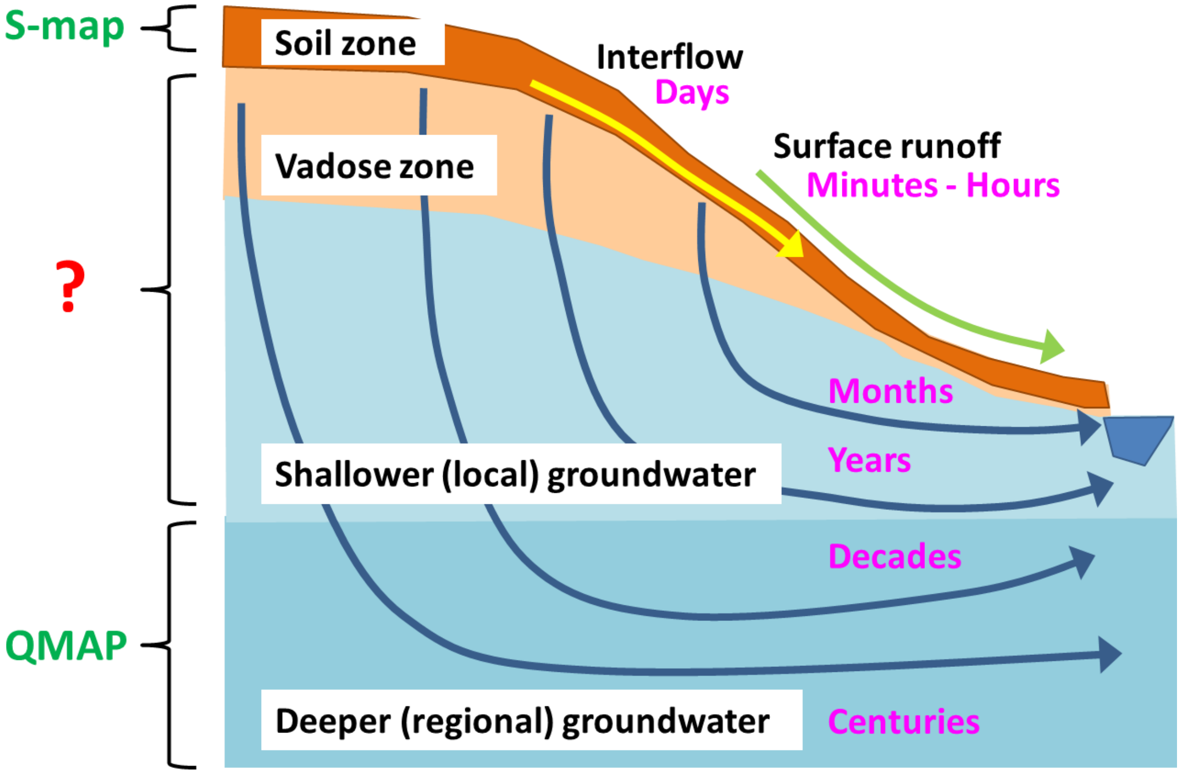

Fig. 2: Schematic illustrating key transfer pathways (surface runoff, interflow, shallow and deep groundwater flow) and associated lag times. The scarcity of geospatial information on the shallow subsurface that often hosts most of the vadose zone and the shallow groundwater zone is indicated by the ? at left.

To overcome these challenges, we are introducing an innovative multi-scale measurement, data analysis and modelling approach (Fig. 3) that enables us to coherently link transect, sub-catchment and catchment scale hydrogeophysical information:

- A novel geophysical measurement suite will provide information on structural, hydrological, and chemical characteristics controlling N transport and attenuation, particularly in the critical shallow subsurface zone (top 20m). As the first step, we have introduced the airborne transient electromagnetic SkyTEM system to New Zealand and used it in February 2019 to carry out catchment scale surveys of our two pilot catchments using parallel flight paths 200m apart (Fig. 4). The set-up was specifically optimised for our research focus on the shallow subsurface based on advice by our collaborators from Aarhus University, the developers of this system (http://hgg.au.dk/).
- Complementary to the catchment scale SkyTEM surveys, higher-resolution ground-based tTEM and borehole surveys, together with a range of conventional measurements, will be carried out subsequently at the sub-catchment and transect scales (Fig. 3). Sub-catchment selection will be informed by the heterogeneity observed during the catchment scale survey and take factors such as existing monitoring sites, *a priori* available geospatial data (e.g. S-map, land use distribution), and ease of land access into account.

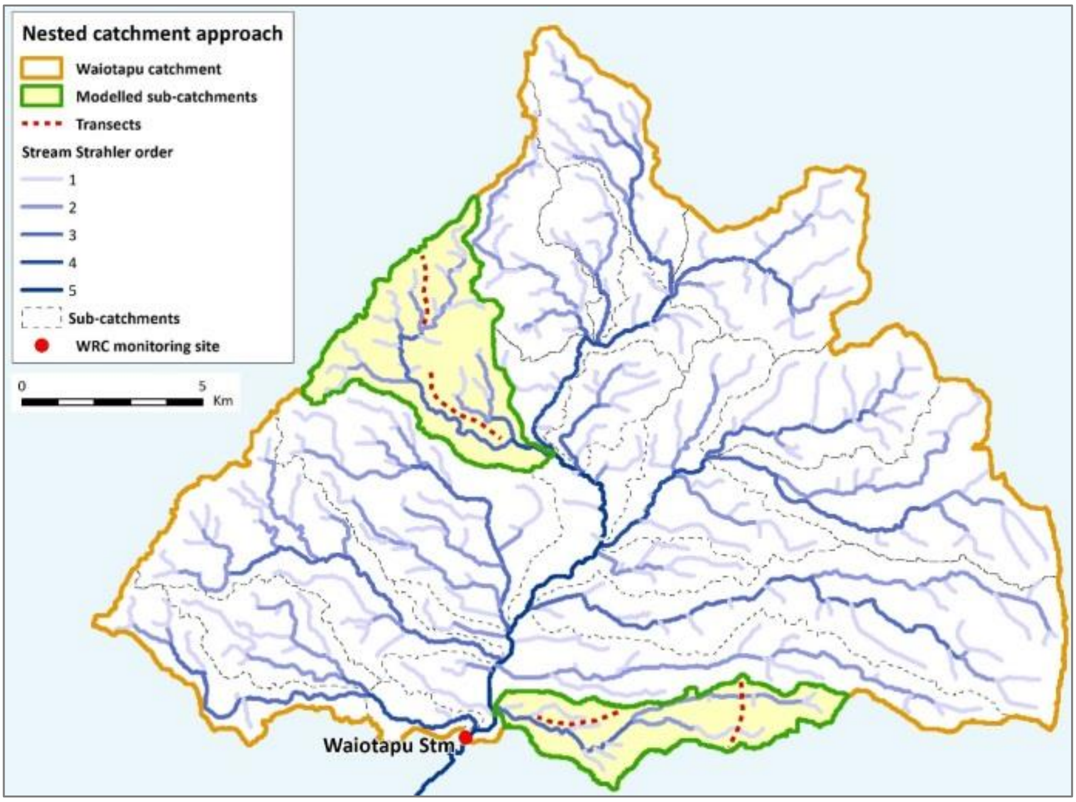

Fig. 3: Map illustrating on the example of the Waiotapu Stream catchment our nested catchment approach, consisting of measurements and modelling at the catchment, sub-catchment, and transect scales. (The shown sub-catchments and transects are arbitrarily chosen for illustration purposes only).

- The analysis of the 'Big Data' resulting from the SkyTEM surveys will build on previous work on innovative machine learning workflows to integrate airborne electromagnetic and other hydrogeophysical data (Friedel et al., 2015; Friedel et al., 2016; Iwashita et al., 2018).

- We will use the hydrogeophysical units identified by Environmental Data Analytics (EDA) techniques to conceptualise and develop the subsurface structure of the flow models for our catchments and nested sub-catchments. To simulate the sub-catchment scale flow, transport, and attenuation, we will nest finer resolution models within the coarser catchment models using information gathered at the sub-catchment scale.
- Acknowledging that biogeochemical reactions like denitrification occur unevenly in space and time (e.g. Stenger et al., 2018; Clague et al., 2019; Kolbe et al., 2019), we will test a newly developed stochastic cumulative reactivity approach (Loschko et al., 2016, 2018) for its suitability to describe denitrification in our pilot catchments.
- Our in-depth measurements at selected transects will provide the basis for developing new pedotransfer functions (PTFs) for predicting hydrologic and redox characteristics of the vadose zone (= unsaturated zone between soil surface and groundwater table). This work will also support future S-map updates and extensions beyond our pilot catchments (Pollacco et al., 2017; McNeill et al., 2018).
- Additional datasets provided by our collaborating Regional Councils (Waikato, Taranaki, Hawke’s Bay) will be analysed using EDA techniques to facilitate transfer of information generated in our pilot catchments to a wider range of catchments (Friedel et al., 2011).

Fig. 4: The SkyTEM system carrying out the helicopter-borne electromagnetic survey of the Piako River headwater catchment, February 2019.

Concurrent with our biophysical research we are pursuing economic and Vision Mātauranga goals:

- Informed by the outcomes of the biophysical research in our two pilot catchments and reviews of a) corresponding international studies, b) the cost/benefits of mitigations, and c) extrapolation methods, we will develop a cost/benefit method that enables us to quantify the net benefit of identifying and mitigating flows of nitrogen at the sub-catchment scale.
- Applying principles of kaupapa Māori theory we have started developing a kaupapa Māori consistent knowledge exchange process in collaboration with our iwi partners Ngāti Hauā and Ngāti Tahu – Ngāti Whaoa (Smith, 1997; Awatere et al., 2017). With our partners, we endeavour to uphold Kaupapa Māori Research Practices (Pipi et al., 2004). Combining of

mātauranga, contaminant transfer science, and economics will allow development of assessment frameworks that acknowledge Kaitiakitanga for investment decisions around development/management of iwi lands.

Pilot catchments

Informed by previous research (e.g. Woodward et al., 2016; Woodward and Stenger, 2018) and in consultation with our stakeholders, two intensively farmed catchments with contrasting hydrological and biogeochemical conditions were chosen as case studies (Fig. 5):

- The Waiotapu Stream catchment (≈ 312 km^2) on the North Island's Central Plateau represents a baseflow-dominated upland catchment (297 – 967m amsl) with large groundwater reservoirs in young volcanic deposits. Young Pumice soils of varying permeability dominate the catchment (≈ 61%), with smaller contributions made by Gley soils (≈ 10%) and Organic soils (≈ 6%). The occurrence of poorly drained soils is also reflected in the name of the township Reporoa, which can be translated as meaning 'long swamp'. Plantation forestry and native bush are the main land covers (≈ 55%) and occur largely at higher elevation (e.g. Kaingaroa Plateau), but highly producing pastoral land (≈ 45% of catchment area) dominates in the Reporoa Basin.
- The Piako River headwater catchment (≈ 104 km^2) is a lowland catchment (38 – 488m amsl) in the upper part of the Hauraki Plains with aquifer deposits of lower transmissivity and a large quickflow fraction in the river hydrograph. The dominant soil order is Allophanic soils (≈ 61%) but Granular soils (≈ 21%), Brown soils (≈ 10%), and Gley soils (≈ 8%) also make significant contributions. The catchment is dominated by intensive pastoral land use (≈ 84%), with the remainder being largely native bush (≈15%).

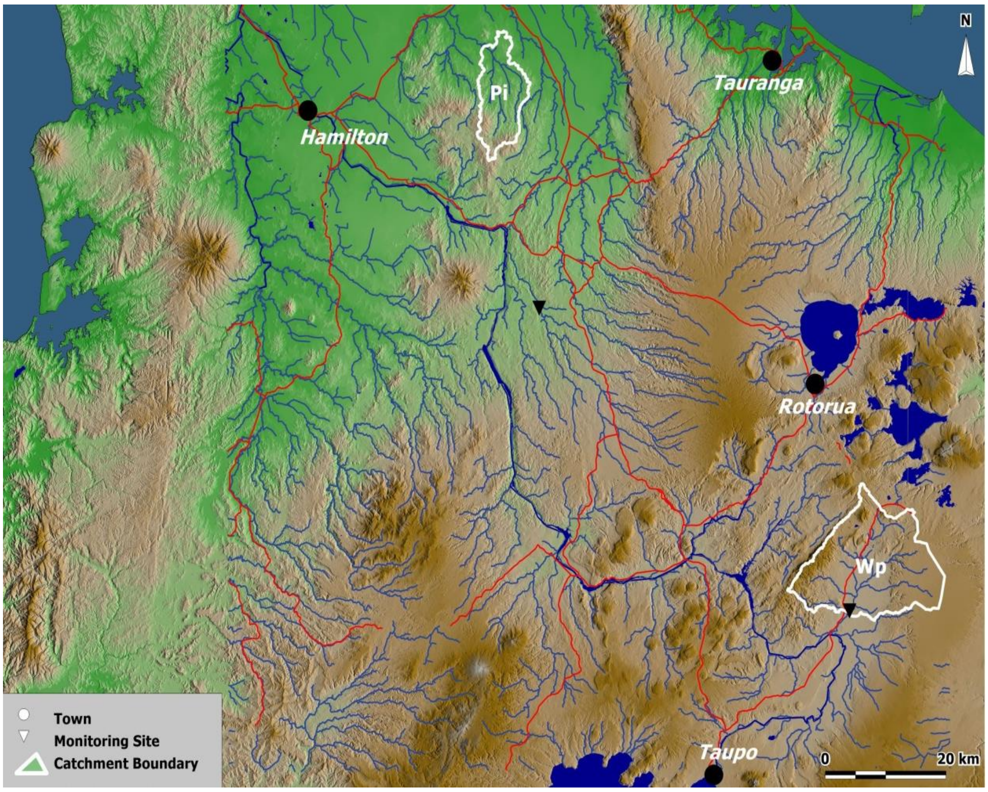

Fig. 5: Map showing the location of the two pilot catchments (Piako River headwaters, Pi; Waiotapu Stream, Wp) on the North Island of New Zealand.

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