WILL WATER SENSITIVE URBAN DESIGN RESULT IN MEASURABLE IMPROVEMENTS IN THE ECOLOGICAL HEALTH OF URBAN STREAMS?

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ABSTRACT

Urban land use results in degradation of waterways including changes to habitat (channelisation, reinforced banks, reduced riparian vegetation), altered hydrology, increased contaminant concentrations, poor water quality, and reduced ecological diversity; the combination of these effects leads to the "urban stream syndrome." Across New Zealand, there is increasing demand (and legislative requirement, e.g., through the National Policy Statement for Freshwater Management 2020), to improve the condition of streams in urban areas, and to reduce the impact of future urban development.

Methods to improve aquatic environments include implementation of stormwater treatment systems, including green infrastructure, or nature-based solutions (GI/NBS; systems that use plants and soil to manage stormwater quantity and quality) such as wetlands, raingardens and tree pits, which are components of Water Sensitive Urban Design (WSUD).

In consultation with decision makers involved in urban water management, we have identified three key science needs around the use of green infrastructure:

1) Improved understanding of the processes that influence the **performance of stormwater treatment/mitigation systems**, and the ability to cost-effectively measure and predict mitigation performance;

2) Methods to **predict the effects of urban land use on stream water quality and ecosystems**, with and without mitigation – ideally in ways that can be used for catchment-accounting and/or limit-setting (i.e., beyond average annual load predictions);

3) Methods or tools to **understand the cumulative effects of multiple stressors** acting on urban stream ecosystems, to enable informed decision-making.

We are currently in the first year of a five-year project aimed at addressing these questions by developing **a model for predicting stream ecological response from the characteristics of urban development (with and without mitigation).** The operational model will be a spatial version of the "effective imperviousness model" created by Chris Walsh and collaborators at the University of Melbourne for the Little Stringybark Creek catchment (Walsh et al. 2022).

The four major tasks required to develop this model also constitute stand-alone goals:

- **Task 1** Assess the performance and build models of selected stormwater treatment devices (raingardens, wetlands, structural soil tree pits).
- **Task 2** Develop and/or implement catchment-scale models for impervious surface identification, and for predicting hydrology and water quality changes.
- **Task 3** Undertake spatial surveys of urban streams across the spectrum of effective imperviousness (i.e. catchments with various imperviousness and degrees of GI implementation).
- **Task 4** Undertake a case study to assess the change in ecological condition over time as a catchment develops from rural land use to urban, incorporating WSUD features/GI interventions.

By presenting an overview of the project and progress at this early stage, we seek feedback on the research design, access to available data, and potential collaboration opportunities.

KEYWORDS

Urban stream, water sensitive urban design, green infrastructure, effective imperviousness, stormwater treatment device

INTRODUCTION

Urbanisation (both during the development phase and after establishment) typically causes degradation of waterways, including habitat changes (e.g., channelisation, reinforced banks, reduced riparian vegetation), altered hydrology, increased contaminant concentrations leading to poor water quality, and reduced ecological diversity. This combination of effects results in what is often referred to as the "urban stream syndrome" (Walsh et al. 2005b). In urban areas across New Zealand, there is increasing demand (and legislative requirement, e.g., through the National Policy Statement for Freshwater Management 2020) to improve the condition of streams and reduce the impact of new and existing urban development. There are multiple knowledge gaps that currently constrain our ability to meet this demand.

At the highest level, councils, iwi partners and other decision-makers involved in urban water management require guidance in two key areas:

- How to improve the condition of streams in existing urban areas; and
- How to prevent the degradation of streams in areas undergoing urban development or further degradation of streams in areas undergoing urban intensification.

Methods to improve the condition of urban streams include mitigating the effects of stormwater runoff on water quality through the use of stormwater treatment devices, including green infrastructure (GI) devices such as raingardens (or bioretention devices), swales, structural soil tree-pits and constructed wetlands that use plants and soil/growth media or detention structures to reduce contaminant concentrations and more closely mimic the hydrology of natural catchments. To reduce contaminant inputs, the use of certain building materials has either been regulated (e.g., copper roofs in Christchurch), recommended (e.g., painting zinc roofs in Auckland), or been the subject of public awareness campaigns (e.g., copper in brake pads). Other restoration activities include stream restoration, including the removal of bank reinforcement, planting of riparian vegetation and, at the more extreme end, stream daylighting (returning buried streams from piped networks back to the surface). Water Sensitive Urban Design (WSUD) is a holistic approach to urban development that is an alternative to more conventional forms and encapsulates most of the measures above (Hoyer et al., 2011; Lloyd et al., 2002; Mouritz et al., 2006; Wong & Brown, 2009). WSUD aims to minimise soil disturbance, limit the creation of impervious surfaces, and maintain natural drainage systems, thus reducing the overall impact on stream ecology. By naturally treating water, WSUD is also aligned to Te Ao Māori (Afoa & Brockbank, 2019). A key component of WSUD includes the use of GI devices for stormwater treatment.

Barriers to the uptake of WSUD in New Zealand and worldwide include the cost (or perceived cost), particularly when retrofitting in urban areas, and uncertainty as to whether the desired outcome (i.e., protecting or improving stream ecological health, flow detention, flood mitigation) will be achieved (Brown & Clarke, 2007; Puddephatt & Heslop 2007; Lee & Yigitcanlar, 2011; Morison & Brown, 2011). In consultation with decision-makers involved in urban water management in New Zealand, we have identified three key science needs related to achieving the outcomes of WSUD:

1) Improving our understanding of the processes that influence the **performance of GI stormwater treatment devices**, and our ability to cost-effectively measure and reliably predict the performance of these devices.
2) Developing methods to **predict the effects of urban land use on stream water quality and ecosystems**, with and without mitigation by stormwater treatment devices – ideally in ways that can be used for catchment-accounting and/or limit-setting (i.e., beyond average annual load predictions).
3) Developing methods or tools to **understand the cumulative effects of multiple stressors** acting on urban stream ecosystems to enable informed decision-making.

PROJECT OVERVIEW

The Mangakootukutuku Urban Research Hub (MURB) project was designed to meet these needs by assessing changes over time in paired catchments as one underwent urban development and implementation of WSUD.

The Mangakootukutuku stream has two branches: the rural/urban Rukuhia and the Tiireke/Peacocke area. The 720 ha Tiireke sub-catchment is located on the southern fringe of Hamilton. This sub-catchment was primarily rural prior to development, with an estimated 84,000 dwellings to house up to 20,000 people scheduled to be built by 2040, as well as the Southern Links Transport Corridor, a major roading project. The initial stage 1 of the development (which used existing infrastructure) is complete. The larger Stage 2 began in 2023.

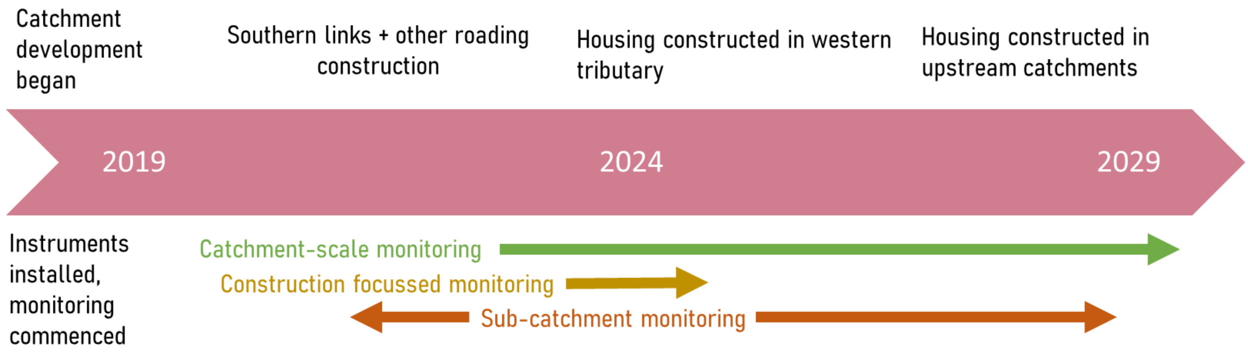

Figure 3: Timeline of Peacockes development and monitoring

Hamilton City Council's integrated catchment management plan for the Tiireke area includes applying best practice environmental protection and mitigation measures during the catchment development, including soakage/infiltration systems to maintain baseflows and reduce runoff volume, incorporating green infrastructure such as rain gardens and wetlands into stormwater treatment, and maintenance and enhancement of riparian vegetation.

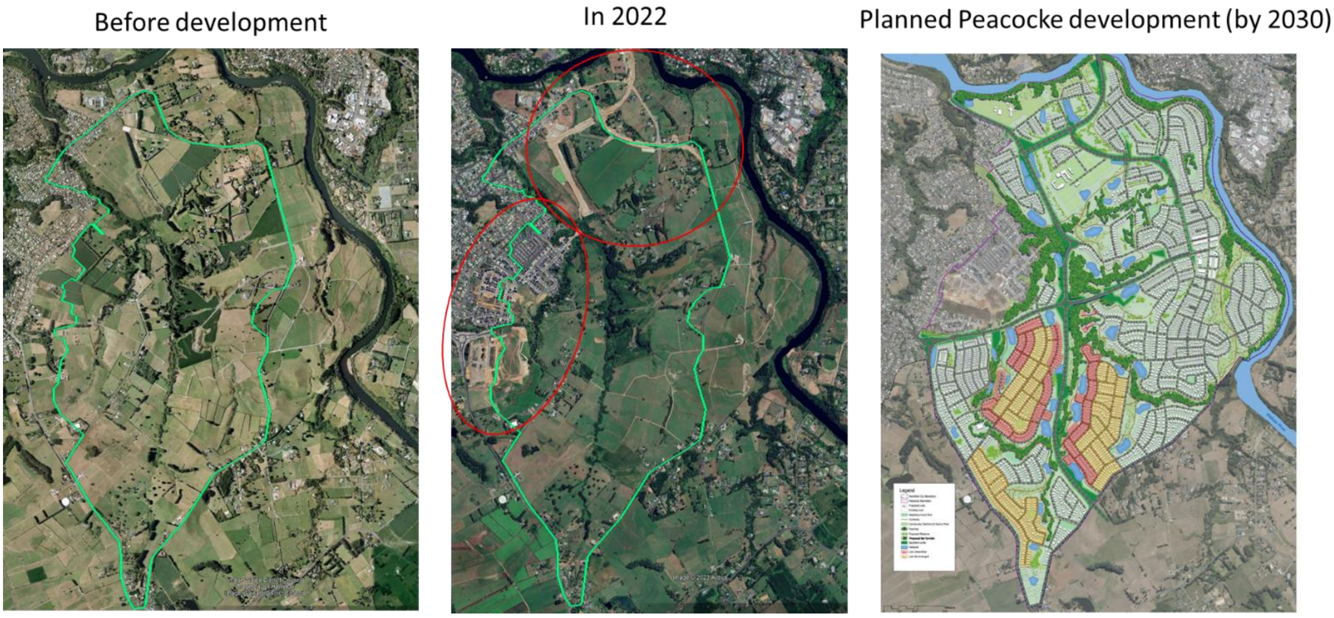

Figure 4: Current and proposed development in Tiireke catchment.

The initial research methodology was based on a Before-After-Control-Reference-Impact (BACRI) design to compare paired catchments representative of (1) "Business as Usual" (urban area with no WSUD), (2) rural and (3) WSUD catchments- before and after the development of the "WSUD" catchment. A network of five hydrometric monitoring stations were established around the Mangakootukutuku catchment: three in the "impact" Tiireke sub-catchment and two in the "control" Rukuhia sub-catchment. A third catchment, the Nukuhau, was identified as a reference site. However, later investigations indicated that this catchment would not be a suitable reference due to fish passage issues and planned development within the catchment.

Hydrology, high frequency water quality, storm event monitoring, and annual ecological surveys were conducted at each of the five sites from 2019-2023. However, after three years, several issues became clear that meant MURB was not going to be able to meet all of the desired objectives:

- About 60% of Rukuhia catchment is in rural land use and has different soils and hydrology to the Tiireke catchment. This means that the catchments are not suited to a paired catchment approach.
- The upstream Rukuhia catchment exports copper and zinc at concentrations higher than expected from rural land use. This makes it difficult to quantify the change in contaminant export directly attributable to the downstream urban land cover (i.e. looking for a small change in a large background signal).
- There are no WSUD devices currently present in the Tiireke catchment that we can monitor for contaminant removal.
- The timeframe for the development extends over 10-20 years, with the first areas to be developed located near the bottom of the catchment, making it difficult to discern the effects of development when "diluted" by the upstream areas that remain in rural land use.
- The monitoring costs are high and budgets are constrained.
- The paired catchment / BACI monitoring design is unlikely to provide sufficient or adequate information to understand and quantify the benefits and performance (or otherwise) of WSUD in the catchment. If the ecological state declines over time, we have no way of understanding whether this was due to insufficient deployment of WSUD or whether the WSUD devices used failed to perform as designed.

This has necessitated a revision of the project and a change in direction - from one that focusses all efforts within the MURB catchment, to an approach that includes monitoring at existing urbanised locations with and without stormwater mitigation (e.g., treatment devices, WSUD), and which will provide useful data, tools and knowledge throughout the duration of a project of much shorter duration. The findings will also be more transferable to other locations.

By presenting an overview of the new re-designed project, now titled "Wai āwhā – protecting and improving urban streams" (and referred to herein as Wai āwhā), at this early stage, we seek feedback on the research design, access to available data, and potential collaboration opportunities.

Wai āwhā brings together and builds on existing urban water quality research at NIWA, as well as incorporating new research, with the goal of developing an empirical model for predicting stream ecological response from the characteristics of urban development with and without mitigation by stormwater treatment devices.

The model will build on the approach of Walsh et al. (2022) for the Little Stringybark Creek catchment in Melbourne. In that study, the authors proposed a method for relating in-stream response variables with a weighted measure of effective imperviousness, where 'imperviousness' is the proportion of the catchment covered by surfaces which water cannot pass through, such as pavement and building roofs, 'effective imperviousness' is the drainage connection of impervious surfaces to the stormwater network, and the weights reflect the performance of stormwater treatment devices.

The Walsh et al. method relates in-stream response variables (such as water quality or ecological values) against weighted effective imperviousness for a single catchment over time, to assess the relative impact of degradation (due to stormwater runoff) and the restorative effect of stormwater treatment devices. Earlier work (Walsh et al. 2005a) related in-stream response variables against effective imperviousness without weighting for attenuation of flow in the treatment devices at a single snap-shot in time across multiple catchments. We propose a similar model, using ecosystem response variables relevant to New Zealand (e.g., macroinvertebrate metrics).

However, unlike the Walsh model, which was for a single catchment, our approach will be based on a space-for-time substitution – using catchment and stream data collected at multiple locations to span as wide a range of imperviousness and degree of mitigation for catchments in New Zealand as possible. Such a model may provide a relationship similar to Figure 1 (for illustrative purposes only).

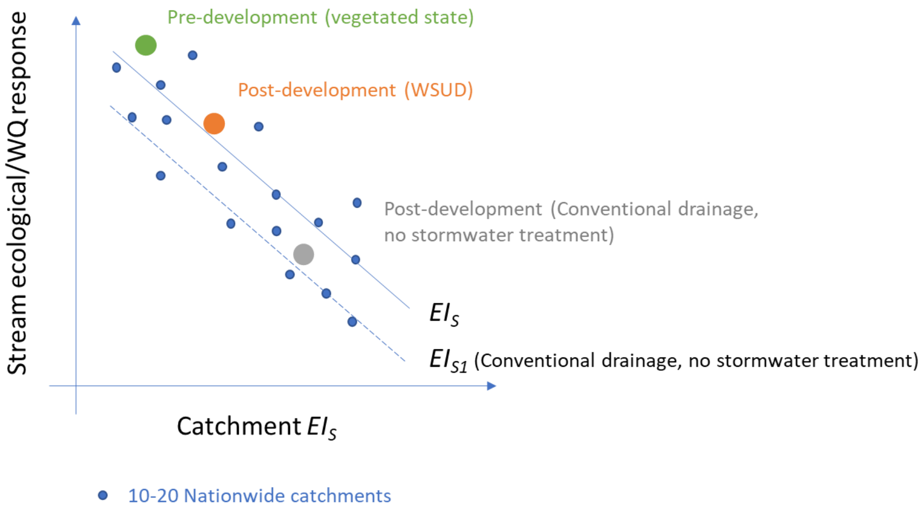

Figure 1: Illustrative representation of an empirical model linking stream ecological and/or water quality response variables with weighted effective imperviousness.

By using a space-for-time substitution, data can be collected immediately, from existing developments, without the need to wait for the Peacocke development to progress. This will enable more rapid development of understanding of WSUD and more rapid development of outputs that can be used by stakeholders. For example, this type of model could be used to predict stream ecological and/or water quality response variables under different development scenarios (e.g., the green, orange and grey markers in Figure 1), or to assess what levels of mitigation, or what combination of mitigation devices, may be required to achieve a desired outcome.

WEIGHTED EFFECTIVE IMPERVIOUSNESS

The full details of the weighted effective imperviousness measure are described in Walsh et al. (2022); here we include a summary for clarity.

For a catchment with N stormwater treatment devices, the weighted measure of effective imperviousness, EI_S, is calculated as

$$EI_S = \frac{1}{A}\left(I_0 + \sum_{n=1}^{N} I_n S_n\right) \qquad (1)$$

where A is the total catchment area (m^2), I_0 is the impervious area not draining to a stormwater treatment device (m^2), I_n is the impervious area draining to stormwater treatment device n (m^2), and S_n is the stream stormwater impact metric for treatment device n (dimensionless).

At device-level, the stream stormwater impact metric is a fraction ranging from 0 (perfectly mimicking a natural catchment) to 1 (representing conventional stormwater drainage with no treatment). Thus, an "ideal" catchment (where all impervious surfaces are treated, and the performance of treatment devices perfectly mimics a natural catchment) would have an EI_S value of zero in Equation (1), whereas a conventionally drained catchment with no stormwater treatment would have an EI_S value equal to the un-weighted value.

The stream stormwater impact metric is calculated as the mean of four sub-metrics, i.e.,

$$S = \mathrm{mean}(S_R, S_F, S_W, S_V) \qquad (2)$$

where S_R is the runoff frequency sub-metric, S_F is the filtered flow volume sub-metric, S_W is the water quality sub-metric, and S_V is the volume reduction sub-metric. These sub-metrics measure aspects of hydrology and water quality that can be addressed through device design, and that have been posited as the primary drivers of stream degradation by urban stormwater runoff.

We may wish to use these same sub-metrics, adopt new sub-metrics, or adjust aspects of them to suit the New Zealand context. For example, the water quality sub-metric uses median concentrations of sediment and nutrients but does not include metals, which would be of interest in New Zealand.

WORK PROGRAMME

We have organised the research required to progress towards our overall goal into five major tasks, most of which also have stand-alone outputs (data, advanced understanding, models, tools) that will contribute towards meeting the key science needs outlined earlier:

- **Task A**. Assess the performance of selected GI treatment devices (raingardens, structural soil tree-pits, wetlands) via field-based monitoring, and build process-based models to reflect the operation of these devices.
- **Task B**. Develop and/or implement catchment-scale models for impervious surface identification, and for calculating hydrology and water quality metrics required for weighted effective imperviousness.
- **Task C**. Undertake a spatial survey of a subset of urban streams in New Zealand across the spectrum of weighted effective imperviousness (i.e., catchments with various levels of imperviousness and degrees of stormwater treatment) using existing monitoring data supplemented by field sampling and GIS-derived catchment data.

- **Task D**. Develop the space-for-time statistical model relating the characteristics of urban development (impervious surfaces, stormwater treatment) with stream ecosystem response.
- **Task E**. Continue monitoring the Mangakootukutuku catchment in Hamilton as a long-term case study to assess changes in stream water quality and ecosystem response over time as a catchment develops from rural land use to urban, incorporating WSUD features and GI stormwater treatment devices. Data from this catchment will also be used for model validation, which will require monitoring over a much longer period.

These tasks involve a mix of monitoring and modelling which will be undertaken over the five-year lifespan of the project. Figure 2 shows a graphical representation of the work programme and illustrates how the different tasks interact. Further details for the tasks are discussed individually below.

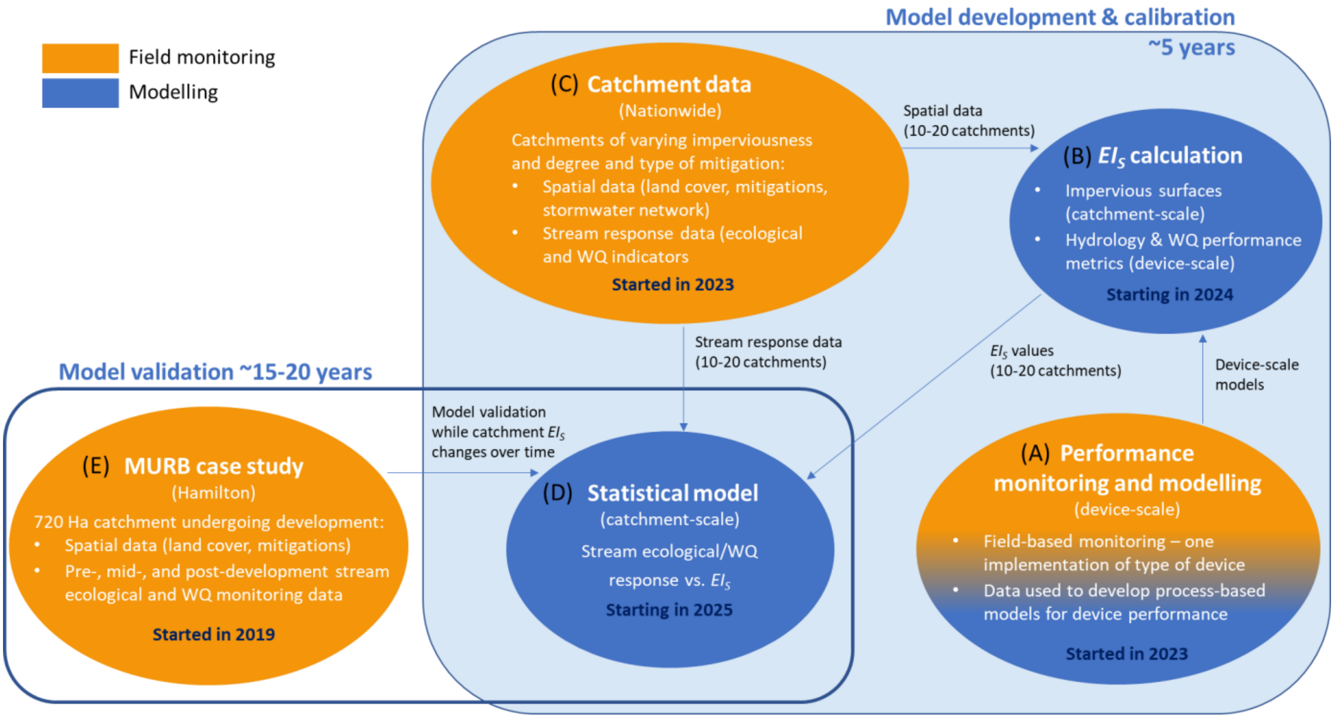

Figure 2: Wai āwhā work programme and timeframes. Task numbers are indicated in parentheses.

TASK A – PERFORMANCE OF GI STORMWATER TREATMENT DEVICES

This task involves both monitoring and process-based modelling of three selected GI stormwater treatment devices, which will be carried out progressively over the five-year project lifespan. The goal is to develop an improved understanding of the processes that influence the performance of these devices, and to predict of device performance in response to changes in design and influent conditions. The process-based models will also feed into the development of the statistical model (Task D), by providing methods for calculating the hydrological and water quality metrics required for assessing weighted effective imperviousness (Task B). The process-based models will be more accurate and more transposable to other systems with differing designs than the reduction factors typically applied to represent device performance (e.g. Walsh et al. 2022).

The selected GI stormwater treatment devices are raingardens, structural soil tree-pits and wetlands, as these devices are commonly used (raingardens, wetlands) or of increasing interest (structural soil tree-pits) in WSUD developments. We have been identifying suitable devices, resulting in a plan to begin by monitoring a structural soil tree-pit in Auckland, which receives road runoff.

Instrumentation of the structural soil tree-pit is currently underway, with sampling to start as soon as possible after instrumentation. We aim to sample approximately 12 storm events for each device, including inlet and outlet flows and concentrations of contaminants (sediment, metals, nutrients), tree evapotranspiration, and soil moisture levels.

As a first step in developing process-based models, we have been reviewing literature to establish the processes acting for each device, as well as reviewing existing modelling approaches and platforms.

TASK B – CATCHMENT-SCALE MODELS

This task involves developing and/or implementing existing models to identify and quantify impervious surfaces, as well as land cover changes over time, from GIS or satellite imagery, and for calculating hydrology and water quality metrics required for weighted effective imperviousness. This will include calculating EI_S values for the catchments identified in the spatial survey (Task C), which will then be used to develop the statistical models of EI_S vs stream response (Task D).

As a first step, we have been identifying the hydrology and water quality metrics and modelling methods used by Walsh et al. (2022), assessing their relevance to New Zealand conditions, and scoping modelling requirements. For example, the water quality sub-metric is calculated based on concentration reduction factors derived from Australian monitoring data and does not include metals. Concentration reduction factors are also a rough assessment of performance, whereas the process-based models for device performance developed under Task A will provide alternative methods for this sub-metric and enable more accurate prediction of performances depending on the device design.

TASK C – SPATIAL SURVEY

This task involves a desktop survey of urban streams across a gradient of imperviousness and stormwater mitigations nationwide. The collected data will be used to build a statistical space-for-time model of EI_S vs stream response (Task D). The space-for-time approach will allow us to develop the model much faster than a traditional before-after study like MURB or Walsh et al. 2022. It will also be more generalizable to other locations.

The study will leverage existing monitoring across NZ by local and regional councils. The first step currently underway is a review of existing sites where hydrological, water quality (including heavy metals), and ecological responses (i.e., stream macroinvertebrates) are monitored. In the next phase we will use available GIS layers and satellite imagery to identify green infrastructure within the upstream catchment for each site. A subset of survey sites will be selected to represent a range of mitigation actions, from minimal to full WSUD (if possible), as well as sites representing three dominant urban land uses (residential vs industrial vs commercial).

TASK D – STATISTICAL MODEL

The information and outputs from Tasks A, B and C will be integrated to develop a statistical model relating catchment-scale drivers (such as land use type/impervious surfaces/mitigation methods) with water quality/ecological responses. The first iteration will be a proof-of-concept model developed using the same methods as Walsh et al. (2022) to calculate the EI_S metrics, or if necessary (e.g., for GI types where Walsh did not provide models), using similar assumptions to develop those metrics. These EI_S metrics will be related to our field collected stream response data via a hierarchical linear model. The model will indicate where water quality improvements are better (or worse) than expected based on the changes in weighted effective imperviousness.

TASK E – MANGAKOOTUKUTUKU CASE STUDY

The Mangakootuktuku case study will assess the change over time as the Tiireke sub-catchment in Kirikiriroa/Hamilton develops from rural land use to urban, incorporating WSUD features/GI interventions. We have undertaken considerable work in this catchment since 2019.

We have been monitoring two sites in the catchment, one upstream of most planned development for the next 5-10 years, and one mid-catchment, since late 2019. Continuous measurements of flow, temperature, turbidity, dissolved oxygen, conductivity, and pH have been recorded at both sites since 2019. In addition, monthly spot samples of nitrogen, phosphorus, sediment, E. coli, visual clarity, and metals (zinc and copper) have been collected since late 2020. Storm event samples have been collected using ISCO autosamplers since 2021. Annual ecological surveys of macroinvertebrates and fish have been conducted each summer (November-January) since summer 2021-2022.

Annual monitoring throughout the development process will help us determine whether the observed recent declines in macroinvertebrate metric scores and fish abundance are natural variation or linked to the increasing development within the catchment. The observed fluctuations in both macroinvertebrate metric scores and fish densities to date remain within the range of historical variation seen in other Tiireke catchment sites.

SUMMARY

Through this project, we aim to improve our understanding of the effects of multiple stressors in urban streams and the relative influence of catchment-scale versus reach-scale stressors, as well how WSUD can be best applied to mitigate these stressors.

We hope that presenting an overview of the project and progress so far will open opportunities to build collaborations with others working on stormwater and urban design. In particular, we are currently seeking information on potential catchments where WSUD has been implemented for inclusion in the spatial survey. If you know of any potentially suitable sites, please feel free to come talk to us during the conference or get in touch via phone or email.

ACKNOWLEDGEMENTS

We thank MBIE Strategic Science Investment Fund and Hamilton City Council for co-funding this work.

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