Engineers & Consultants

Taking the pain out of the treatment train: continuous simulation modelling for integrated water management

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Abstract

The implementation of stormwater management strategies has become commonplace across New Zealand. As the objectives and drivers of these strategies become increasingly complex and multi-faceted, a clear understanding of the changes in hydrology and water quality resulting from urban development is recognised as being critical to support decision making and align with regulations.

The planning of stormwater management assets in New Zealand has historically relied on conceptualising elements largely in isolation from other assets. The design and sizing of devices such as wetlands and bioretention systems, and the treatment performance inferred from these, has typically depended on calculating target water quality volumes and attenuation requirements. In reality, however, the temporal variability of rainfall and runoff are fundamental to the operation of these stormwater management devices, and the inter-relationships of multiple devices in series needs to be reflected to accurately quantify the performance of management strategies at a sub-catchment or precinct scale.

Continuous simulation modelling provides a means of evaluating the effectiveness of stormwater management strategies by simulating the relationships between rainfall, runoff and stormwater devices in urbanised catchments. This reflects the highly variable characteristics of stormwater during rainfall events which in turn affects the hydraulic function of systems and the corresponding water treatment performance. The Model for Urban Stormwater Improvement Conceptualisation (MUSIC) is one such tool developed to support the design of complex stormwater management strategies at a range of scales. MUSIC has become the industry standard across Australia and has more recently been used in other parts of the world. In New Zealand, MUSIC is being used on an increasing number of projects in both greenfield and retrofit situations.

Morphum Environmental Limited (Morphum) have used MUSIC as an effective means of assessing the hydrological and water quality impacts downstream of urban developments, and for evaluating the benefits of fully integrated solutions. These include stormwater treatment devices combined with rainwater and stormwater harvesting and reuse, to emulate pre-development hydrology. The model allows for iterative refinement of designs and clear communication of benefits resulting from comprehensive stormwater management strategies to improve the protection of receiving environments from urbanisation.

Keywords

Continuous simulation modelling, MUSIC, treatment train, rainwater harvesting, hydraulic neutrality

Presenter profile

Stu Farrant is an ecological engineer who specialises in the water aspects of ecologically sustainable development, particularly integrated water cycle management and water-sensitive urban design. Stu has designed and delivered many innovative projects across Australia and New Zealand including constructed urban wetlands to provide stormwater treatment and ecological enhancement of urban spaces.

Reuben Ferguson is a water resources scientist with a background in hydraulic modelling and flood risk assessment. He currently focusses on applications of water sensitive urban design for managing the stormwater quantity and quality impacts of urbanisation, drawing on a combined background in ecology and water engineering, and an interest in protecting and restoring waterways and using water more efficiently.

1.0 Introduction

The design of stormwater treatment devices in New Zealand has historically focused on the concept of an event-based design water quality volume (WQV) for the sizing of treatment elements. For the Auckland region, for example, the WQV – corresponding to the 24-hour runoff from the 95th percentile storm (with only 5% of storms having a greater depth) – is determined to be the quantity of water required to be captured by a treatment device such as a wetland or raingarden to remove 75% of total suspended solids. While this method can be effective for the design of isolated treatment elements, it has difficulty accurately describing the fate of contaminants in devices that are connected in a sequential treatment train. Further, it has difficulty accounting for flow (and associated contaminants) in more integrated solutions which might include 'losses' through reuse or infiltration, or the diversion of flows from large catchments based on available land for treatment rather than best practice sizing.

Similarly, the event-based approach does not necessarily account for the nuanced changes in frequent flow hydrology that can be detrimental to aquatic life through reduced baseflow, increased flashiness and changes to the frequency and duration of high velocity flows. Managing the water quantity impacts of urbanisation has generally focussed on reducing flood risk through the attenuation of large infrequent storm events. While the usual interpretation of 'hydraulic neutrality' – generally taken to mean the restriction of post-development peak flows to those of the pre-development condition – may satisfy a flood mitigation objective, it does not emulate other parts of the hydrograph which are important from an ecological perspective, and does little to mitigate the water quality effects of urbanisation. A non-dynamic modelling approach makes it difficult to verify or otherwise the attainment of volume reduction targets, such as retention of the 90th percentile 24-hour rainfall and detention of the 95th percentile 24-hour rainfall, in order to establish whether or not a treatment train represents an optimal balance of environmental and economic objectives for a particular catchment or site.

Recognising the limitations of the event-based approach, and the narrowness of the 'hydraulic neutrality' principle, continuous simulation modelling is increasingly being applied internationally as a means of evaluating the performance of interconnected stormwater treatment and flow attenuation devices. One such model – the Model for Urban Stormwater Improvement Conceptualisation (MUSIC) – uses long-term gauged rainfall data to model existing and future catchment characteristics and the effects of stormwater management actions, in terms of flow behaviour and water quality, to demonstrate outcomes for receiving environments during frequent rainfall events. MUSIC enables rapid testing of multiple and complex management scenarios, including the harvesting and reuse of rainwater and stormwater, and the balance of treated and untreated discharges.

This paper outlines some contemporary objectives of stormwater management and illustrates the role that continuous simulation modelling can play in optimising integrated stormwater treatment and attenuation devices to achieve these objectives. It uses the example of a typical greenfield development discharging to an open stream to demonstrate the way in which MUSIC can be used to evaluate various stormwater management scenarios such that an approximation of pre-development hydrology and water quality can be achieved.

2.0 Stormwater management objectives

Contemporary stormwater management must respond not only to the flooding implications of modified hydrology associated with urban developments, but also to the impacts that changes in water quality and quantity have on receiving environments. A number of water quality and quantity issues are known to adversely impact the health of freshwater ecosystems as result of urban development. These include:

- Discharge of contaminants including suspended solids, heavy metals, nutrients and hydrocarbons from vehicles, building materials and residential gardens.
- Changes in the frequent flow hydrology including reduced baseflow, increased flow rates in minor rainfall events and increased overall volume of runoff. These can increase stress on biota and worsen scour and erosion downstream.
- Increased temperature of stormwater flows from impervious surfaces such as roofs, roads and paved areas following summer rainfall.

Natural systems are typically resilient to peak flow rates from low frequency, large rainfall events and are more susceptible to impacts from an increased frequency of small 'flashy events'. From an ecological perspective, true hydraulic neutrality therefore requires solutions which provide a direct reduction in the volume of runoff being discharged to waterways. This can be achieved by harvesting and reusing rainwater or stormwater, which has the additional benefit of reducing demand on potable water supplies, or through utilising infiltration and evapotranspiration to better mimic the pre-developed catchment processes.

3.0 Continuous simulation modelling

Continuous simulation modelling was developed to assess the performance of proposed stormwater treatment and attenuation systems at a conceptual level. It uses historical rainfall time series over a long period, rather than the statistically-derived design storms that underpin most hydraulic modelling undertaken in New Zealand for flood attenuation design. Through the application of concentration-based contaminant profiles (derived from the sampling of rainfall events to quantify concentration means and standard deviations), continuous simulation enables the relationship between hydrology and water quality to be reflected in a stochastic manner. While the traditional event-based approach is well suited to quantifying changes in runoff from certain magnitude events and the treatment of contaminants based on simplistic systems, it does not permit assessment of systems under expected real rainfall conditions and dry spells.

Compared to single-event models, continuous simulation takes account of the variability in rainfall duration and intensity, evapotranspiration, varying inter-storm periods, and antecedent soil moisture conditions. This allows more integrated solutions, such as rainwater harvesting and reuse, targeted infiltration and detention systems to be evaluated alongside centralised treatment solutions. In addition to supporting the modelling of water quality improvements, this approach allows the impact and mitigation of changes in frequent flow hydrology (flow rates and volumes) to be assessed so that appropriate levels of protection can be provided for downstream receiving environments.

3.1 MUSIC

MUSIC is a conceptual design tool that is used to predict catchment runoff, pollutant export, and the treatment and attenuation performance of interconnected stormwater management systems. This enables assessments to be made against quantitative stormwater management objectives and ultimately helps to understand the effects that different land and water management practices have on frequent flow hydrology and pollutant fate, and therefore on aquatic ecosystems.

MUSIC uses a network of nodes to represent areas with similar characteristics, including land use type, position within catchment, and connections with downstream catchments. Nodes are assigned an impervious fraction, soil storage and infiltration parameters (representing seepage to deep and shallow groundwater), and event mean concentrations and standard deviations for total suspended solids (TSS), total phosphorus (TP) and total nitrogen (TN). These contaminants represent the range of particulate and dissolved pollutants which are commonly observed in urban stormwater.

The performance of treatment nodes is simulated for either a single device or for a group of stormwater management measures configured in series or parallel to form a treatment train. Treatment and attenuation elements, such as bioretention systems, constructed wetlands and rainwater tanks, are then connected using drainage links to represent piped or overland flow. Contaminant removal processes are represented by the k-C* first-order decay model. All nodes converge on a single receiving environment node which supports analysis and reporting on a range of hydrology and water quality metrics.

Modelling is conducted at a short time step, typically 6 minutes, to represent the highly variable nature of urban runoff and to enable the simulation of hydraulic structures which control flows into treatment devices. The short time step is important for describing rainfall-runoff characteristics and the performance of stormwater management interventions, particularly when devices are connected in series, so that cumulative 'pass down' contaminant reduction effects are accounted for. Simulations are typically performed over a long duration (e.g. 10 years) to reflect seasonal variability and to enable reporting of long-term averages.

Understanding the interactions between catchment characteristics, treatment devices and pollutant generation and removal enables a range of interventions to be optimised for reducing the frequency, rate and volume of stormwater runoff and associated contaminants. This information is used to support decisions relating to water quality and quantity management and to communicate the expected performance of increasingly complex systems to approvals authorities and clients.

4.0 Example application of MUSIC

Morphum has recently undertaken a number of projects utilising continuous simulation with MUSIC. This includes developing a site-wide stormwater management strategy for a large residential development in the Wellington Region (Figure 1). The site drains to waterways of high ecological value which are to be piped in their headwaters as part of a consented development. A perched wetland is present in one of the waterways; this was identified as an uncommon ecosystem type and was prioritised for protection. The intent of the strategy was therefore to emulate pre-development hydrology and provide a high level of water quality treatment in order to protect sensitive downstream receiving environments.

There are currently no explicit regulatory requirements in the region to manage stormwater discharges from developments. However, an existing consent condition for the site requires protection of the wetland within Tributary 1. Mitigation of flow or water quality impacts in Tributary 2 is motivated by environmental benefits rather than mandatory requirement, with potential to further improve these outcomes as the project progresses.

MUSIC was used to simulate the effects that different stormwater management scenarios had on the flow regime and contaminant loading in receiving environments, with a focus on the changes in hydrology from frequent flows rather than infrequent storm events. The modelling tested different scenarios including manipulation of catchment extents and inclusion of distributed stormwater source controls such as rainwater harvesting and bioretention devices, to produce a design that resembled as closely as possible the runoff frequencies and volumes of the existing condition.

4.1 Project objectives

In response to the site's ecological context, and the intent to mitigate ongoing impacts, the following stormwater management objectives were proposed for the site:

- Protect the perched wetland from changes in hydrology and water quality
- Mitigate impacts from changes in frequent flow hydrology on Tributary 2
- Reduce temperature impacts on downstream receiving environments
- Reduce pollutant loads from urban development

The objectives were addressed through an integrated approach based on the following general strategies:

- Implement rainwater harvesting and reuse, and modify catchment extents, to mimic as closely as practical the pre-development frequent flow hydrology entering the wetland and Tributary 2. This required matching the mean annual volume of discharge, the mean flow rate and the frequency of discharges (assessed through cumulative frequency analysis).
- Capture and treat stormwater runoff prior to discharge through dedicated bioretention systems to remove contaminants including sediments, metals, hydrocarbons and nutrients, reduce temperature impacts and retain a portion of water through inclusion of a saturated zone to provide a reservoir for vegetation during prolonged dry spells.

4.2 Methodology

Models were created for the pre-development condition and various iterations of the developed condition in order to develop the most effective and efficient stormwater management strategy. The proposed lot layout was largely locked in place prior to Morphum's involvement so stormwater designs were essentially modelled as retrofit interventions. Scenario testing focused on reducing runoff volumes through rainwater harvesting and reuse at the individual lot scale (including constant internal demands such as toilet flushing and seasonally variable irrigation demands), and manipulating the allocation of lot and road surface runoff to one of two bioretention devices prior to discharge to the receiving waterways.

While in this instance the primary objective was to mitigate hydrological impacts on the receiving environment, MUSIC was developed to also model the generation and removal of typical urban contaminants, these being total suspended solids (TSS), total nitrogen (TN) and total phosphorous (TP).

4.2.1 Pre-development model structure

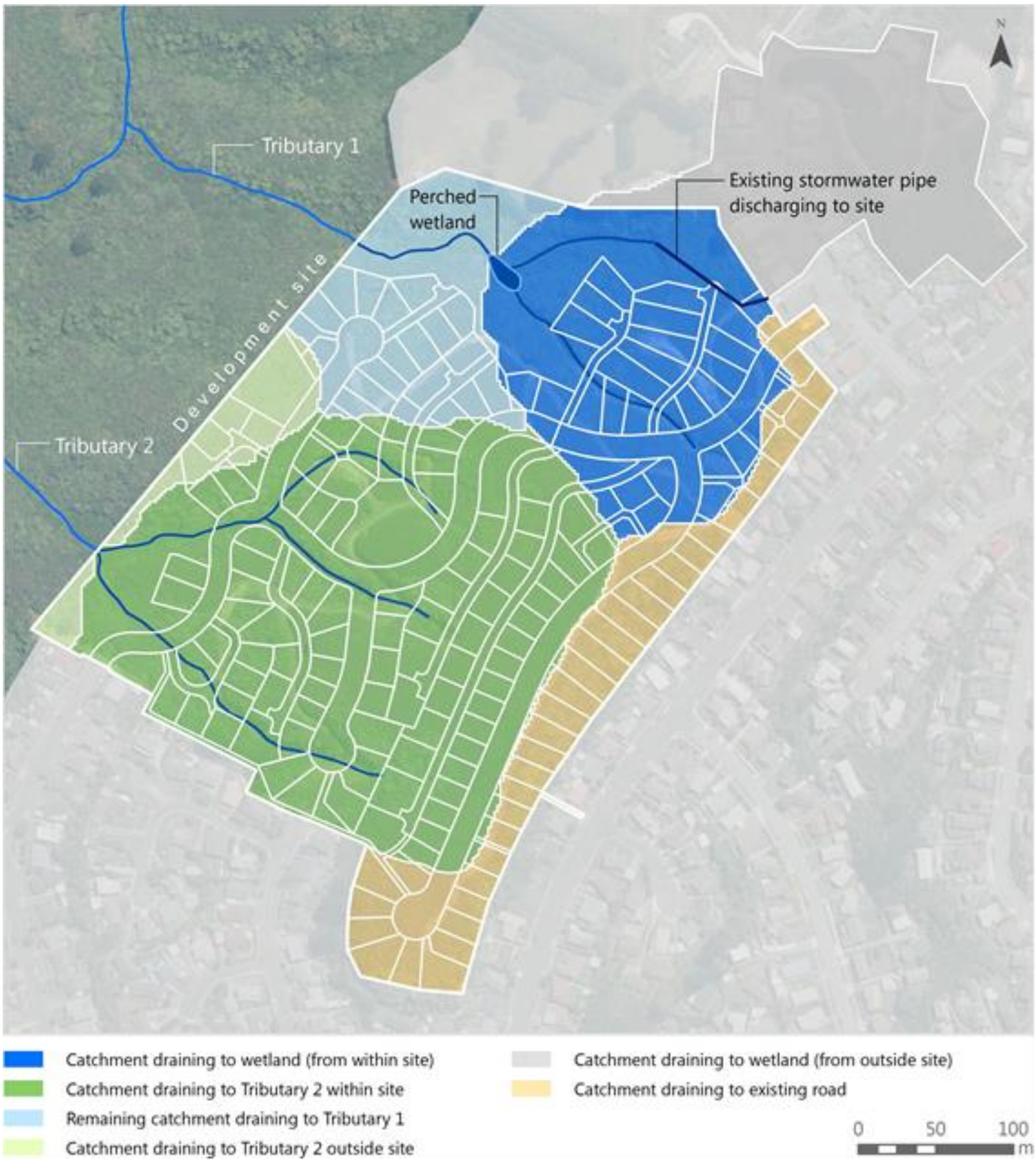

Figure 1: Pre-development catchments and drainage patterns

The pre-development scenario represents the existing catchment characteristics, including two receiving waterways and a perched wetland (Figure 1). The catchments were modelled as 100% pervious with regenerating scrub cover, with 3.1 ha draining to the wetland and 6.8 ha draining to Tributary 2. An additional 2.5 ha outside the development site currently drains into the wetland catchment. This includes roads and residential development and was estimated to be 35% total impervious based on aerial photographs. All pre-development flows are considered to be unmanaged.

Figure 1 shows the existing topographic catchments and drainage patterns in relation to the proposed development. Figure 2 shows the configuration of the pre-development scenario within MUSIC.

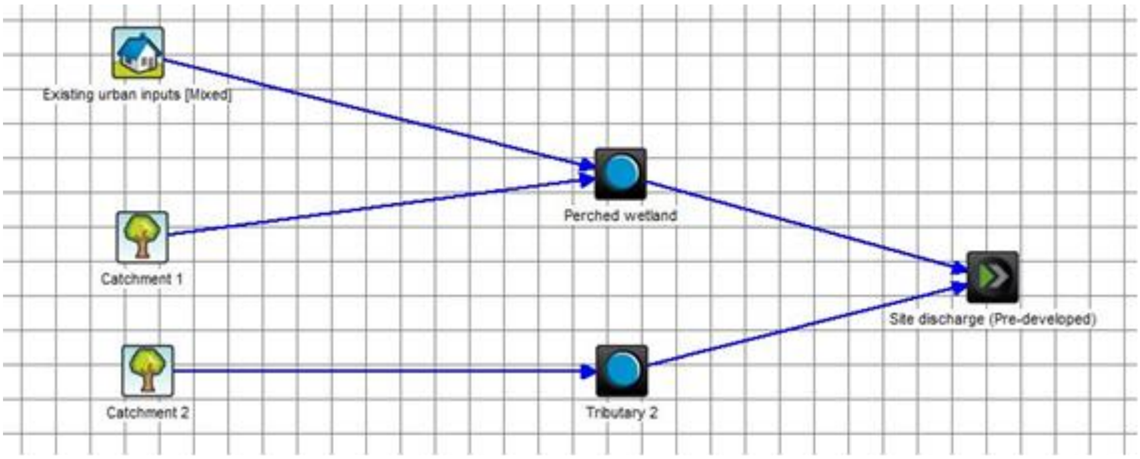

Figure 2: MUSIC structure for the pre-development condition

4.2.2 Post-development model structure

Post-development modelling was undertaken on an iterative basis to determine the optimum configuration to support the stated objectives. Scenarios allowed for changes to sub-catchment boundaries and realignment of stormwater pipes. The runoff response was assessed under multiple model runs so that the most efficient layout and integrated water management approach could be determined.

The configuration of lots, and their allocation to the respective treatment devices, is shown in Figure 3. Figure 4 shows the final post-development configuration in MUSIC. This is based on the following management interventions:

- Combined roof areas (100% imperviousness) connected to lumped rainwater tanks (single node representing multiple tanks) with daily and seasonal demands.
- Remaining lot areas are combined and modelled at 35% imperviousness.
- Combined road areas are calculated and included separately (90% imperviousness).
- Areas draining to centralised treatment (including overflow from rainwater tanks) discharge to bioretention systems (250 m^2 and 500 m^2 for sub-catchments 1 and 2, respectively).
- Areas which are unable to be conveyed to treatment are modelled separately to bypass the bioretention systems and discharge directly to receiving waters.
- All catchment nodes ultimately drain to defined points for reporting (such as the wetland area).
- Existing urban areas (outside development) which currently drain to the wetland catchment are included (and remain unchanged pre- and post-development).

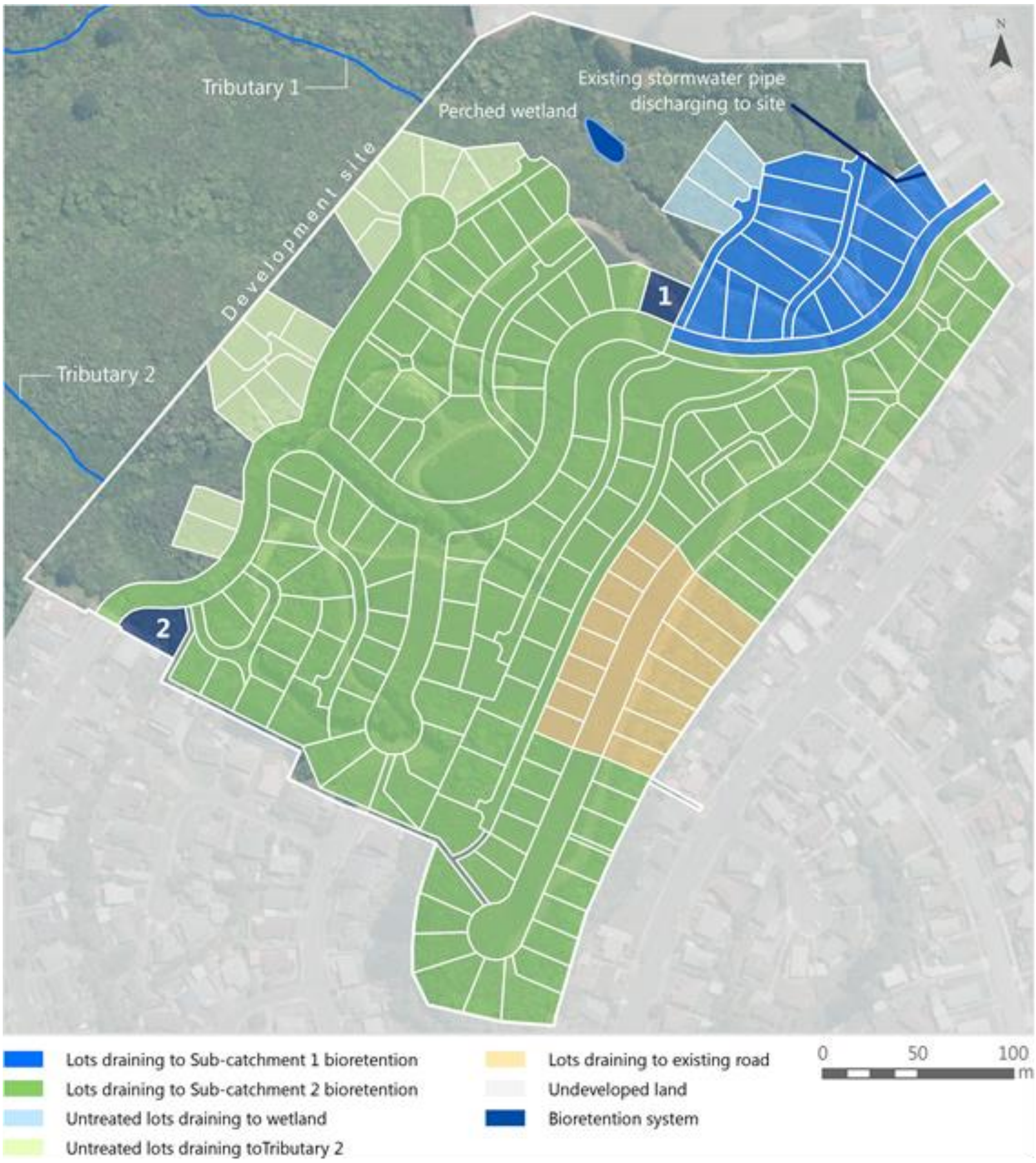

Figure 3: Post-development catchments and treatment locations

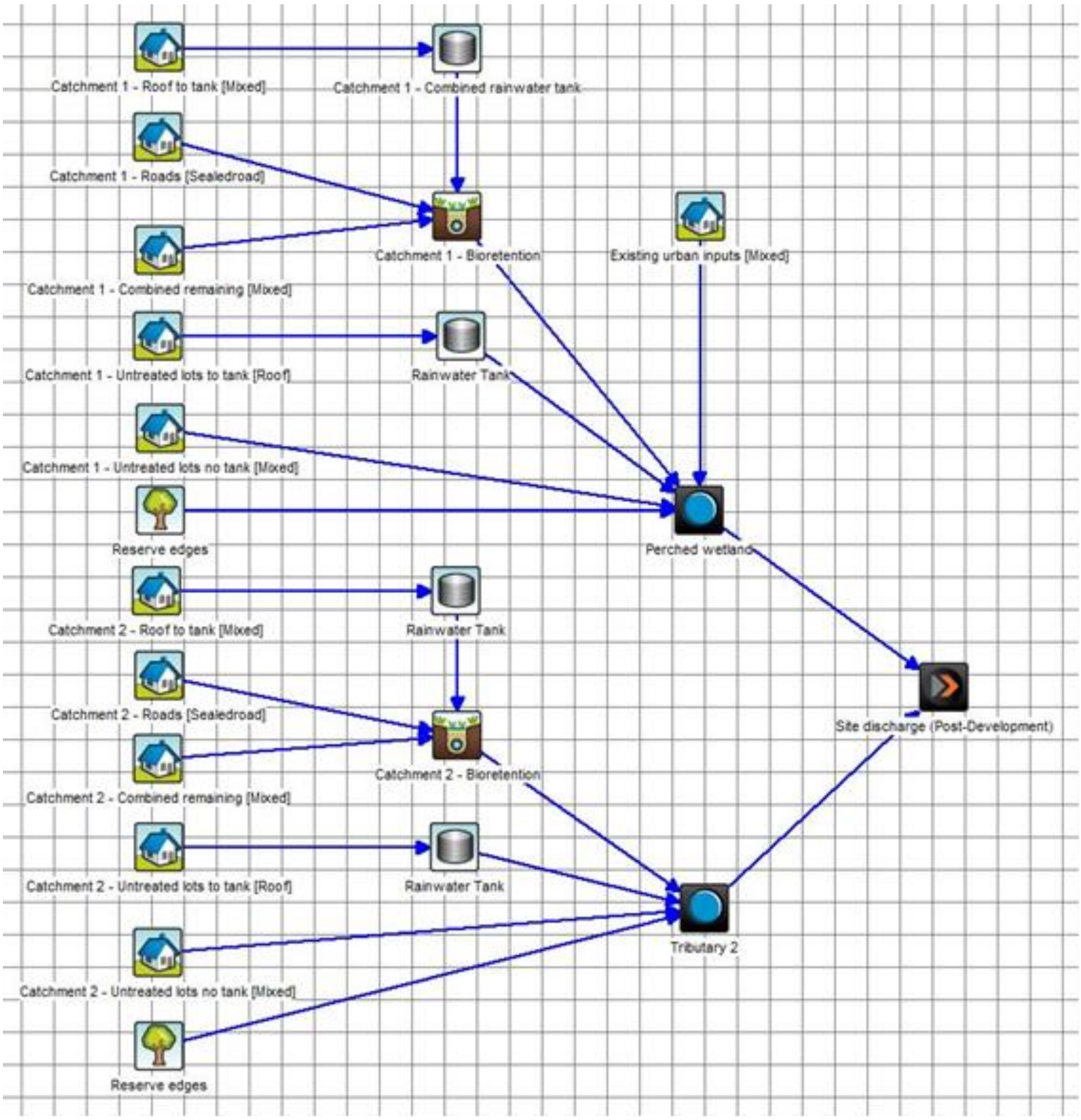

Figure 4: MUSIC structure for the post-development condition with integrated stormwater management

4.3 Results

Model results were assessed in terms of hydrological changes resulting from the proposed interventions. These can be expressed in a number of ways:

- The number of surface runoff days occurring per year
- The percentage of flows which exceed a predetermined baseflow threshold
- Cumulative frequency curves to identify the percentage of time for which a particular flow is exceeded. Curves can be examined to determine changes in the frequency of occurrence of a particular flow rate which corresponds to a predetermined flow rates to be evaluated for ecological reasons.
- Lumped water balance attributes such as mean annual flow (baseflow and stormwater), ET, and losses to shallow and deep groundwater.

4.3.1 Perched wetland catchment

Discharges to the existing wetland were to be managed to mimic the natural flow regime as closely as practical. This was achieved by restricting the post-development catchment extent, retaining flows within lots through rainwater capture and reuse, and detaining and treating flows in a bioretention system prior to discharge. The overall performance of the proposed interventions, compared to the existing state and an unmitigated developed state, is shown in Table 1.

This demonstrates the combined benefit of the proposed integrated water management, with post-development flows closely matching the pre-developed flows and delivering a 45% reduction in annual inflow compared to the unmitigated case. Importantly, the mean flow rate also closely matches the pre-developed case.

Table 1: Summary of flows into the wetland area

	Unit	Pre-developed catchment (existing)	Post-developed catchment (unmitigated)	Post-developed catchment (mitigated)
Mean annual inflow	m^3	24,400	41,500	22,600
Mean flow rate to wetland	L/s	0.77	1.31	0.72

The change in flow across a range of event frequencies and magnitudes within the 5-year time series is shown in Figure 5. Inflows to the wetland under the unmitigated case (green line) diverge from the existing regime at or about 60%, indicating that flow rates would exceed those of the existing case for approximately 40% of the time.

With the proposed mitigation in place (red line), flow rates are consistent for approximately 92% of time with comparatively less divergence from the existing conditions (blue line). This relationship, based on the continuous simulation methodology, highlights the performance of the integrated approach to stormwater management based on the analysis across a range of rainfall intensities and durations throughout the time series. This is considered to better reflect the rainfall-runoff relationship rather than the design storm approach which is less suited to the complexities of stormwater management devices in series, and solutions which include harvesting of rainwater or stormwater.

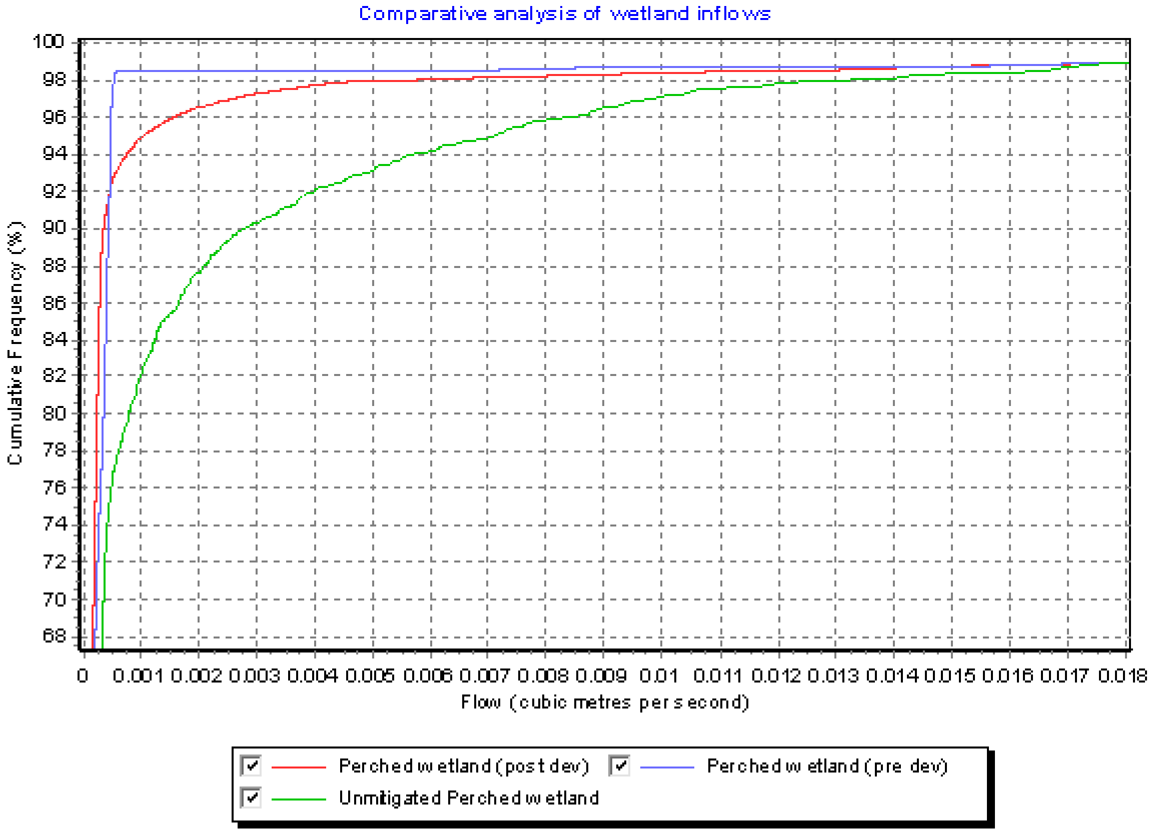

Figure 5: Cumulative frequency plot of discharge to perched wetland

4.3.2 Tributary 2 catchment

Discharges to Tributary 2 were to be managed to reduce the overall volume and to mitigate the 'flashiness' of post-development flows as much as practical. The retention of flows within lots, through rainwater reuse and detaining and treating flows in a bioretention system prior to discharge, were modelled.

Table 2 provides a comparison of flow behaviour between the existing situation, development with the proposed stormwater management approach, and unmitigated development.

Table 2: Summary of flows into Tributary 2

	Unit	Pre-developed catchment (existing)	Post-developed catchment (unmitigated)	Post-developed catchment (mitigated)
Mean annual inflow	m^3	54,200	94,000	84,300
Mean flow rate to wetland	L/s	1.72	2.98	2.67

The integrated water management approach provided a 10% reduction in annual inflow compared to the unmitigated case. The increase in mean annual volume (relative to the existing condition) stems largely from the increased catchment area which was imposed to satisfy the objective to prioritise a very high level of protection for the existing wetland.

The cumulative frequency plot in Figure 6 shows that the inflows to the tributary under the unmitigated case (green line) diverge from the existing regime at or about 70%, indicating that flow rates would exceed the existing case approximately 30% of the time. With the proposed mitigation in place (blue line), flow rates are comparable to those of the existing condition (red line) for approximately 90% of events.

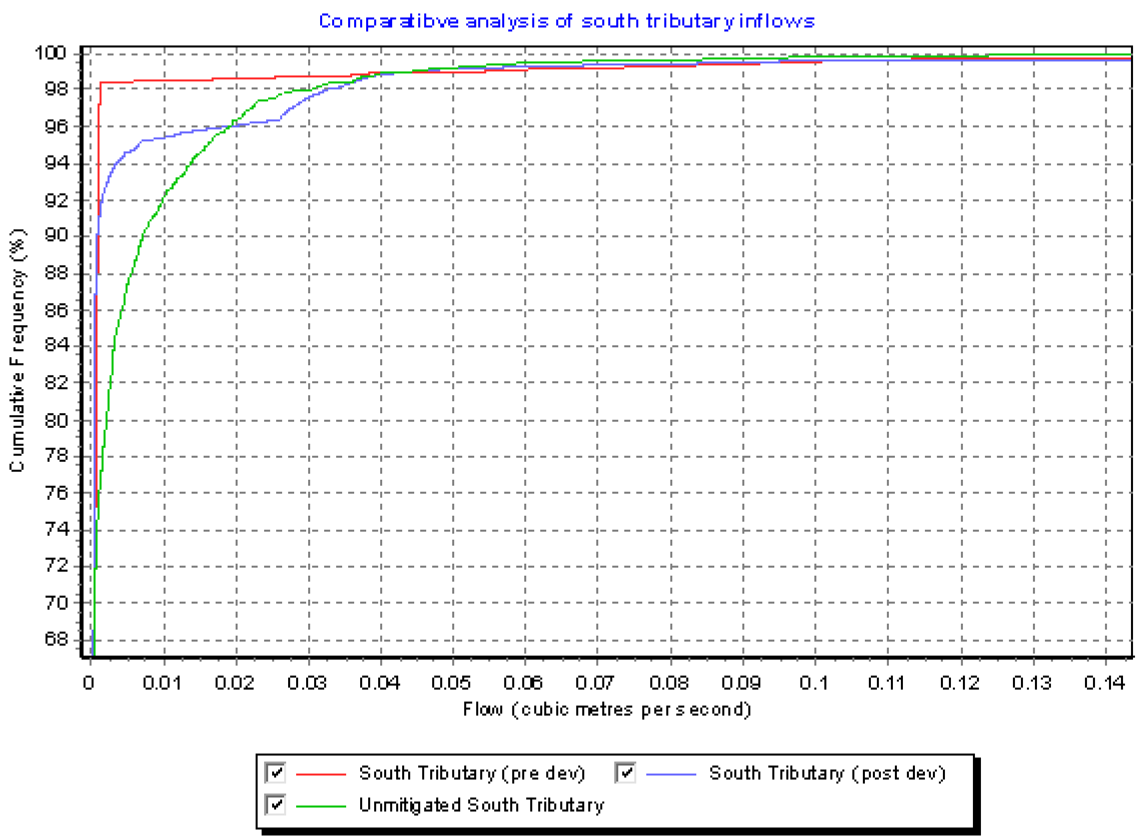

Figure 6: Cumulative frequency plot of discharge to Tributary 2

4.3.3 Water quality performance

MUSIC is also used to estimate the water quality performance of management options. These include load reductions through dedicated treatment elements (in this case bioretention) as well as reductions which result from capturing and reusing rainwater or infiltration and evapotranspiration losses.

The overall water management performance of the proposed development was quantified at a theoretical outlet which represents the combined pollutant generation and treatment for the entire site. Table 3 summarises this performance and demonstrates the benefit of the integrated approach adopted. While there are currently no explicit load reduction targets for the Wellington region, the results compare favourably with targets adopted elsewhere. In particular, Auckland typically requires a 75% reduction in TSS, and Australian states require reductions of 85%, 45% and 45% for TSS, TN and TP, respectively.

Based on this, it is concluded that in addition to the hydrological benefits (assessed at the respective tributary discharge points) the site-wide water management strategy also delivers best practice water quality outcomes.

Table 3: Overall stormwater management performance for the site

	Unit	Total generated	Total discharged	% Reduction
Mean annual flow	m^3	108,000	97,100	10
Total suspended solids	kg/y	22,700	4,290	81
Total nitrogen	kg/y	266	118	56
Total phosphorous	kg/y	43	23	47

5.0 Limitations of continuous simulation modelling

It is recognised that the continuous simulation approach has a number of limitations for application in New Zealand which stem mainly from the data requirements and calibration necessary to accurately describe the system being modelled. The primary data requirement is a rainfall time series covering an extended period (e.g. 10 years) which is at sufficiently high temporal resolution (e.g. 5 minutes) to enable flow through hydraulic structures to be represented. While this information is not universally available within New Zealand, it is typically available for many urban centres at 5-minute or other sub-hourly time steps.

The computation of contaminant loads and treatment performance within MUSIC requires locally-validated concentrations of the contaminants of interest. These data are entered as event-based mean concentrations and standard deviations to enable stochastic generation of catchment loads. There is currently limited event-based data of this nature for New Zealand.

Accurate estimation of flows, and consequent prediction of contaminant concentrations and device treatment performance, depends on having an appropriately calibrated model. This requires a flow series to be obtained for the study catchment so that representative rainfall-runoff parameters can be derived. This does not have to be done for every model that is produced, however. Rather, the establishment of agreed regional default values based on a national approach to calibration, as has been done for Australia, would give confidence in the use of rainfall-runoff parameters on a regional basis.

MUSIC does not explicitly model metals. It expressly models only flow, TSS, TP and TN on the basis of research in Australia and elsewhere which has demonstrated that treatment measures targeted at these contaminants (in both dissolved and particulate form) also result in the treatment of metals. There is also currently a lack of integration between MUSIC and other software packages that may be used to calculate model parameters, such as Excel and GIS. This necessitates the manual transcription of values from these other packages into MUSIC, and the re-entry of these values as inevitable changes are made, imposing a time cost and creating opportunities for entry errors.

6.0 Conclusions

As the varied and sometimes nuanced impacts of urbanisation on water environments become better understood, the effectiveness of traditional methods for managing these comes under more scrutiny. The event-based approach underpinning the notion of water quality volumes and peak flow management cannot adequately describe these impacts in ecological terms, or accurately quantify the treatment and attenuation performance of complex, interconnected stormwater management systems.

Continuous simulation tools are able to provide a clearer understanding of treatment train performance against management objectives by defining the movement of water and contaminants through treatment devices at a high temporal resolution, and accounting for the antecedent effects which influence performance in the long term.

The continuous simulation model MUSIC supports the growing tendency internationally towards a more integrated approach to water management. By incorporating rainwater capture and reuse and vegetated treatment elements, MUSIC supports the development of conceptual stormwater management designs which provide multiple environmental and flow attenuation benefits, while improving the resilience of urban landscapes in the face of a changing climate.