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Te Awarua-o-Porirua Collaborative Modelling Project – Urban Hydrology Modelling

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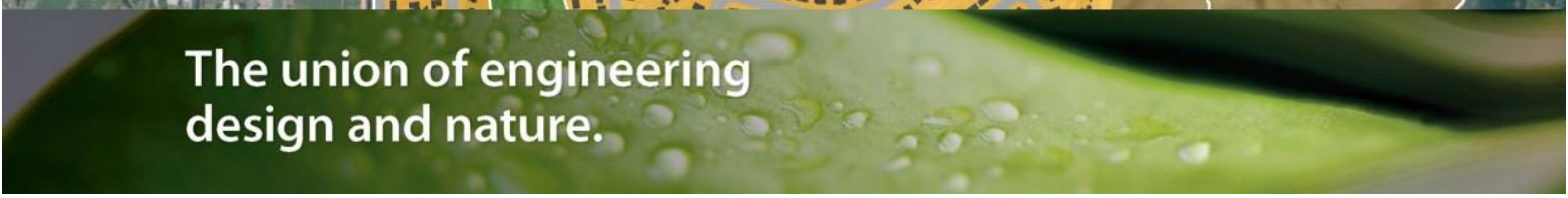

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Executive Summary

Morphum Environmental Ltd (Morphum) was engaged by Greater Wellington Regional Council (GWRC) to investigate the effect that various development and stormwater management scenarios may have on the frequent flow regime within two catchments draining to Te Awarua-o-Porirua Harbour. This work formed part of a wider collaborative modelling project undertaken as part of GWRC's Te Awarua-o-Porirua Whaitua process. The objective of the modelling was to generate information to support the Whaitua Committee in making informed decisions about land and water management practices within the Porirua Harbour catchment that will help reduce the impacts of urbanisation on receiving waterways.

The continuous simulation modelling package MUSIC was used to simulate the runoff response under scenarios of existing development, 'business-as-usual' (BAU) development, 'improved' development, and 'water-sensitive' development. Modelling was conducted separately for two catchments, representing infill (urban intensification) and greenfield development typologies, to reflect the range of possible development types.

Integrated water management strategies, including rainwater and stormwater harvesting and reuse, bioretention, permeable paving and wetlands, were simulated to investigate their effect on catchment runoff characteristics. Aspects of the flow regime that were investigated included mean annual runoff volume, frequency of exceedance of 'channel-forming' flows, and cumulative frequency distributions.

The water-sensitive scenario maintained a runoff volume and target flow rate exceedance frequency close to that of the pre-development condition. Within the urban component of the study catchments, water-sensitive land use practices and device implementation reduced the mean annual runoff volume by 41.3% for the infill catchment, and 52.6% for the greenfield catchment, when compared to the respective BAU scenarios. Rainwater tanks alone reduced runoff volumes by 22.3% and 25.2% for the infill and greenfield catchments, respectively, when harvested water was reused for non-potable purposes within dwellings.

The improved scenario reduced the frequency with which target flow rates were exceeded but had a lesser effect on reducing runoff volume. Compared to the BAU scenarios, improved land use practices and device implementation reduced annual runoff volumes by 6.0% and 12.2% for the infill and greenfield catchments, respectively. The improved scenario resulted in target flow rate exceedance frequencies comparable to those of the undeveloped condition for both study catchments.

Broad flow metrics for each scenario within the two catchments are presented in the table below.

Development type	Scenario	Mean annual flow (ML/y)	Mean 1-2-year ARI exceedance frequency	95% CFD flow (L/s)
Infill (416 ha)	Existing	2200	15.8	37
	BAU	2250	15.4	40
	Improved	2160	3.6	27
	Water-sensitive	1610	2.6	15
Greenfield (212 ha)	Existing	809	4.4	6
	BAU	1180	16.0	20
	Improved	1140	5.0	12
	Water-sensitive	804	3.2	5

The results demonstrate that adopting integrated water management practices within residential developments helps mitigate the impacts of urbanisation on aquatic ecosystems, as well as reduce demands on mains water supply. While partial adoption of stormwater management devices under the improved scenarios was shown to deliver modest benefits, the more comprehensive water-sensitive scenario was shown to produce a runoff regime that approximated that of the pre-development condition. This is likely to result in improved outcomes for receiving environments and stream ecology.

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1.0 Introduction

1.1 Background

Future urban development within Te Awarua-o-Porirua catchment can be expected to alter the flow regime of receiving waterways by increasing the volume, rate and frequency of stormwater runoff discharges. The degree of impact this has depends on the characteristics of land development and the type of stormwater management practices that are adopted within the developments.

To better understand the nature of these impacts, and potential means of mitigating them, Greater Wellington Regional Council (GWRC) engaged Morphum Environmental Ltd (Morphum) to undertake modelling of frequent flow hydrology within two catchments draining to Te Awarua-o-Porirua Harbour. This work is part of a wider modelling project within GWRC's Te Awarua-o-Porirua Whaitua process that is investigating the effects of different land and water management practices on receiving waters.

The objective of the urban hydrology modelling is to evaluate the effects that land use changes and stormwater management practices may have on the runoff regime during frequent rainfall events. The information generated is intended to support decision-making by the Whaitua Committee about possible land and water management strategies to adopt within the catchment to reduce the impacts of urbanisation on receiving environments.

1.2 Frequent flow hydrology

Stormwater engineering practice has historically focussed on managing flooding associated with large, low-frequency storm events. More recently, however, the scope has broadened to include the environmental consequences of stormwater discharges, and in doing so has shifted the emphasis to managing lower magnitude, high-frequency flows, since these have the strongest influence on channel form and ecosystem health. These frequent events are also subject to the greatest relative increase in flow following conversion of land from pervious to impervious cover.

Frequent stormwater discharges from urban environments have impacts on:

- Ecology (water levels, velocities, duration of elevated flows)
- Geomorphology (channel form and stability)
- Groundwater (recharge and maintenance of baseflow)

Strategies for managing these impacts seek to reduce runoff volumes, peak flow rates, and the frequency with which specific flow rates are exceeded. The effectiveness of these strategies are best understood using a continuous simulation modelling approach which describes the runoff response to different development states and the long-term performance of stormwater management devices.

1.3 Case study catchments

Modelling was conducted in two case-study catchments, representing both infill (urban intensification) and greenfield development types, in accordance with planned growth strategies within Porirua City. (Figure 1). Models were run for medium density residential development within each catchment. The case-study catchments were defined by GWRC.

The 416 ha infill catchment drains to Kenepuru Stream and comprises typical New Zealand medium density residential development, consisting predominantly of standalone, single-family dwellings built in the 1960s (Figure 2). The 212 ha greenfield catchment drains to Taupo Stream (and wetland). It is predominantly pasture with scrub-filled gullies and is planned for a mixture of suburban and rural-residential development under Porirua City Council's Northern Growth Area Structure Plan (Figure 3).

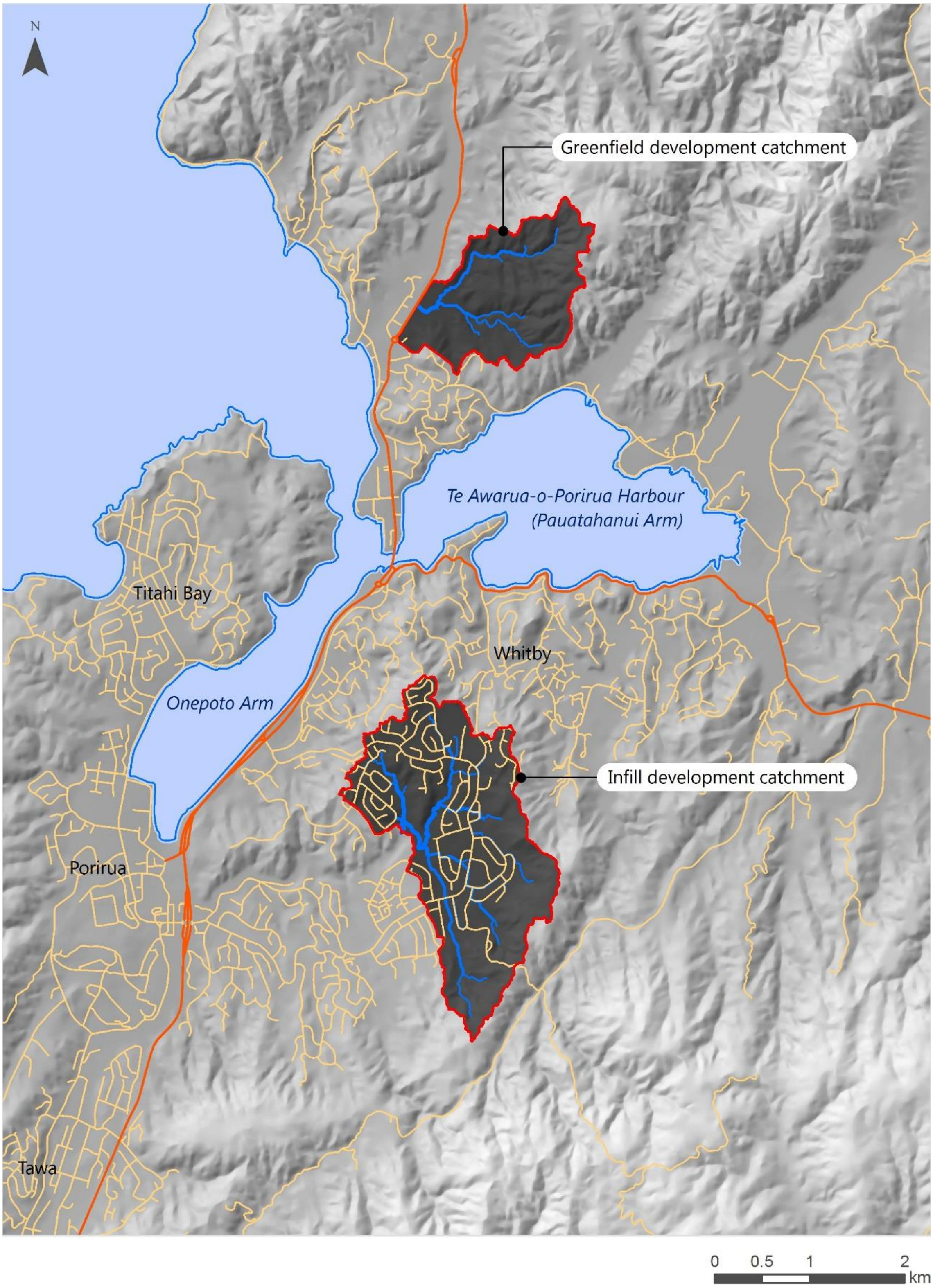

Figure 1. Location of infill and greenfield case study catchments

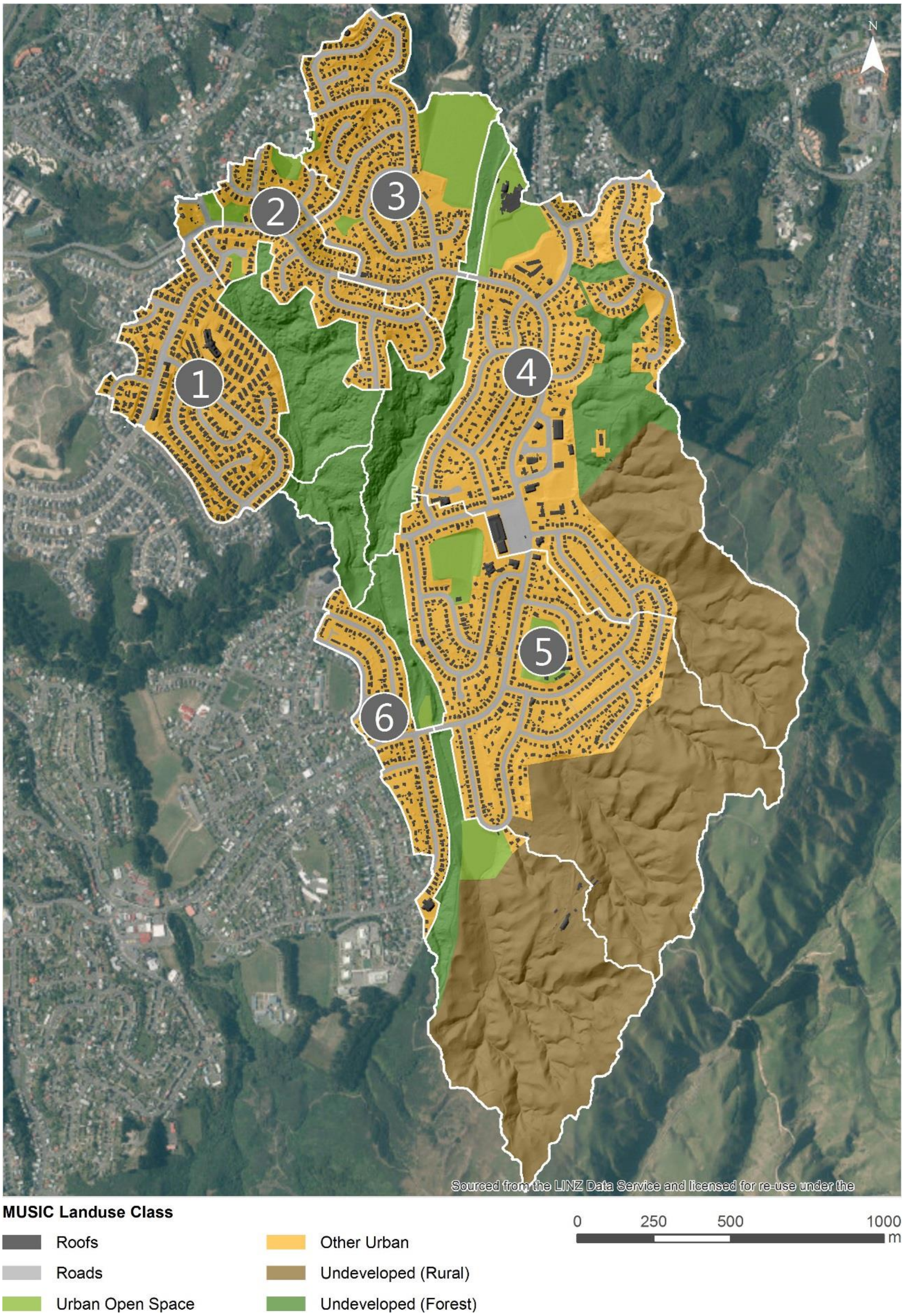

Figure 2. Existing land use classification and sub-catchments for the Infill catchment

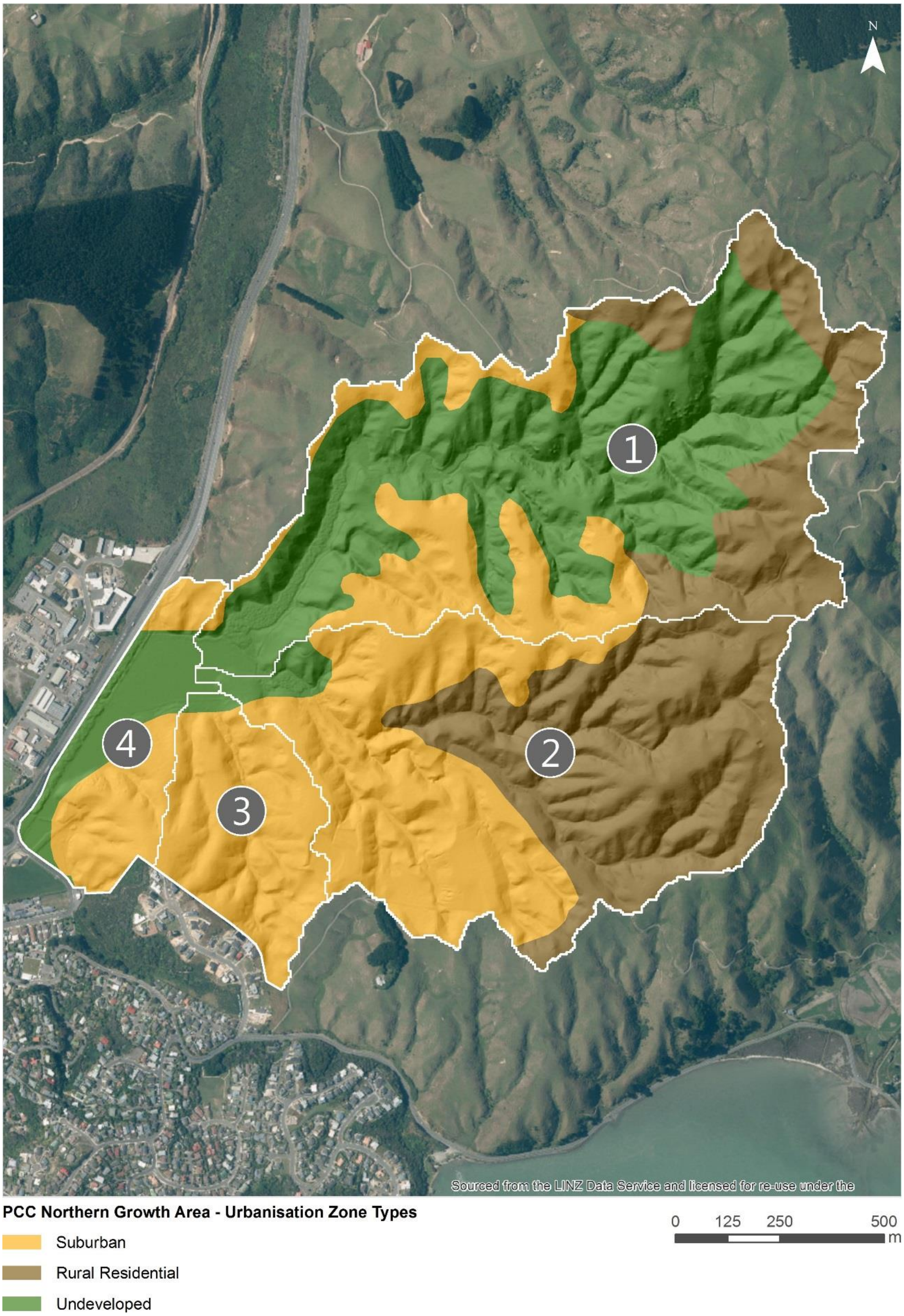

Figure 3. Future development designations and sub-catchments for the Greenfield catchment

1.4 Development scenarios

For each catchment, the existing state of development was modelled along with three alternative scenarios that adopt different proportions of each land use type (and associated surface imperviousness) and different stormwater management strategies. The scenarios, and their respective land use and stormwater management assumptions, are:

- Business-as-usual (BAU) scenario
  - Higher dwelling densities than existing condition with increased surface imperviousness
  - Conventional reticulated stormwater network
- Improved scenario
  - Dwelling density and imperviousness as for BAU
  - Adoption of current New Zealand best-practice stormwater management strategies[1]
  - Partial deployment of stormwater mitigation techniques designed to intercept and slow down runoff
- Water-sensitive scenario
  - Dwelling density as for BAU and improved but with smaller dwelling footprints and reduced imperviousness
  - Adoption of international best-practice stormwater management strategies, including harvesting and reuse of rainwater and stormwater
  - Widespread deployment of stormwater mitigation techniques designed to intercept and store/release water through infiltration or in-house reuse

Detailed assumptions of each model scenario are described in Section 3.0 and Appendix 1.

[1] Management strategies defined as ‘current best practice’ were based on input from the modelling project team and Whaitua Committee working group, and experience with developments in other parts of New Zealand.

2.0 Methodology

2.1 MUSIC model

Modelling was performed using the continuous simulation package 'Model for Urban Stormwater Improvement Conceptualisation' version 6.3 (MUSIC) (eWater, 2017). All models were run at a 5-minute time-step to describe the variability within a single rainfall event and to define water level fluctuations and flow rates through stormwater devices. Continuous simulation (as opposed to single-event simulation typically used in flood studies) describes the full range of runoff characteristics for a particular catchment over the simulation period, including antecedent conditions (length of preceding dry and wet spells) which have a strong influence on device performance.

MUSIC enables rapid evaluation of the effects that multiple land use and stormwater management scenarios have on the runoff profile. The model allows stormwater management strategies to be tailored to achieve a particular outcome, such as an approximation of the pre-development mean annual runoff volume.

2.2 Model inputs

In order to generate runoff information, MUSIC requires rainfall and evapotranspiration data, the surface area and imperviousness of land use categories for each scenario, pervious surface runoff parameters, and data on household water demand which in turn depends on daily per capita water use and dwelling densities. Model inputs were sourced from a variety of agencies and reports and are described below.

2.2.1 Rainfall and evapotranspiration

A continuous 5-year sequence of observed rainfall depths (2008-2012) from the *Taupo Stream at Whenua Tapu* rain gauge), recorded at 5-minute intervals, was used as the rainfall input. This data showed a narrow spread about the long-term monthly and annual means for the gauge, and even spread about the cumulative depth line, indicating good 'representativeness' of the data for the area (M. Harkness, pers. comm., 7 February, 2017).

Mean monthly potential evapotranspiration (PET) depths were calculated as the average of values from the *Kelburn* and *Paraparaumu AWS* weather stations (NIWA, 2014).

2.2.2 Land use and development form

Existing land use data for the infill catchment was obtained from Jacobs (via GWRC) and was generalised into the following broad classes for modelling purposes:

- Roofs (houses and other buildings)
- Roads (entire road reserve from lot boundary to lot boundary)
- Urban open space
- Other (effectively the non-roof component of lots, comprising pervious and impervious elements)
- Undeveloped (Rural)
- Undeveloped (Forest)

Land use was defined on a sub-catchment basis so that model results could be reported at a range of spatial scales (Figure 2 and Figure 3). Development designations for the greenfield catchment were adopted from the current Northern Growth Area Structure Plan. The proportion of each land use class assigned for each scenario, and their associated impervious fractions, are given in Appendix 1.

2.2.3 Stormwater management devices

MUSIC simulates the routing of water through stormwater management devices which can be connected in series throughout the catchment to deliver cumulative reductions in flow. The flow detention and retention performance of each device is governed by a suite of parameters which define their size, infiltration rates, and the reuse characteristics of harvested flows. The specific devices used in the modelling, and their parameters, are described in Section 3.2. MUSIC is also intended to be used to quantify contaminant generation and removal through treatment devices but has been applied only with regard to hydrologic and hydraulic analysis in this instance.

2.2.4 Water demand

Household water demand was specified on the basis of recorded per capita consumption (ARC, 2004) and the projected mean number of people per household within Porirua City (TBA, 2017). Water demand comprises a constant daily volume (toilet flushing and laundry) and a seasonally-varying annual volume (e.g. garden watering and car washing). Reuse of harvested rainwater is described in Section 3.2.1.

2.3 Model calibration

The models were calibrated against a 12-week flow series of a tributary of Taupo Stream that was collected by GWRC for this purpose (4/3/17-24/5/17). A rainfall record for the corresponding period, from the *Taupo Stream at Whenua Tapu* rain gauge, was also provided by GWRC. Rainfall and flow were both collected at 5-minute intervals.

The Taupo Stream tributary drains the greenfield catchment so calibration was conducted on this catchment, using an inferred imperviousness of 5% in the model. Rainfall-runoff parameters were manually adjusted until a reasonable match was achieved between the observed and modelled runoff patterns in terms of total runoff volume, peak flow rates, and baseflow rates (Figure 4). Final parameters adopted for all source nodes on the basis of this calibration are given in Table 1.

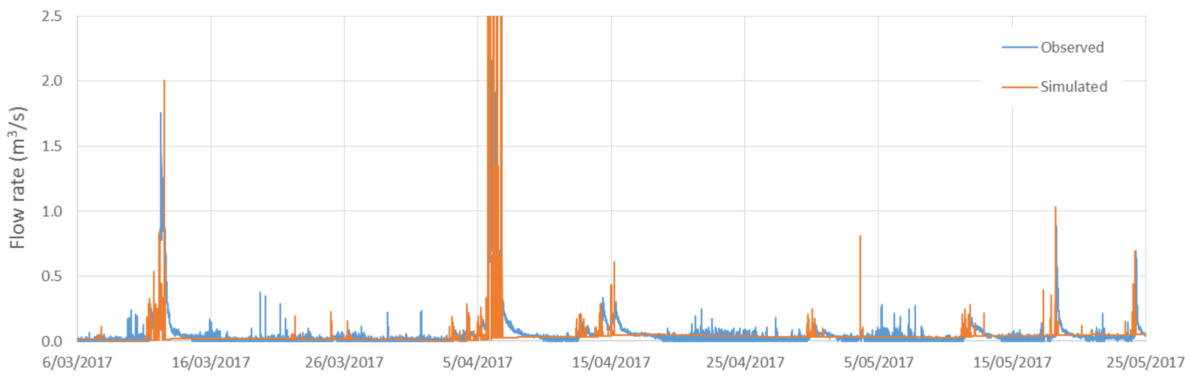

Figure 4. Observed and simulated flow series used for model calibration

Runoff volume checks were conducted on different parts of the flow record to investigate concordance between the simulated and observed records. While the total runoff volume over the calibration period was comparable, at 361 ML and 370 ML for the observed and simulated records, respectively, discrepancies were apparent during individual events. This is to be expected given the difficulties in representing the highly variable losses associated with vegetation interception, shallow soil soakage/storage and transpiration. The largest recorded event (5-7 April) produced runoff of 104 ML for the observed record and 139 ML for the simulated record, with corresponding mean flow rates of 401 L/s and 537 L/s, respectively. This equates to an over-prediction of 33%.

The model does not replicate the fine baseflow oscillations of the observed record (due to its inability to model variable seepages and interflow rates between events), instead applying a relatively constant, but declining, flow rate following cessation of rainfall. A volume check on the inter-event period of 8-12 April nevertheless indicated comparable runoff volumes of 15.5 ML and 14.8 ML for the observed and simulated records, respectively, with mean flow rates of 36 L/s and 34 L/s, respectively.

Table 1. Rainfall-runoff parameters adopted in MUSIC models

Parameter	Parameter value	Unit
Impervious area properties		
Rainfall threshold	1	mm/day
Pervious area properties		
Soil storage capacity	130	mm
Initial storage	25	% of capacity
Field capacity	100	mm
Infiltration capacity coefficient - a	200	-
Infiltration capacity coefficient - b	1.00	-
Groundwater properties		
Initial depth	10	mm
Daily recharge rate	25	%
Daily baseflow rate	5	%
Daily deep seepage rate	0	%

Periodic spikes in the simulated record, where no corresponding peak appears in the observed record, were assumed to stem from the fact that the rainfall gauge used for calibration is approximately 3 km north of the infill catchment and therefore potentially exposed to different rainfall patterns, particularly the intensity of small, frequent events. Similarly, flow peaks in the observed record which are not reflected in the simulated flows were assumed to arise for the same reason.

Further parameter adjustment was able to resolve some discrepancies between the two records but in doing so induced deviations elsewhere. This is not surprising given that a model of this nature is not able, nor intended, to replicate the more nuanced runoff processes inherent to natural systems that result from, for example, spatially-varying surface soil types, underlying geology, vegetation characteristics and their associated infiltration rates. These processes are inherently complex, with the greatest discrepancies observed during small high frequency rainfall events. It is also noted that the calibration is limited by the short gauging sequence which does not fully capture seasonal characteristics of the flow regime.

While further parameter adjustment could potentially improve the fit between the two flow series, it is also noted that the modelling study is interested principally in *relative* rather than absolute differences in flow characteristics between scenarios, to the extent that a more robust calibration is not considered essential. Furthermore, the final models proved relatively insensitive, in volumetric terms, to adjustments in the pervious area parameters, given that runoff is overwhelmingly generated from the impervious surfaces. For these reasons we consider the adopted parameters to be appropriate for the intended application.

3.0 Model architecture

3.1 Development scenarios

Eight models were created to simulate the range of scenarios required, spanning greenfield and infill development types, and existing and alternative development states, for medium density development (Table 2).

Table 2. Summary of model scenarios

Development type	Greenfield catchment	Infill catchment
Existing development	✓	✓
Business as usual - medium density	✓	✓
Improved - medium density	✓	✓
Water-sensitive - medium density	✓	✓

Each model consists of a series of connected nodes which describe the area and imperviousness of each land use type (source nodes), stormwater devices and their specifications (device nodes), including information on reuse of harvested rainwater and stormwater, and receiving nodes. The nodes are linked to describe the drainage configuration within the catchment. Runoff is generated at each source node and routed through the system at the specified time-step. A water balance can be obtained from any node, allowing results to be reported at a range of spatial scales.

An example of a model structured within MUSIC is shown in Figure 5.

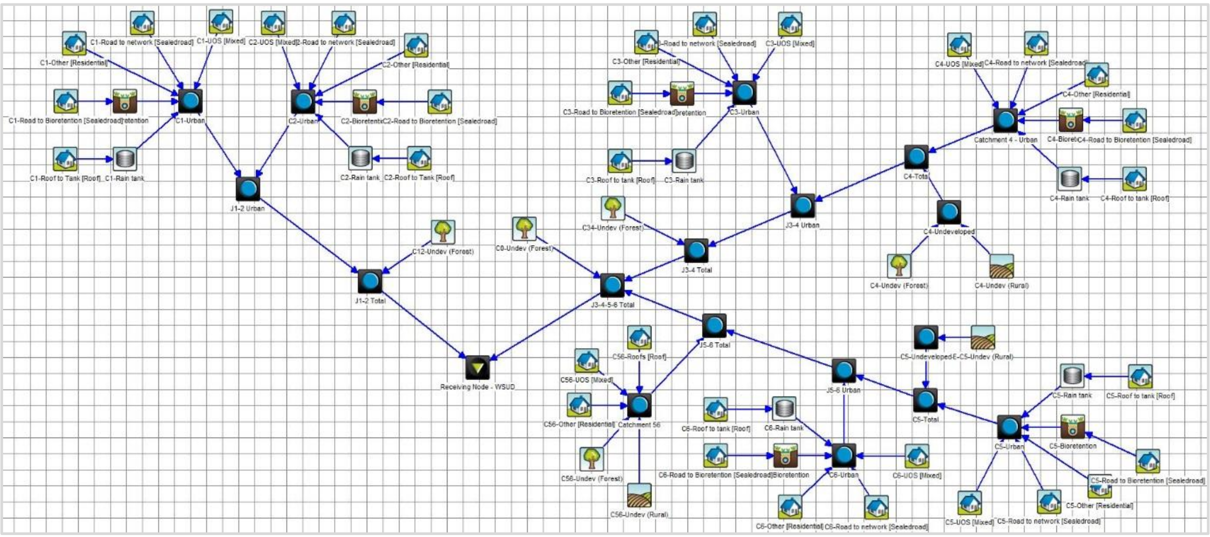

Figure 5. MUSIC model showing source nodes, device nodes and receiving node

Surface imperviousness and stormwater device implementation for each scenario are shown in Table 3.

Table 3. Scenario assumptions

	Existing	BAU	Improved	Water-sensitive
Urban imperviousness - infill (%)	51	54	54	45
Urban imperviousness - greenfield (%)	5	60	57	39
Rainwater tanks	x	x	√	√
Bioretention	x	x	√	√
Permeable paving	x	x	x	√
Wetlands	x	x	√	√

3.2 Stormwater management devices

Stormwater devices manage runoff through volume reduction (i.e. flow retention) via water reuse, infiltration and evapotranspiration, and flow attenuation (via detention). Devices modelled in MUSIC, and their respective functions for managing urban runoff, included:

- Rainwater tanks – harvesting and reuse of runoff from house roofs
- Bioretention systems – evapotranspiration and infiltration of road runoff
- Wetlands – evapotranspiration and reuse of treated stormwater
- Permeable paving – infiltration of within-lot runoff

3.2.1 Rainwater tanks

Rainwater tanks apply to the improved and water-sensitive scenarios only. Tank sizes were optimised to provide a reliability of supply[1] of 80-85%. Increases in tank size beyond the optimum size result in progressively smaller increases in reliability, reducing the tank's efficiency. On the basis of optimisation testing, 2 kL tanks were adopted for the improved scenarios and 10 kL tanks for the water-sensitive scenarios.

Water reuse for internal non-potable applications (i.e. toilet-flushing and laundry) was modelled as 40% of daily demand (BRANZ, 2009). Water reuse for external applications was configured as 15% of daily demand for the improved scenarios, and as 500 mm/y applied to 50% of the pervious fraction of the 'Other' land use classification (representing garden irrigation) for the water-sensitive scenarios. Key parameters adopted for rainwater harvesting and reuse are summarised in Table 4.

Table 4. Rainwater tank parameters

Parameter	Improved	Water-sensitive
No. people per dwelling	2.9	2.9
Water demand per person (L/day)	165	165
Water demand per dwelling (L/day)	479	479
Non-potable fraction (internal use) (%)[2]	0	40
Non-potable fraction (outdoor use) (%)[3]	15	0[4]
Constant daily reuse (internal use) (kL/dwelling/day)	0	0.19
Variable annual reuse (kL/dwelling/y)	26.2	Variable[5]
Rainwater tank size (kL)	2	10
Existing (retained) dwellings with rainwater tanks (%)[4]	10	50

New dwellings with rainwater tanks (%)	50	100
Fraction of roof are draining to tank (%)	75	100

[1]Reliability of supply is defined as the proportion of total non-potable demands which are able to be met by the respective rainwater tank configurations.

[2]Internal non-potable use includes toilet flushing and laundry.

[3]Outdoor use includes garden watering, car washing etc.

[4]Outdoor use in the water-sensitive scenarios are based on an annual irrigation depth of 500 mm/y applied to 50% of the pervious fraction of the lot (rather than as a percentage of total demand as is the case in the improved scenarios).

[5]Refers to infill development only in which the developments are assumed to comprise 50% existing dwellings which are retained, and 50% new dwellings.

Sub-catchment 1 of the infill catchment was assumed from aerial photographs to be fully developed such that 100% of dwellings were considered to be existing for the alternative development scenarios. This results in disproportionately smaller tank sizes and lower reuse demands than for the other sub-catchments.

3.2.2 Bioretention systems

Bioretention devices were configured to receive runoff from roads in the improved and water-sensitive scenarios. Runoff from lots, including overflow from rainwater tanks, was assumed to discharge directly to the reticulated stormwater network, bypassing the bioretention devices. The devices were assumed to be unlined, permitting exfiltration to the native soil. Key parameters adopted for bioretention systems are summarised in Table 5.

Table 5. Bioretention system parameters

Parameter	**Improved**	**Water-sensitive**
Road area draining to bioretention (%)	40	90
Bioretention surface area as percentage of catchment (%)[1]	2	2
Extended detention depth (mm)	350	350
Exfiltration rate (mm/h)	2	2

[1]Percentage of impervious fraction of contributing catchment only.

3.2.3 Wetlands

While intended primarily as stormwater quality treatment devices, constructed wetlands can also provide flow attenuation through extended detention of storm flows and volume reduction through the reuse of treated outflows for non-potable applications such as irrigation of public open spaces and street trees.

Wetlands were simulated in MUSIC for the improved and water-sensitive scenarios only. Reuse of harvested stormwater was configured as 500 mm/y applied over 50% of the pervious component of the 'Urban open space' land use classification for the water-sensitive scenarios only. Wetland parameters, and harvesting and reuse strategies, are presented in Table 6.

Table 6. Constructed wetland parameters

Parameter	Improved	Water-sensitive
Catchment area draining to wetland (%)	100	100
Wetland surface area as percentage of catchment (%)[1]	3	3
Extended detention depth (mm)	350	350
Variable annual reuse (kL/y)	0	Variable

[1]Percentage of non-road impervious fraction only.

3.2.4 Permeable paving

Permeable paving can be used to reduce effective catchment imperviousness while still providing a hard surface within residential lots. It was assumed that 50% of the paved (i.e. impervious) portion of the 'Other' land use type was permeable. Permeable paving was applied to the water-sensitive scenarios only, and assumed an exfiltration rate of 2 mm/h.

4.0 Results

Changes to the runoff regime as a result of the different land use and stormwater management scenarios are described in the following terms:

- Mean annual runoff volume
  - Provides a broad indication of the overall change in runoff generation and discharge due to development form and stormwater device implementation.
  - Encapsulates the variance in other more complex flow measures and is therefore adopted to provide simplified 'big picture' results.
  - Contains the variability that creates ecologically stressful conditions and can indicate a shift towards less diverse macroinvertebrate communities with fewer sensitive species.
- Flow exceedance frequency
  - Describes changes in the frequency with which particular flow rates of interest are exceeded, e.g. the 1-2-year ARI 'channel-forming' flow, or 'bed-disturbing' flows.
  - High frequency bed disturbance directly affects habitat and food availability. This can lead to lower diversity communities dominated by a few tolerant species (typically small, rapidly-colonising species) while more sensitive species are lost.
- Cumulative frequency distribution curves
  - Indicate a tendency towards a broadly higher or lower flow regime by describing the percentage of time that a flow rate of interest is likely to be equalled or exceeded.

These indicators allow quantification of the extent to which development scenarios may deviate from the pre-development condition and to which the ecological impacts of hydrological changes as a result of urban development are altered.

4.1 Mean annual runoff volume

Mean annual runoff volumes were significantly influenced by land use changes and the implementation of stormwater management devices. The change in runoff volume between scenarios is shown in Figure 6 and Figure 7 for the infill and greenfield catchments, respectively. Unless otherwise stated, the information presented relates only to the urban component of the catchments.

The reduction in runoff following transition from BAU to water-sensitive development (i.e. the two development extremes) was 41.3% for infill development and 52.6% for greenfield development. When the entire catchment is taken into account, i.e. including undeveloped areas, runoff reductions of 28.4% and 32.4% were predicted for the infill and greenfield catchments, respectively.

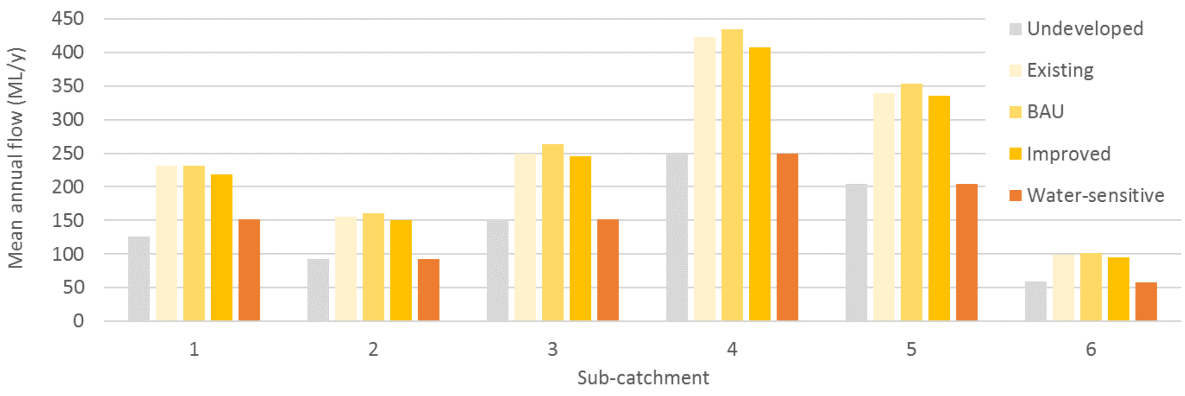

Figure 6. Comparison of mean annual runoff volumes for infill scenarios

For the infill catchment, the BAU scenario was shown to generate slightly higher (3.1%) runoff volumes than the existing condition. In adopting an improved development state, runoff volumes were reduced by 3.1% compared to the existing condition, and by 6.0% compared to the BAU condition. Implementation of the water-sensitive strategy reduced runoff volumes by 39.4% compared to the existing scenario, and brought mean annual flows almost exactly in line with those of the catchment in an undeveloped state (Figure 6).

The greenfield catchment showed a broadly similar pattern but with a more pronounced reduction in flows between the BAU and improved scenarios (12.2%). The water-sensitive scenario reduced flows to below those of the undeveloped condition (Figure 7).

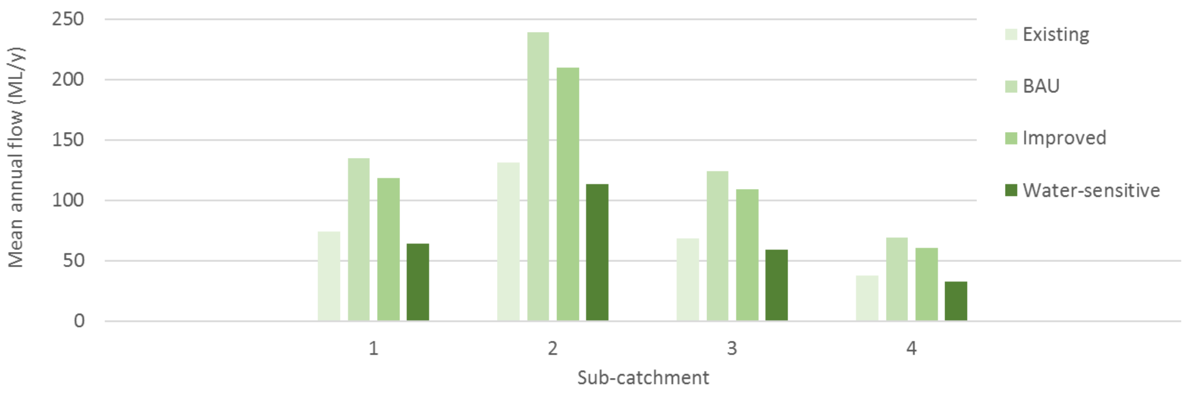

Figure 7. Comparison of mean annual runoff volumes for greenfield scenarios

Total runoff volumes, reported separately for the urban areas only, and for the total catchment including undeveloped areas, are shown in Table 7.

Table 7. Mean annual runoff volume (ML/y)

Catchment	Domain	Existing	BAU	Improved	Water-sensitive
Infill	Urban area only	1498	1545	1452	907
	Whole catchment	2200	2250	2160	1610

Greenfield	Urban area only	310	567	498	269
	Whole catchment	809	1180	1140	804

For both catchments, the total reduction in runoff volume between BAU and water-sensitive scenarios reflects the combined effect of both land use changes and stormwater device implementation. It can be useful to separate the relative contributions of each element to support management decisions.

To isolate the influence of land use changes alone, the initial runoff generation ('source') must be compared between the two scenarios. Conversely, to account for device influence alone, the initial ('source') and remaining ('residual') runoff volumes must be compared within a single scenario.

Considering differences in land use proportions and impervious fraction alone (for urban areas only), the infill water-sensitive scenario generated 7.0% less runoff than the BAU scenario (source flow rates of 1545 ML/y and 1437 ML/y, respectively).

The effect of devices alone within the infill water-sensitive scenario accounted for a 36.9% reduction in flow (source flow rate of 1437 ML/y compared to residual flow rate of 907 ML/y). For the greenfield catchment, the corresponding contributions to volume reduction from land use changes and device implementation were 17.5% and 42.6%, respectively.

4.2 Device performance

The contribution to runoff reduction that is attributable to each device is shown in Table 8. Rainwater tanks show a modest effect on volume reduction under the BAU scenarios. The influence of tanks increases significantly under the water-sensitive scenarios given their more extensive implementation and wider reuse applications. The effect of rainwater tanks are especially pronounced in the greenfield water-sensitive scenario due to the higher tank adoption rate (assigned to all dwellings versus the partial retrofit of the infill catchment), and a greater proportion of the roof area draining to the tanks.

The relative importance of each device also shifted across scenarios. Wetlands and bioretention systems are proportionally less important in the water-sensitive scenarios given that they are sized according to the catchments' impervious fraction which decreases from the improved to the water-sensitive scenarios.

Table 8. Runoff reduction contribution from each device type (urban areas)

Catchment	Stormwater device	% of total reduction		% Contribution	
		Improved	Water-sensitive	Improved	Water-sensitive
Infill	Rainwater tank	1.9	22.3	30.9	60.5
	Bioretention	1.7	3.7	27.9	10.0
	Permeable paving	0.0	5.1	0.0	13.9
	Wetland	2.4	5.8	39.6	15.7
	Total	**6.2**	**36.9**	**100**	**100**
Greenfield	Rainwater tank	4.7	25.2	50.0	59.2
	Bioretention	2.1	5.2	22.6	12.2
	Permeable paving	0.0	4.8	0.0	11.4
	Wetland	2.3	7.2	25.0	16.8
	Total	**9.3**	**42.6**	**100**	**100**

4.3 Flow exceedance frequency

Changes to the frequency with which a particular flow rate occurs as a catchment is developed can be a useful indicator of alterations to channel stability and in-stream habitat conditions. The 'channel-forming' flow, or 'bankfull discharge' is generally regarded as the flow rate which occurs on average every 1-2 years and is important in controlling channel form.

The channel-forming flow rate was estimated for the two catchments in their undeveloped states using the Rational Method. The HIRDSv3 1.58-year ARI rainfall intensity, at a storm duration equal to the catchments' time of concentration (t_c), was adopted for this purpose. This yielded a peak flow rate of 4.7 m^3/s for the greenfield catchment, assuming t_c = 38 minutes, and a peak flow rate of 7.6 m^3/s for the infill catchment, assuming t_c = 49 minutes. The number of times these flow rates were exceeded over the five year simulation period was divided by five to approximate an average annual exceedance frequency. The analysis was repeated for additional flow rates of the same ARI based on rainfall intensities of 10 and 20 minutes to reflect shorter times of concentration.

The change in frequency with which the target flow rates were exceeded across the different scenarios are shown in Figure 8 and Figure 9. Following a similar pattern to that of the mean annual runoff volumes, the BAU scenarios result in a greater frequency of exceedance of the target flow rate than the undeveloped state, and the water-sensitive scenarios result in a frequency of exceedance that is lower than that of the undeveloped state, for both catchments.

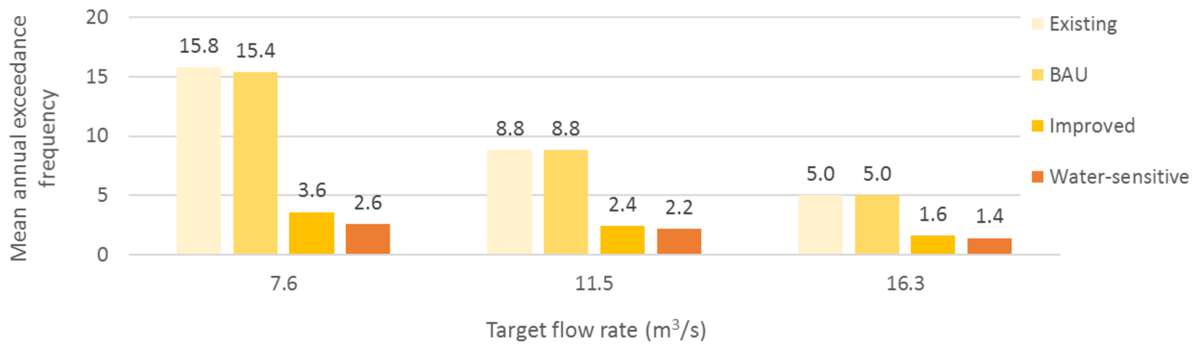

Figure 8. Mean annual flow exceedance frequency for infill scenarios

In contrast to the mean annual runoff pattern, in which the improved scenarios had only a moderate effect on total volume reduction, the improved scenarios had a significant effect on reducing peak flow rates compared to the BAU case, due to the flow attenuating effects of partial device implementation.

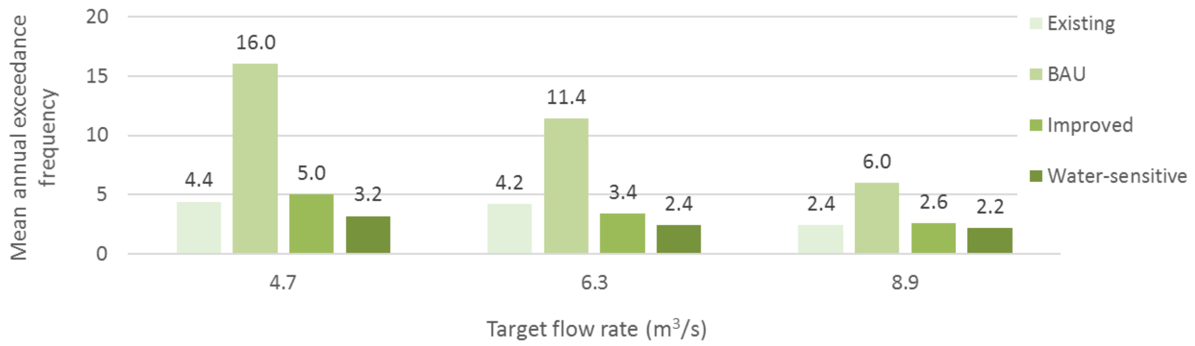

Figure 9. Mean annual flow exceedance frequency for greenfield scenarios

The emphasis of this project is on frequent flows given their influence on channel stability and aquatic ecological function. Testing the exceedance frequency of flows from shorter duration, higher intensity storms at the same ARI, or from larger ARI events for the same duration, showed that the change across scenarios diminishes as stormwater management devices are overwhelmed and their attenuation function is largely negated.

4.4 Cumulative frequency distribution

Cumulative frequency distribution curves describe the percentage of time that a particular flow rate is equalled or exceeded. The shape of the curves describes the full range of flows from a catchment over the simulation period. A comparison of curves across scenarios can therefore reveal a shift towards a broadly higher or broadly lower discharge regime as the land use and stormwater management practices within a catchment change.

Cumulative frequency curves were produced for the urban component of each sub-catchment at daily, hourly and 5-minute time-steps. Curves are presented below for both the infill (Figure 10) and greenfield (Figure 11) catchments, in both cases using Sub-catchment 3 as an example. Larger scale versions of the graphs are shown in Appendix 2. While the 5-minute variants most accurately describe the actual catchment response, the more generalised curves below, based on average daily flows, most clearly demonstrate the general trend across scenarios.

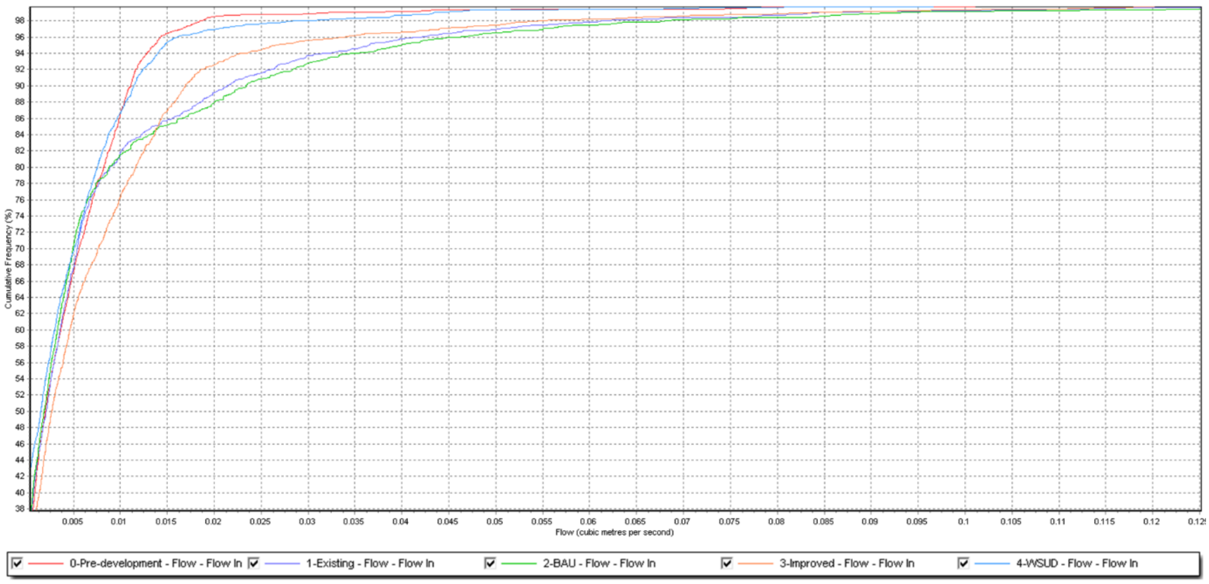

Figure 10. Cumulative frequency curve for the infill catchment (daily time-step)

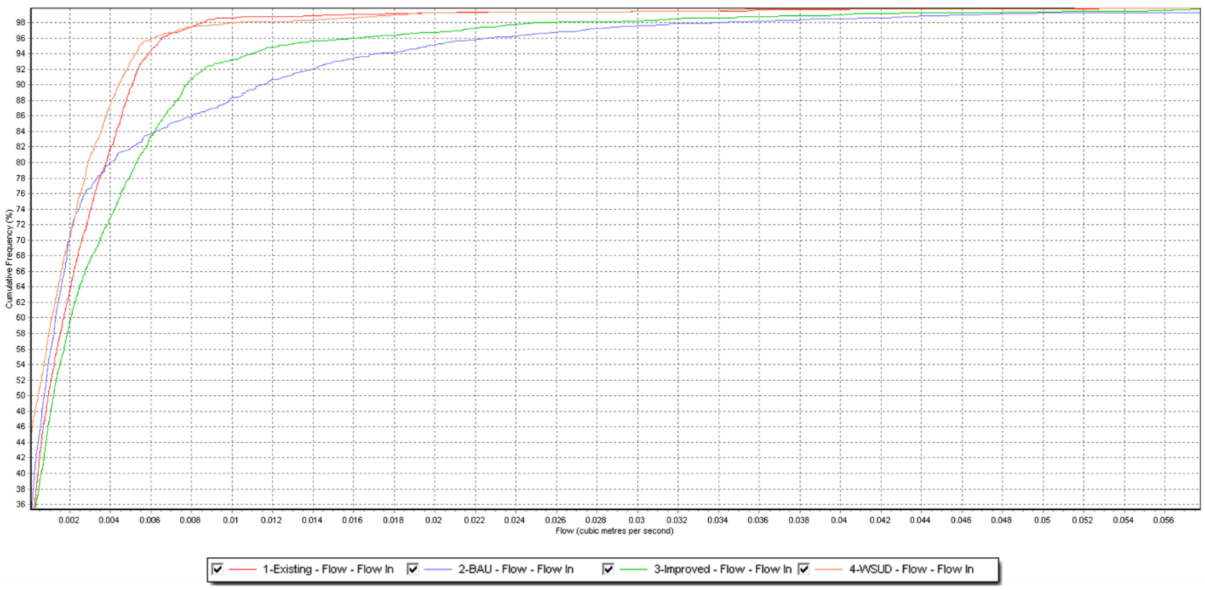

Figure 11. Cumulative frequency curve for the greenfield catchment (daily time-step)

The curves demonstrate that, for both catchments, a transition from BAU to improved to water-sensitive shifts the general pattern of flow behaviour towards that of the undeveloped condition as they tend towards a greater proportion of lower flow rates. Differences in flow across scenarios can be examined either by evaluating the change in percentile that corresponds to a particular flow rate, e.g. 20 L/s, or by comparing how the flow rate varies across scenarios at a particular percentile.

In the infill catchment, 87% of flows throughout the simulation period were less than or equal to 20 L/s under the BAU scenario (Figure 12). Under the water-sensitive scenario, this increased to 97%, indicating that 20 L/s is exceeded only 3% of the time, compared to 13% under BAU. It is noted that these measures refer to the proportion of total time for which flow rates are exceeded, rather than counts of individual events, to reflect the variance in flow rates observed over the duration of any given event.

The greenfield catchment shows a similar pattern but with the water-sensitive scenario more closely approximating the existing (undeveloped) condition (Figure 12). The reduced greenfield flows can be attributed largely to the more extensive implementation of rainwater tanks under this scenario compared to the infill catchment.

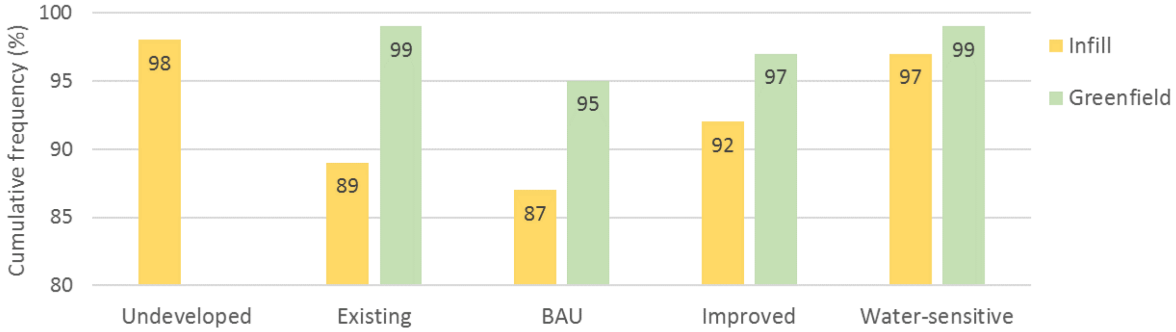

Figure 12. Cumulative frequency value corresponding to flow rate of 20 L/s across scenarios

In percentile terms, the 95th percentile flow defines the flow rate that is equalled or exceeded for 5% of the flow record.

For the infill catchment, the 95th percentile BAU flow corresponded to 40 L/s, i.e. 5% of flows were greater than or equal to 40 L/s (Figure 13). Under the water-sensitive scenario, the flow rate at the corresponding percentile was 15 L/s, indicating a pronounced shift to a generally lower flow regime, and a tendency towards that of the undeveloped condition.

The greenfield catchment reflects that pattern, showing a 95th percentile shift from 20 L/s to 5 L/s between the BAU and water-sensitive scenarios (Figure 13).

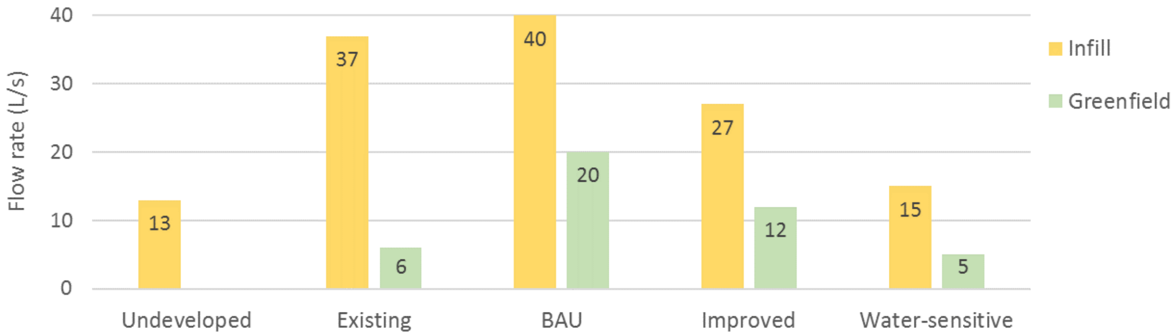

Figure 13. Flow rate corresponding to 95% cumulative frequency across scenarios

5.0 Discussion

Continuous simulation modelling of the two study catchments has demonstrated the influence that land use configuration and stormwater management measures are able to have on catchment runoff regimes and ultimately on the quality of the aquatic receiving environments. The results indicate that partial or comprehensive water-sensitive approaches to residential development can reduce the impacts of urbanisation or attain a runoff response which approximates that of the undeveloped catchment. This was shown to be the case for both intensification of existing developments and development of greenfield sites.

The influence of the improved and water-sensitive scenarios on runoff behaviour can be attributed to both land use changes (especially a reduction in surface imperviousness) and the adoption of stormwater 'treatment trains'. The flow management devices and their specific configurations were shown to have the greatest influence on post-development hydrology, with the land use changes alone being less significant.

The implementation of stormwater management devices was shown to address two hydrological metrics of ecological importance – attenuation of peak flow rates for individual events (i.e. stormwater detention), and reduction of total runoff volumes (i.e. stormwater retention) – and to affect the overall flow regime as described by cumulative frequency distributions.

The improved scenarios showed a relatively modest effect on reducing flow volumes but were important in moderating the peak flows associated with frequent rainfall events. In particular, the runoff detention effect of rainwater tanks and bioretention systems was able to reduce the frequency with which channel-forming flows occurred.

The water-sensitive scenario was able to demonstrate both detention and retention effects due to extensive reuse of harvested rainwater and stormwater. Reuse results in a net reduction in runoff volumes as water used for internal household applications is disposed of via the wastewater system and so is removed from the catchment entirely. Reduced surface imperviousness, increased infiltration through permeable paving and bioretention, and reuse of harvested stormwater, further enhance the water-sensitive scenario outcomes.

The strongest modifications to flow behaviour are able to be achieved in a greenfield context in which opportunities for water management are not constrained by existing development. This allowed rainwater tanks to be fitted to *all* dwellings in the water-sensitive scenario, and the house roofs designed to maximise the fraction that contributes to the tanks. The increased detention effect of this arrangement is amplified by also allowing for more extensive reuse of harvested water such that overall discharge volumes are reduced.

These effects are further illustrated by the cumulative frequency curves which indicate a shift towards broadly lower flow regimes through the transition from BAU to improved to water-sensitive scenarios as runoff volumes are reduced and infiltration is increased, reducing the number of runoff events that exceed a threshold flow rate. The flow rate corresponding to the 95th percentile 'low-flow' metric, of particular importance in ecological terms, was significantly reduced in both study catchments in response to the water-sensitive scenario.

The modelling demonstrates that in order to emulate a pre-development runoff regime across a range of aquatic ecological metrics, a large-scale, co-ordinated, multi-device approach to stormwater management is needed for residential developments.

6.0 Summary and conclusions

A range of residential development forms and stormwater management practices were simulated within Te Awarua-o-Porirua, and their effect on the flow regime of receiving waterways was evaluated. The modelling showed that adoption of water-sensitive urban design principles, such as reduced surface imperviousness, rainwater harvesting and reuse, and the use of treatment devices (bioretention and wetlands), were able to reduce the volume, peak flow rate, and frequency of urban runoff events for both infill and greenfield developments.

While land use changes, particularly reductions in surface imperviousness, were shown to drive improvements in runoff patterns, the greatest benefits were achieved through the use of flow management devices. Partial implementation of stormwater management devices had useful but modest benefits in improving the runoff regime of a developed catchment, whereas a comprehensive, catchment-wide approach to stormwater management was shown to maintain a hydrological condition that is close to the pre-development state.

The results demonstrate that stormwater treatment trains can be tailored to achieve specific runoff targets based on the nature of development within a catchment. The various design parameters of stormwater management devices, and their configuration within a particular catchment, can be refined until an appropriate degree of protection for receiving waterways is obtained.

The enhanced benefits conferred under greenfield development conditions emphasise the importance of making provision for treatment trains at the planning stage of proposed developments so that opportunities for improved urban water management can be incorporated. While retrofitting stormwater devices within existing catchments was shown to still produce good outcomes for receiving waters, the relative complexity and associated cost may disincentivise this approach.

Continuous simulation modelling has identified strong patterns of relativity across scenarios and laid the basis for developing rules that can inform urban development policy on matters of integrated water management. Should the Whaitua Committee wish to develop recommendations for integrated water management practices, further work may be necessary to develop defensible targets for the capture, detention and retention of rainfall in order to mimic particular hydrological characteristics on the basis of absolute numbers, and to consider the best means of demonstrating compliance with these.

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