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Research article

Demonstrating the need to simultaneously implement all water sensitive design methods for aquatic ecosystem health

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ABSTRACT

The practices commonly known as ‘Water Sensitive Design’, or ‘Low Impact Urban Design and Development’, provide a comprehensive package of practices, (building blocks), that respect and work with the natural water cycle and enhance biodiversity. Much previous research has focussed on determining the sustainability gains achieved by the implementation of a narrow range of closely related techniques, such as the installation of at-source devices for stormwater retention and treatment. Other research has investigated the gains for the health of an ecosystem from the reduction of impervious surfaces, or from riparian revegetation, or from the clustering together of buildings. Relationships between these practices and techniques have been observed, but urban developers continue to implement practices such as these in isolation whereas it is suspected that the aquatic ecosystems need all of the practices and techniques to be implemented simultaneously. Without the synchrony of simultaneous implementation, degradation of the ecosystems may still occur and the real cause of it may be missed. The purpose of this research is to monitor, using a biotic index, the ecosystem responses of streams to the simultaneous implementation of as many as possible of these practices (the building blocks) at two different urban densities in paired sub-catchment studies within the Hauraki Gulf catchment of Auckland, New Zealand. Significant differences in the health of the ecosystems of the streams between some treatment and control sub-catchments are observed at both densities. The failure to apply all the techniques (building block methods), or to apply them appropriately in some of the case study sub-catchments, demonstrates a consequent degradation of the ecosystems of the streams that is expected to have negative consequences, not only for local streams but for the marine receiving environment.

1. Introduction

The United Nations (2007) estimated that 40% of the world's population lives within 100 km of the coast, and as population density and economic activity increase, pressures also increase, including those of habitat conversion, land cover change, and pollutant loads on coastal ecosystems also increase. Land cover change, for example from rural to urban within coastal catchments, changes the stresses on coastal ecosystems, although these may be eased by water sensitive/low impact approaches to urbanisation. Low Impact Development (LID) has been evolving in the U.S.A since the late 1980s to address some of these stresses through an alternative approach to stormwater management. LID emphasises at-source stormwater retention and treatment in contrast to traditional approaches of catchment drainage through piped networks for discharge to waterways. Similar but divergent practices, discussed below, have evolved since in other countries.

Evidence in support of LID is presented by Dietz and Clausen (2007) who compared traditional urban and LID catchments in the U.S.A, and reported a significant two orders of magnitude of increases in annual stormwater runoff and plant nutrient loads in the traditional urban catchments. The load of Total Nitrogen and Total Phosphorus exported from the LID development remained unchanged from that of the predevelopment levels. The LID catchment had minimal increase in annual runoff volume relative to the predevelopment condition, and levels were similar to those in a forested catchment. In 2017 several reviews of LID performance on catchment scales were published (Jefferson et al., 2017; Li et al., 2017; Ahmed and Vogel, 2018). Prominent conclusions were, firstly, that LID is most efficient for small storm - high frequency events, and much less efficient during high flow events, and secondly, that the literature demonstrated the potential to improve the water quality and the hydrologic regimes of aquatic ecosystems, and increase their resilience with respect to climate change. However, the implementation of

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catchment-scale low impact/water sensitive approaches has been slow (Ahmed and Vogel, 2018). Ira et al. (2016) state that experience both in New Zealand and internationally indicates that water sensitive stormwater management solutions are likely to be more robust and resilient than conventional piped systems in the face of climate change, earthquakes, and the risk of both blockages and cross contamination from adjacent sewers. The water sensitive solutions may include stormwater treatment devices where plants provide part of the treatment, as well as interconnected waterways, wetlands, forests and other green open spaces that maintain natural ecological processes and provide a framework for land development and built infrastructure planning (McMahon and Benedict, 2002).

Water Sensitive Design (WSD; Lewis et al., 2015), Water Sensitive Urban Design (WSUD; National Water Commission, 2004) and in particular Low Impact Urban Design and Development (LIUDD; van Roon and van Roon, 2009 appendix 1) focus on much more than just stormwater management. In these practices fully separated sewage reticulation and treatment is assumed, and streams are retained in as near a natural state as possible. Some leakage from sewerage and water supply networks to stormwater systems and groundwater is assumed. In Melbourne, Australia, Walsh et al. (2016) stated that researchers in the future need to guide the design and use of urban lands to optimise the condition of waterways. This aligns with the Australian National Water Commission (2004) WSUD definition that called for urban planning to be sensitive to, and conservative of natural hydrological and ecological processes through the management, protection and conservation of the urban water cycle.

The transition from stormwater device installation to holistic design within nature, including the creation of multi-functional regional eco-corridors, has occurred in some northern European cities since the late 20th century, for instance in Malmo, Sweden, as described by Stahre (2008). The transition towards Water Sensitive Cities as expressed through the concept "Urban Water Transitions Framework" is led by the Australian CRC Water Sensitive Cities (2020). In the Netherlands water is increasingly integrated into spatial planning and design, and lessons are being shared with the United Kingdom (Dolman et al., 2013; Salinus Rodriguez et al., 2014).

The literature, referred to in the following paragraph, provides support for a list of urban catchment characteristics that are known to contribute to the health of streams in urban New Zealand. These characteristics are the minimum 'building blocks' of WSD or LIUDD, and define the urban form and infrastructure that is understood to be necessary to achieve a stream health equivalent to, or close to, the reference condition within the urban environment. The 'building blocks' include but are not limited to: design of urban development using the catchment as the design unit (Auckland Regional Council, 2004; van Roon and van Roon, 2009), design particularly with regard to maintaining the connections between linked waterways and between land and water (Auckland Regional Council, 2004), minimising the reconfiguration of the topography and the need for urban earthworks (Heijs et al., 2008), keeping streams natural and not piped, retaining or re-establishing wide riparian native vegetation strips along the edges of waterways (Collier et al., 2008), and clustering housing to free up open space in riparian, flood-prone and steep parts of the catchment (Heijs et al., 2008). Also minimising impervious surfaces (Allibone et al., 2008), maximising vegetation, reticulating sewage collection, and treating sewage separated from stormwater, managing stormwater at-source rather than at end-of-catchment (Lewis et al., 2015) and harvesting rainwater for non-potable water supplies.

Particular attention is given within LIUDD and WSD to an urban form and urban design that protects or restores a broad corridor of the riparian indigenous vegetation of each stream. Vegetated catchment and riparian areas complement ecologically engineered devices such as raingardens, swales, bioretention strips and porous paving, in processing stormwater at source and providing habitats. Many instream invertebrates have adult life stages in the riparian zone. Rainwater capture and its use for non-potable demands diverts this portion to sewer or garden infiltration/evapotranspiration and ultimately reduces stormwater volume in line with the design objectives. The clustering and footprint reduction of housing within the non-riparian and the bush covered parts of each catchment is encouraged to minimise impervious surfaces and retain urban density.

The objective of this research is to build confidence in the need for holistic WSD/LIUDD as defined by van Roon and van Roon (2009) Appendix 1, and by Lewis et al., (2015). The 'building blocks', as listed above, are defined by these publications. The efficacy of each individual 'building block' method, in terms of its individual contribution to stream ecosystem health, has been demonstrated. However if, as is common in Auckland, one or more of the 'building blocks' is not implemented, the ecosystem may degrade and the efficacy of other 'building blocks' often begins to be questioned. In this article the objective is to demonstrate the cumulative efficacy of implementing multiple 'building blocks' simultaneously.

The research questions are:

1) Does the simultaneous implementation, within a greenfield residential development, of the 'building block' methods common to 'Water Sensitive Design', result in healthier stream ecosystems than when compared with those typical of streams in conventionally developed catchments where these 'building blocks' are not all applied together? This comparison is primarily but not exclusively made within, not between, urban (500m2 lots) and countryside (5000m2 lots) densities.
2) Is there a coincidence in some sub-catchments of aquatic ecosystem degradation and the failure to apply all 'building block' methods, or to apply those methods inappropriately?
3) Do countryside living sub-catchments (with a lot size averaged over the site of 5000m^2), always have healthier stream ecosystems than urban sub-catchments (with a lot size averaged over site of 500m^2? How does the implementation of certain building blocks influence whether low density countryside neighbourhoods have healthier stream ecosystems than the stream ecosystems of medium density urban neighbourhoods?

2. Materials and methods

2.1. The case study of Auckland

The estuarine and marine waters of the Hauraki Gulf (Figure 1), in Auckland, New Zealand are valued by the community as the focus of an outdoor lifestyle, of international tourist experiences, and of marine industries, including fisheries and aquaculture. This lifestyle attracts locals, migrants and tourists. Recent levels of immigration (MBIE, 2017) to Auckland have increased the demand for vehicles and housing. The median house price to median household income ratio is nine, placing Auckland amongst the 10 least affordable cities globally (Cox and Pavletich, 2018).

The Hauraki Gulf Forum (2017) documented the biodiversity value of the Gulf, the effects of fishing and catchment land uses, and the ongoing decline in Gulf water quality and ecosystem health. Stormwater systems discharge contaminants including sediments, nutrients, heavy metals, hydrocarbons, pathogens and micro-plastics that impact the streams, the rivers, the estuaries, and the Gulf itself. Other stormwater induced stressors on the Gulf include decreased dissolved oxygen, pH changes, and modified hydrology of input streams in frequent small events. Indicators of water quality and the ecological health of streams, estuaries and marine environments have been measured over several decades (Auckland Council, 2015). The highest concentrations of most of the contaminants (Auckland Council, 2015 pp. 174–180), and the least healthy benthic ecosystems (Auckland Council, 2015 pp. 171, 185) are found in the streams and estuaries of the oldest urbanised parts of Auckland, including the Waitemata Harbour and the Tamaki Estuary.

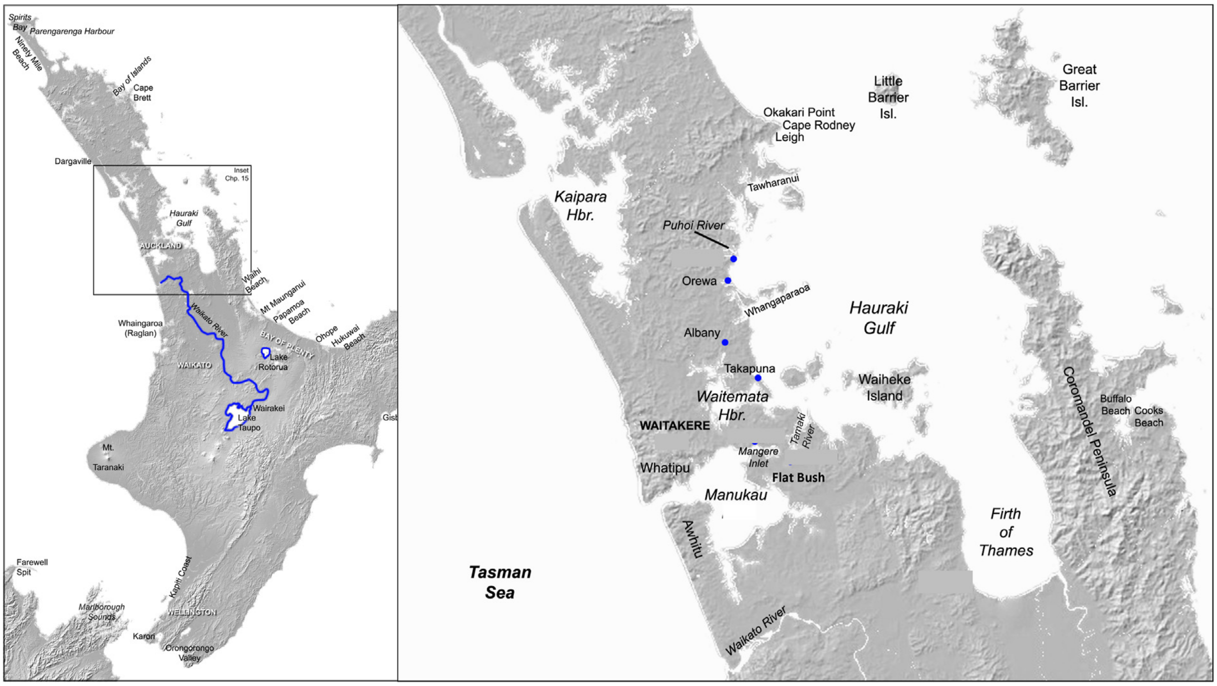

Figure 1. The location in the North Island of New Zealand and the spatial layout of Auckland including the Hauraki Gulf. Auckland extends 60 km north to south, west of the Hauraki Gulf. Flat Bush is the location of the comparative study.

Several top predatory species of the Gulf food chain have been reduced by 80% over the last century, changing the structure of the ecosystem. The Gulf now supports less than 45% of the biomass present in 1925 (Hauraki Gulf Forum, 2017). The Forum considers that the degradation of the health of the Gulf is restorable but requires reductions in the diverse discharges into the Gulf.

Contaminant input, via the streams and estuaries of the urban catchments of Auckland, contributes to the Gulf's degradation and changing ecological functionality. Of particular concern are copper and zinc (Mills and Williamson, 2008; Auckland Council, 2013; Auckland Council, 2017) and fine sediments (<63 μm), which accumulate in benthic zones of estuaries. Concentrations of copper and zinc in urban runoff often exceed water quality criteria such as those of the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (Australian Government, 2018). The two most abundant sources of zinc are galvanised iron roofs and road runoff. Common sources of copper are atmospheric deposition, building material, marine antifouling paint and vehicle brake pads (Auckland Council, 2013). The Auckland Unitary Plan (Auckland Council, 2016a) responds by setting design effluent quality requirements of $\text{T Cu} < 10\ \mu\text{g/l}$ and $\text{T Zn} < 30\ \mu\text{g/l}$ that are known to be achievable through the use of stormwater treatment devices such as the raingardens common to WSD and also stormwater ponds. The percentage load reductions of suspended solids, total zinc and total copper within raingardens in Auckland, which vary with media permeability, range from 41% to 97% (Jayaratne et al., 2010). Internationally, as reviewed by Skorobogatov et al. (2020), the reduction of peak flows and the retention of metals and suspended solids by bioretention systems, has been successful, but the removal or capture of dissolved contaminants is variable and challenging.

The period 2013-16 saw the addition in Auckland of 813 ha of greenfield urban development (Hauraki Gulf Forum, 2017, p44). Most of the 400,000 new houses required over the next 30 years (Auckland Council, 2016a) will be within the small coastal catchments of the region, largely on mobile clay soils vulnerable to runoff with attached contaminants, many of which will be of vehicular or construction origin. These contaminants include the zinc and copper (Gunawardana et al., 2014) which are accumulating in Auckland's waterways. The Auckland Unitary Plan (Auckland Council, 2016a) provides for 15,000 ha of new urban development of rural land (all of which drains to the coast). Evidence is needed of methods that will enable urban expansion or intensification while minimising further aquatic ecosystem degradation.

Water Sensitive Design (WSD) (Lewis et al., 2015) is recommended by the Auckland Council as its preferred approach to sustainable stormwater management. The retention and treatment of urban stormwater as part of WSD will moderate urbanisation disturbances to hydrological regimes such as reduced baseflow, elevated peak flow and reduced hydrological response time. It will also reduce the generation and discharge of a range of stormwater contaminants from new residential developments. Auckland also has mandatory requirements (Auckland Council, 2016b) for the detention and treatment of fine sediments from urban earthworks, although these preceded WSD.

2.2. *The use of bioindicators*

Causes of degradation in large receiving water environments such as the Hauraki Gulf are complex and multifaceted. Chemical and physical indicators, when used to measure receiving water effects, ignore the related biological consequences. Biological indicators of effects need to be used to trace the ecosystem health of streams (Collier et al., 2014) that discharge into the Gulf. Locally resident ecosystem components (such as benthic macroinvertebrates) can be and are being used (Collier et al., 2014) as bio-indicators to ensure that the responses measured result from exposure to local pressures, such as land use, over an extended period of time. Macroinvertebrates remain in one place for long periods of time, and are cumulatively influenced by physical and chemical stream conditions over that time. (Instantaneous water quality measurements by comparison measure only one specific parameter at certain moments in time.) The biotic indices calculated by using bioindicator species are geographically specific. In Australasia ecologists in research institutions and networks are using bioindicators, for this purpose, and specifically using macroinvertebrate indices appropriate to location and waterway type. Australian examples of such institutes include the CRC Water Sensitive Cities (2019); the Waterway Ecosystem Research Group at the University of Melbourne (Walsh and Webb, 2013; Walsh et al., 2016);

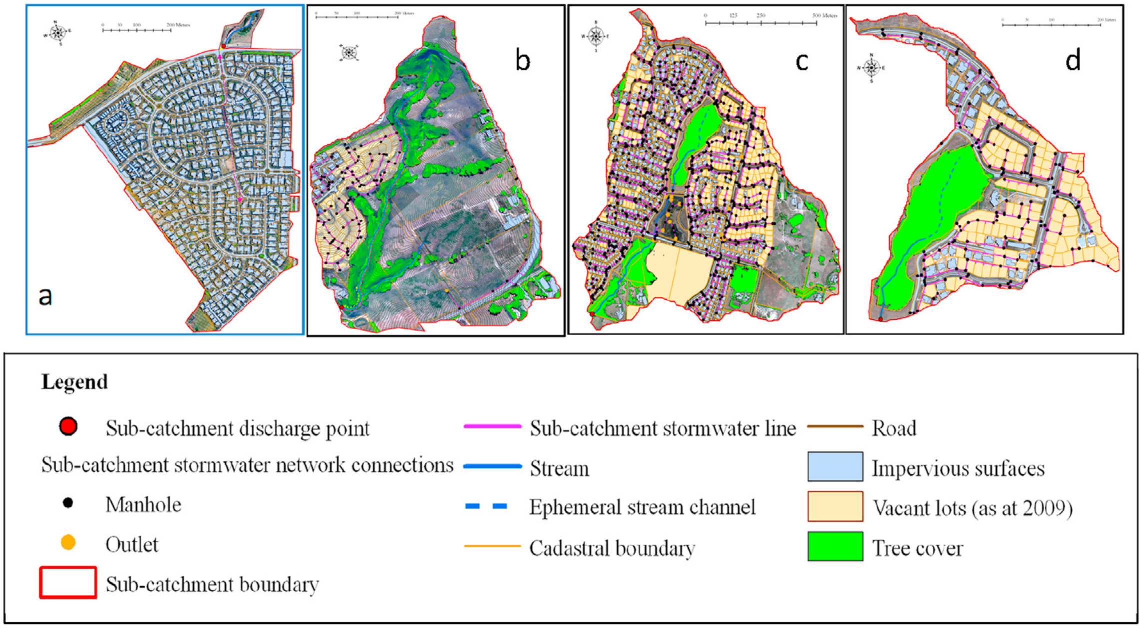

Figure 2. Land cover of urban sub-catchments as at 2009–10. Point View a; Jeffs Sullivans b; Jeffs Lower Norwood c; Jeffs Upper Norwood d. Note c encompasses d. Over the period 2011-20 houses have been built on all vacant lots of b-d, and subdivision has been extended throughout the South-Eastern side of b. Concept: Marjorie van Roon, Graphic design: Tamsin Rigold

and collaborative researchers in Perth (Gwinn et al., 2018). Walsh et al. (2015) reported on the as yet little-changed biological and water quality responses of a comparative catchment experiment where they retrofitted 289 stormwater retention systems to the treatment catchment. New Zealand examples include research by national and regional level government agencies, such as the Auckland Council (Neale et al., 2017) (including the RIMU group) and Greater Wellington Regional Council (Warr et al., 2009), all of which have used Macroinvertebrate Community monitoring as described below.

2.3. Monitoring sites of comparative sub-catchments

This research is based on a comparison of examples of 'traditional/conventional residential urban form and development' against 'WSD residential urban form and development'. The best available examples were selected at the time of establishing the paired sub-catchment comparison. This research began in 2004. Available examples of WSD when the investigation began, varied in the degree/promise of implementation of the desirable urban design, spatial planning and engineering characteristics that are the 'building blocks' of WSD. In 2004 in Auckland, no WSD examples were available where all WSD 'building blocks' had been implemented, construction was complete and residential landuse was in a stable post-construction phase. Most examples of WSD in 2004, were in the early stages of construction according to an approved plan that included some WSD characteristics. Development in the WSD sub-catchments has generally unfolded over the period 2004–2019 according to consented plans with minor deviations. Comparative examples of conventional development were more readily available and typically where landuse was more stable and in a post-construction phase.

Headwater sub-catchments, adjoining a common ridgeline, were chosen and are ideal for such comparisons for the following reasons: they receive no surface water or contaminant inputs from land use areas upstream beyond the experimental area; they also share a prior pastoral land use history and common biophysical characteristics such as moderate to steep slopes, clay soils, native vegetation species (e.g. Taraire: *Beilschmiedia tarairi*), climate and stream types (60% are seasonally intermittent). Thus the number of variables in the comparison of sub-catchments was minimised. Past agricultural land use may similarly influence water quality in all comparative sub-catchments, particularly through the loss of plant nutrients to streams during urban earthworks.

Two comparative clusters of headwater sub-catchments were established each with several WSD sub-catchments, and at least one conventional sub-catchment. The sub-catchments that are shown in Figures 2 and 3 represent two different densities of residential development, that is, urban and countryside living respectively. The urban cluster contains four sub-catchments, three of which exhibit varying degrees of WSD or LIUDD compliance, including existing mature riparian forest. Those three sub-catchments are Jeffs Upper Norwood, Jeffs Lower Norwood and Jeffs Sullivans. The fourth (Point View) has a conventional development form and infrastructure. The countryside living cluster contains six sub-catchments, four treatment sub-catchments which exhibit WSD/LIUDD (Regis Figure 3b), and two control sub-catchments; one of which is conventional but partially re-vegetated (Tiffany Figure 3a) and the second (Redoubt Figure 3c) is in a conventional development form.

The occurrences of the 'building blocks' (BB) of LIUDD and WSD practices[1] within case study sub-catchments are shown in Table 1. Each BB within Table 1 has been assigned a number for reference in the text below. Further details of the characteristics of each sub-catchment are explained here.

Particular features of note (Table 1) in the urban sub-catchments that may influence stream ecological health outcomes are as follows. The Jeffs Norwood Upper and Lower, and the Jeffs Sullivans adjacent sub-catchments conform to the idealised LIUDD land cover configuration with forest and stream protection, optimised open space, and adjacent house clustering. The wide riparian native forests are dominated by a mature Taraire (*Beilschmiedia tarairi*) canopy and a re-established understorey following historical cattle grazing. The streams are mostly un-piped and unmodified with the exception of a section where the Norwood stream was in 2003 diverted to a channel along the valley slope. This enabled the construction in the valley floor of a large offline stormwater pond with peripheral vegetation and overflow in the upstream section of the Jeffs Norwood Lower reach (see Figure 4). The Jeffs

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[1] Note that the acronym LID is not used here as the practices described by the different acronyms cannot be equated.

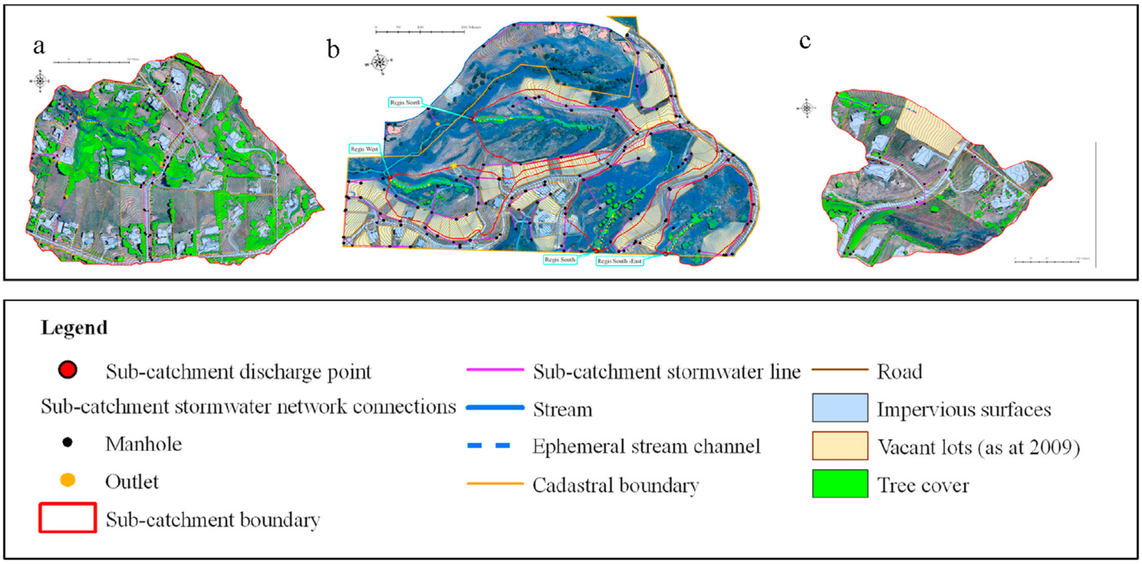

Figure 3. Land cover of countryside living sub-catchments as at 2009–10. Tiffany a; Regis b including Regis South, Regis South-East, Regis North and Regis West as marked; Redoubt c. Over the period 2011-20 houses have been built on all vacant lots of b and c. Forests planted in 2004 have continued to mature throughout all Regis stream valleys. Concept: Marjorie van Roon, Graphic design: Tamsin Rigold.

Norwood Upper sampling site is in the forest immediately upstream from this pond. Treated surface overflow from the large pond discharges to the natural stream path downstream of the pond and flows through the Jeffs Lower Norwood sampling reach.

Subdivision and house construction (500 m^2 lots) in the Jeffs Norwood Upper sub-catchment was completed around 2005 followed by the Jeffs Norwood Lower sub-catchment construction of both similar and higher density town-housing and a school. Subdivision and house construction in the Jeffs Sullivans sub-catchment began around 2005 and was ongoing in the upper sub-catchment in 2020. All subdivisions are serviced by regional sewerage systems. There is no stormwater treatment on private residential lots and no bioretention or infiltration devices in the streetscape. The absence of these devices may mean that under some definitions of 'water sensitive' or 'low impact' this development would not qualify. It was chosen for its critical urban form and implementation of most WSD 'building blocks'.

The control sub-catchment for this cluster of urban sub-catchments is Point View (Figure 2a), which is in the adjacent neighbourhood. This is a conventionally designed and constructed complete headwater sub-catchment neighbourhood, with piped stream, no stormwater treatment, no detention devices, the municipal sewerage network and offsite regional treatment, stand-alone houses on 500m^2 lots, scattered ornamental exotic street trees, and none of the following: parks, forest corridors, schools or commercial areas.

The countryside living cluster shown in Figure 3 and Table 1, includes four WSD sub-catchments (Regis, Figures 3b and 5), and two control sub-catchments (Redoubt and Tiffany). All of these sub-catchments, like those of the adjacent Jeffs urban cluster, occur along the headwater ridgeline of the Flat Bush/Otara Stream Catchment. The countryside living zone requires a mean lot size of 5000 m^2 if divided equally and geometrically between lots, as it is in the Redoubt and Tiffany controls. The Redoubt sub-catchment that was chosen in 2004 as a control, initially had a land use typical of conventional countryside residential zones in New Zealand, being divided into equal size lots, no additional open space, septic tanks with soakage fields and no riparian vegetation. Over the decade that followed neighbouring residents planted native trees and shrubs in a narrow riparian strip on both sides of the incised, and latterly shaded, stream.

The Tiffany sub-catchment has some of the building block characteristics of WSD, in that the residents have cooperated to retain and interplant the native forest riparian corridor of the stream which flows through the downslope backyard of every subdivided lot. However, the stream is subject to untreated stormwater and the overland flow of septic tank effluent seepage. Tiffany was retained within the cluster as a control to indicate the degree to which these non-conforming characteristics influence stream ecological quality.

The four Regis sub-catchments conform to WSD/LIUDD, having comprehensive onsite separated stormwater and sewage treatment, ample revegetation, and no other effluent inputs. The sub-catchments lie back to back meeting at a common secondary ridgeline. The Regis land was subdivided unequally in 2004–5, clustering the lots and reserving 60% of the development area for privately owned common open space and infrastructure. The urban form of each Regis sub-catchment includes primary roads along ridgelines with house lots adjacent, and a natural stream bed and small wetland surrounded by a wide gully revegetated in predominantly native trees and wetland plants. The immaturity of the forests planted in 2004 is noteworthy when considering stream ecological health. A total of 66 building platforms were sequentially excavated and houses were constructed between 2008 and 2016. A sewage treatment plant situated in Regis West services all houses in all the Regis sub-catchments, and the treated effluent is dispersed within the forest of Regis West only. Every house has a downslope backyard raingarden, any overflow from which is also dispersed to the forest slopes. These raingardens collect stormwater from roofs and paved surfaces on individual lots. Stormwater from the typically steep but predominantly narrow streets is collected and trickle irrigated to sub-catchment forests.

2.4. Stream sampling, sample processing and data analysis methods for bioindicators

Samples from streams were collected by hand net, and analysed using standard methods for the New Zealand Macroinvertebrate Community Index (MCI) (MfE, 2007), modified for 'soft-bottom' streams (MCIsb) (Stark and Maxted, 2004). The hand net has a mesh size of 0.5 m.m., which is a standard mesh size used for all comparative MCI determinations in New Zealand's soft-bottomed streams. The 10 stream sites were sampled in early summer each year during two periods, that is 2005–2008 inclusive, and 2012–2016 inclusive. Sampling, which was concurrent for conventional and WSD sub-catchments, was undertaken using Protocol C2 (Stark et al., 2001). The Stark et al. (2001; Stark and Maxted, 2004) sample collection method was followed precisely.

Table 1. Sampling sites defined by WSD/LIUDD building blocks complied with (✓) or not (X). Point View, Redoubt and Tiffany are controls. Note: 'Septic tanks' and 'urban density' are not LIUDD building blocks and stormwater ponds pre-date LIUDD but they are identified here because of their influence on ecology.

Building block reference number	-	1	2	3	4	5	6	7	8	9	10	11	12	-
Building blocks (BB) of LIUDD/WSD Note: BBs are numbered → Catchment ↓	Urban density note: not BB	Catchment as design unit	Design connects nature	Riparian tree cover as % of catchment	Maximise vegetation	Design to retain topography	Streams natural, not piped	Houses clustered	Minimise impervious surfaces	Separate sewerage & stormwater networks	Stormwater biofiltration	Stormwater ponds	Rainwater harvesting	Septic tanks note: not BB
Norwood Upper 14.5 ha	med	✓	✓	40	✓	✓	✓	✓	X	✓	X	X	X	X
Norwood Lower 90 ha	med	✓	✓	11	✓	✓	✓	✓	X	✓	X	✓	X	X
Sullivans 34 ha	med	✓	✓	22	✓	✓	✓	✓	X	✓	X	✓	X	X
Point View 39 ha	med	X	X	3	X	X	X	X	X	✓	X	X	X	X
Regis North 5 ha	low	✓	✓	60	✓	✓	✓	✓	✓	✓	✓	X	X	X
Regis South 5 ha	low	✓	✓	60	✓	✓	✓	✓	✓	✓	✓	X	X	X
Regis S. East 4 ha	low	✓	✓	60	✓	✓	✓	✓	✓	✓	✓	X	X	X
Regis West 4 ha	low	✓	✓	60	✓	✓	✓	✓	✓	✓	✓	X	X	X
Redoubt 6.5 ha	low	X	X	10	X	X	50%	X	X	X	X	X	X	✓
Tiffany 24 ha	low	✓	✓	30	✓	✓	✓	✓	X	X	X	X	X	✓

Figure 4. Jeffs Upper Norwood sub-catchment is shown in the background with its mature riparian forest and clustered housing. In the foreground are the stormwater pond and revegetation of the upper part of the Jeffs Lower Norwood sub-catchment.

Figure 5. Regis countryside residential development as at 2020 with completed revegetation, but before all houses were constructed.

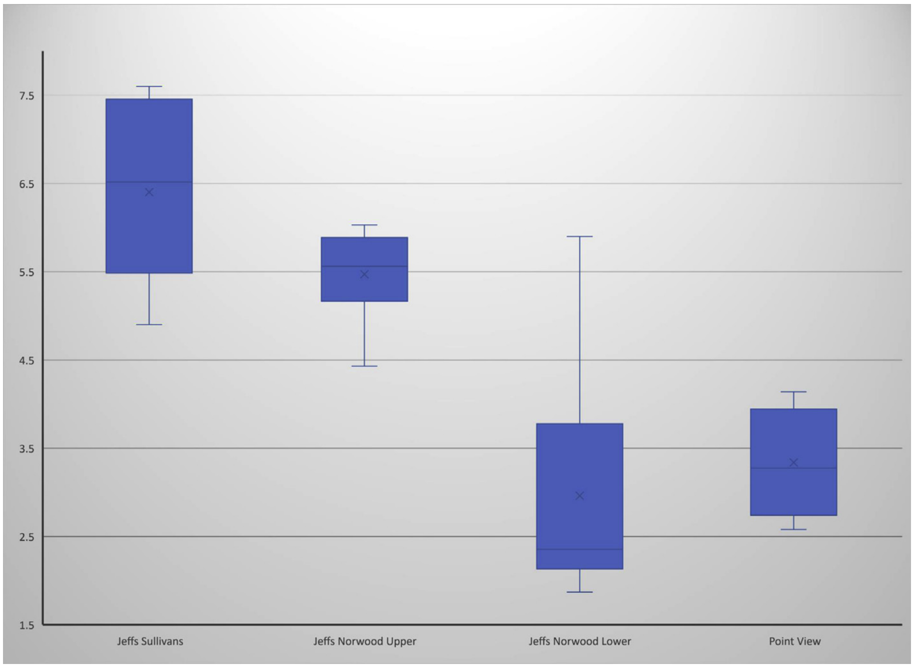

Figure 6. Box and whisker plot showing the results for the distribution of Semi-Quantitative Macroninvertebrate Community Index (for soft bottomed streams) in results for comparative sub-catchments for the period 2005–2016. The sub-catchments are zoned urban for residential use. Point View is the control sub-catchment with conventional development.

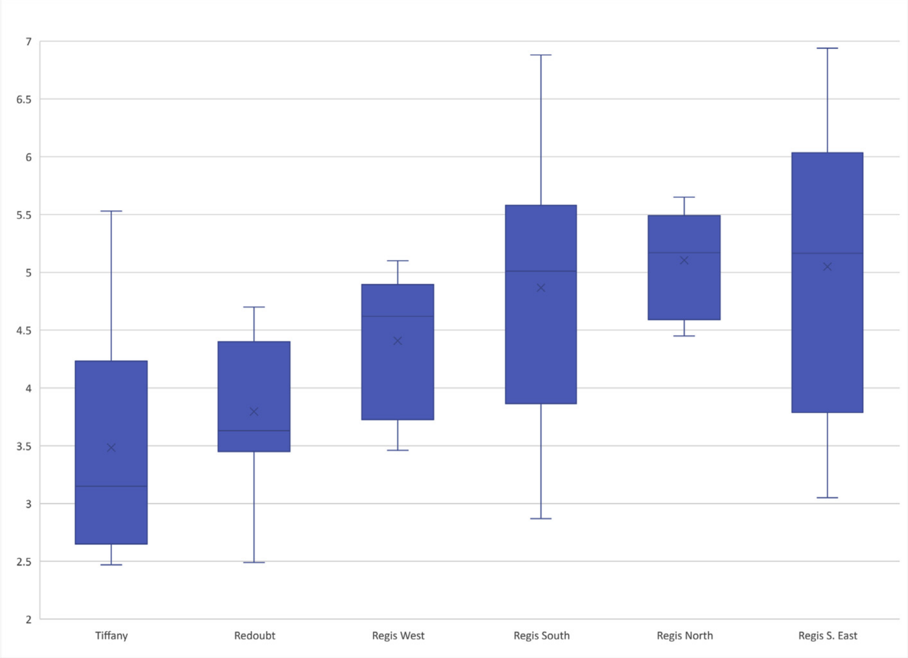

Figure 7. Box and whisker plot showing the results for the distribution of Semi-quantitative Macroninvertebrate Community Index (for soft bottomed streams) in comparative sub-catchments for the period 2005–2016. The sub-catchments are zoned countryside living for residential use. Redoubt and Tiffany are the control sub-catchments.

Macroinvertebrates were identified, abundances recorded, and taxonomic richness and community composition were assessed. Species composition was observed, and the occurrence and dominance of species, particularly indicators such as Ephemeroptera, Plecoptera and Tricoptera (EPT), freshwater crayfish and fish were noted. The semi-quantitative Macroinvertebrate Community Indices for soft bottom streams (SQMCIsb) were calculated using coded abundances (assigned to the Rare, Common, Abundant, Very Abundant and Very Very Abundant classes), and the formula presented by Stark and Maxted (2004 p.9). SQMCIsb indices range from 0 to 10. Sites are assigned to quality classes in the following categories: excellent >6.0; good 5.0–6.0; Fair 4.0–5.0; poor <4.0 (Stark and Maxted, 2007).

The Significance ($p < 0.05$) of differences between the means for SQMCIsb for paired sites with differing degrees of WSD were determined (Vasavada, 2016) using the Scheffé, Bonferroni and Holm multiple comparison tests (Holm, 1979), including a two-way Analysis of Variance (ANOVA) and the Tukey HSD test, which was used for a more detailed analysis of significance for every pair of sites. These post-hoc tests

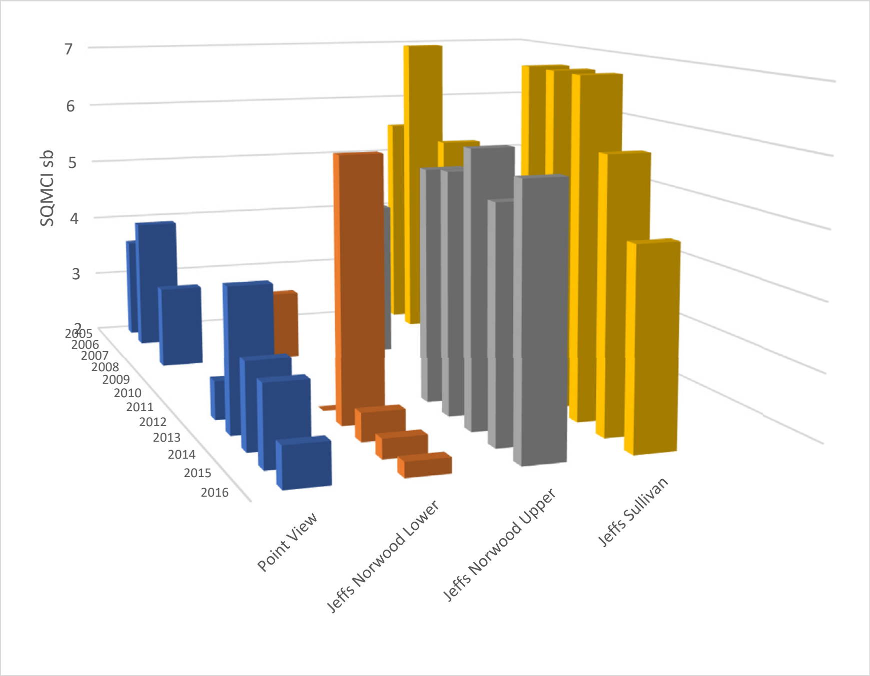

Figure 8. Semi-quantitative Macroinvertebrate Community Index for the soft bottomed streams in the urban zoned residential sub-catchments between 2005 and 2016.

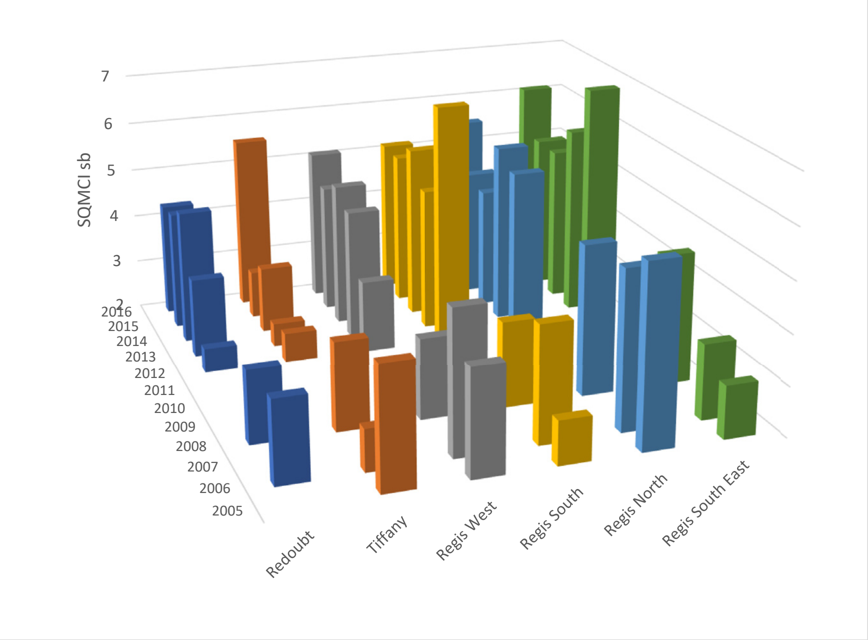

Figure 9. Semi-quantitative Macroinvertebrate Community Index for the soft bottomed streams in the countyside residential subcatchments between 2005 and 2016.

Table 2. Significant ($p < 0.05$) differences between the SQMCIsb for paired urban sites. Building blocks (BBs) for each site are shown and described in Table 1.

Site 1 (urban)	Site 2 (urban)	P value
Point View (BB 9)	Jeffs Upper Norwood (BBs 1–7, 9)	0.004
Point View (BB 9)	Jeffs Sullivans (BBs 1–7, 9, 11)	0.001
Jeffs Lower Norwood (BBs 1–7, 9, 11).	Jeffs Upper Norwood (BBs 1–7, 9)	0.001
Jeffs Lower Norwood (BBs 1–7, 9, 11).	Jeffs Sullivans (BBs 1–7, 9, 11)	0.001

Table 3. Significant ($p < 0.05$) differences between the SQMCIsb for paired countryside living sites. Building blocks (BBs) for each site are shown above and in Table 1.

Site 1 (countryside)	Site 2 (countryside)	P value
Tiffany (BBs 1–7)	Regis North (BBs 1–10)	0.027

Table 4. Significant ($p < 0.05$) differences between the SQMCIsb for countryside living (sites 1) versus healthier urban (sites 2). Building blocks (BBs) for each site are shown above and in Table 1.

Site 1 (countryside)	Site 2 (urban)	P value
Tiffany (BBs 1–7)	Jeffs Upper Norwood (BBs 1–7, 9)	0.010
Tiffany (BBs 1–7)	Jeffs Sullivans (BBs 1–7, 9, 11)	0.001
Redoubt (BBs 3, 6)	Jeffs Sullivans (BBs 1–7, 9, 11)	0.001
Regis West (BBs 1–10)	Jeffs Sullivans (BBs 1–7, 9, 11)	0.004
Regis South (BBs 1–10)	Jeffs Sullivans (BBs 1–7, 9, 11)	0.045

Table 5. Significant ($p < 0.05$) differences between the SQMCIsb for two sewage free urban streams versus sewage free countryside living sites with different stormwater treatment methods. Building blocks (BBs) for each site are shown above and in Table 1.

Site 1 (urban)	Site 2 (countryside)	P value
Point View (BB 9)	Regis North (BBs 1–10)	0.011
Point View (BB 9)	Regis South East (BBs 1–10)	0.023
Jeffs Lower Norwood (BBs 1–7, 9, 11).	Regis North (BBs 1–10)	0.003
Jeffs Lower Norwood (BBs 1–7, 9, 11).	Regis South (BBs 1–10)	0.023
Jeffs Lower Norwood (BBs 1–7, 9, 11).	Regis South East (BBs 1–10)	0.006

identify which of the pairs of treatments (sub-catchments) are significantly different from each other (Wright, 1992).

3. Results

Semi-quantitative Macroinvertebrate Community Indices for soft-bottomed streams (SQMCIsb) for all sub-catchments for the period 2005–2016 are shown in Figures 6, 7, 8, and 9. Results for the urban sub-catchment streams are separated into two pairs indicative of near reference stream quality (Jeffs Upper Norwood and Jeffs Sullivans), versus ecologically degraded stream quality (Jeffs Lower Norwood and Point View sub-catchments). The degree to which the implementation of the WSD building blocks contributes to this contrast will be discussed below.

The range of SQMCIsb indicating stream health in countryside living sub-catchments shows less divergence between treatment sites (Regis sub-catchments: BBs 1–10 inclusive), and control sites (Tiffany: BBs 1–7 and Redoubt: BBs 3, 6) relative to the urban streams. All Flat Bush countryside headwater sub-catchments are encouraged by the Auckland Council to revegetate riparian corridors, and this has been progressing since 2002 for the Redoubt, and particularly the Tiffany, control sub-catchments. Land use and inadequately treated discharges have been constant in these control sub-catchments during the monitoring period. This is in contrast to the Regis sub-catchments, where revegetation and house construction (the latter completed in 2016), have been ongoing, and all indirect discharges have been increasing in volume although they are well treated and dispersed.

A summary of all significant ($p < 0.05$) differences between the SQMCIsb for paired sites is shown in Tables 2, 3, 4, and 5. The difference between the SQMCIsb means of all other paired sites were not significant. The statistical analysis to determine the significance of the differences between the means of SQMCIsb for the groups of all sites are presented in the tables of the separate Appendix file on the Heliyon website.

Within the urban cluster there is a clear and very significant difference (Table 2) in stream health, as indicated by SQMCIsb, between treatment sub-catchments (BBs 1–7, 9), and the control sub-catchment Point View (BB 9), barring one exception, that is Jeffs Lower Norwood.

The only significant difference between countryside living sites (see Table 3) of SQMCIsb, was for Tiffany (mean 3.5), when compared with Regis North (mean 5.2).

Significant differences in SQMCIsb between most of the countryside and two of the urban catchments (Table 4) suggests the higher residential densities present in urban catchments do not always result in more degraded stream ecosystems.

The two urban streams are significantly superior in terms of SQMCIsb. The two urban sub-catchments have no sewage effluent inputs and they have more mature riparian forests in contrast to the upper four countryside sub-catchments in Table 4. Note that the difference between Regis South and Jeffs Sullivans has a P value close to 0.05 and Regis South is the only countryside sub-catchment in Table 4 that has no sewage effluent discharge.

The lowest urban SQMCIsb values were recorded for the Point View and Jeffs Lower Norwood streams. In Table 5 significant differences in SQMCIsb values are presented for these two urban streams and all Regis countryside living streams, except Regis West. Regis West treats and disperses the treated sewage effluent for all Regis sub-catchments.

4. Discussion

There are and were severe difficulties of locating and adapting existing urban development sites in order to monitor them as suitable experimental research sites. In 2004 when the sites studied were first selected, practices of LID and LIUDD were in their infancy in New Zealand. (WSD is a later name adopted by Auckland Council.) Demonstration examples showed the partial implementation of desirable characteristics (LIUDD building blocks, see Table 1). This partial implementation continues to the present. It has been necessary to accept and monitor what is available by choosing those examples that include the most important characteristics.

While recognising the above limitations, the three research questions set in the introduction to this article will be responded to.

Question 1) *Does the simultaneous implementation, within a greenfield residential development, of 'building block' methods common to 'Water Sensitive Design', result in healthier stream ecosystems than those typical of streams in conventionally developed catchments where these Water Sensitive Design 'building blocks' are not applied?*

Question 2) *Is there a coincidence in some sub-catchments of aquatic ecosystem degradation and the failure to apply all the Water Sensitive Design 'building block' methods, or to apply those methods inappropriately?*

4.1. Question 1 discussion for countryside living sub-catchments

The countryside residential catchments of Regis Park implemented almost all desirable 'water sensitive' characteristics (BBs 1–10 inclusive). All Flat Bush countryside headwater sub-catchments, whether 'water sensitive' or 'conventional', have been encouraged by Auckland Council to revegetate riparian corridors, and this has been progressing since 2002. Apart from this example, in, the Redoubt, and particularly the Tiffany, control sub-catchments, land uses and inadequately treated discharges have been a constant feature in these control sub-catchments during the monitoring period. By contrast within the Regis 'water sensitive' sub-catchments revegetation and house construction, (the latter completed in 2016), have been ongoing, and all indirect discharges have been increasing in volume, although they are well treated and dispersed. The SQMCIsb for Tiffany was the only one significantly lower than that of Regis North (see Table 3 and Appendix Tukey test results). The land uses and the spatial layout are similar, but Tiffany has a more mature forest, and Regis North, like all but one of the Regis streams, has no discharge of either sewage effluent, or untreated stormwater. One or both of these discharges are the likely causes of the degradation of the Tiffany stream.

As the recently completed Regis development complies with almost all requirements for WSD/LIUDD, and land use at Regis is still maturing and stabilising, the research monitoring needs to continue to determine the outcomes of the Regis' post construction stable state relative to the control sites. The significance of the differences between all Regis streams (rather than just Regis North) and the control streams may become apparent over time.

4.2. Questions 1 and 2 discussion for urban sub-catchments

As noted earlier, there was only partial implementation of the 'building blocks' of LIUDD/WSD in the urban cluster. There were no at-source control stormwater biofiltration devices constructed in lots or streetscapes, and in the past it has been the presence of these devices that has distinguished WSD from other practices. Despite this, the aquatic ecosystem appears to be significantly healthier than that of either the conventionally urbanised catchment, Point View (BB 9 only) and that of the sub-catchment downstream of the Jeffs Norwood stormwater pond.

The near-natural streams of Jeffs Upper Norwood and Jeffs Sullivans, protected by very mature indigenous forest, have had good to excellent ecosystem quality throughout the monitoring period. The stormwater entering the Jeffs Upper Norwood stream section receives no treatment other than natural filtration by the forest and a natural wetland in the stream path. However, the stormwater pond, immediately downstream of Jeffs Upper Norwood, receives most of the stormwater from the Jeffs Upper Norwood catchment housing estate, including roads. This makes the absence of at-source stormwater treatment devices around houses and streets in the Jeffs Upper Norwood sub-catchment, irrelevant in terms of the ecological health of the stream at the discharge point.

The Jeffs Sullivans sub-catchment (BBs 1–7, 9, 11), by contrast to the Jeffs Upper Norwood sub-catchment (BBs 1–7, 9), has several offline stormwater ponds upslope of the riparian forest corridor with level spreader overflows that trickle down forested valley slopes to the stream. Prior to 2015, the offline ponds of Jeffs Sullivans do not appear to have degraded the Jeffs Sullivans stream, despite partial urbanisation of the sub-catchment, (and have not degraded to the extent that is seen in the significantly different Jeffs Lower Norwood below the direct piped stormwater pond overflow). Adverse thermal effects upon the stream organisms of pond discharges in Auckland have been researched and confirmed (see Young et al., 2013; Quinn et al., 1994). It has been suggested (Winston et al., 2011 cited in Young et al., 2013), that the level spreader method of pond overflow down forested valley slopes may be sufficient to result in the adequate cooling of pond water.

Up until the creation in 2015 of a road cutting across the stream and forest at mid-catchment, Jeffs Sullivans stream, SQMCIsb, was not significantly different to that of Jeffs Upper Norwood, stream. It was significantly healthier as indicated by SQMCIsb (Table 2) than Jeffs Lower Norwood stream (both streams BBs 1–7, 9, 11). A decline, not recorded over the previous decade, in the SQMCIsb for Jeffs Sullivans, was observed the following year. Longer-term monitoring will be required to determine whether this is a significantly different change, or due to a one-off sampling issue.

The Jeffs Lower Norwood stream reach and riparian corridor, subjected to no onsite physical alteration during the development period, has the same ideal forest context as other Jeffs sub-catchments (BBs 1–7, 9). However, this stream reach is the recipient upstream, of both the overflow from the large in-valley stormwater pond (BB 11), (with peripheral revegetation), and the stream diverted around the pond. The monitoring results (Figure 6), and the tests for significant differences (Appendix – Tukey test), indicate that this stream reach is not significantly healthier now than the piped stream of the control Point View (BBs 9), which has no stormwater treatment, and lacks all WSD ‘building block’ features. Visual observation of the Jeffs Lower Norwood stream reach over the last 1.5 decades indicates increased ponding, higher water levels, and a sluggish flow not seen in 2005. The pond discharge has negated the stream ecological health gains that were expected from implementing BBs 1–7 and 9.

Some aquatic ecosystem effects of the stormwater pond overflow into Jeffs Lower Norwood that are deserving of further investigation include habitat changes due to altered flow, benthic sediment accumulation, contaminant discharge, and thermal effects. The confirmation by Young et al. (2013) of the adverse thermal effects of pond discharges in Auckland means that the use of ponds is generally no longer supported due to the recognised poor ecological outcomes. In addition to elevated discharge temperatures there are risks of eutrophication and the tendency to remobilise sediments. The preference now is to design and provide fully vegetated wetlands, which do not have the same issues.

Question 3) *Do countryside living sub-catchments (with a lot size averaged over the site of 5000m^2), always have healthier stream ecosystems than urban sub-catchments (with a lot size of 500m^2)? How does the implementation of certain building blocks influence whether countryside neighbourhoods have healthier stream ecosystems than the stream ecosystems of urban neighbourhoods?*

4.3. *Question 3 discussion – an introduction*

The research reported in this article was designed to primarily demonstrate differences in aquatic ecosystem outcomes within, not between, two different densities of residential developments. However, the Tukey test undertaken here, and the Analysis of Variance (ANOVA), show significant differences between some pairs of sub-catchments with differing housing densities. To what degree, therefore, is housing density influential, if all the other LIUDD ‘building blocks’ are in place for achieving healthy streams? Is there evidence that it may be possible for higher density housing and healthy streams to coexist?

4.4. *Question 3 discussion – positive evidence*

One comparison of urban and countryside sub-catchments provides some evidence. The mean values for SQMCIsb (Figures 6 and 7) for the Jeffs Upper Norwood urban stream (5.5), and for the Jeffs Sullivans urban stream (6.5), are both significantly higher than the means for almost all the Regis countryside living streams (4.5–5.2). All of these sub-catchments have either stormwater diversion or stormwater treatment near to source with trickle irrigation through forest to the stream, and no sewage effluent discharges. The urban sub-catchments have a higher housing density on smaller lots than the Regis sub-catchments.

4.5. *Question 3 discussion – another comparison – contrary evidence explained*

Another comparison of urban and countryside sub-catchments gave contrary results in relation to question 3 above. Table 5 presents significance of differences of SQMCIsb values for the two lowest scoring urban sub-catchments with values for all Regis sub-catchments excluding Regis West. There are no sewage effluent discharges to any of the streams compared in Table 5. Stormwater in the Regis sub-catchments included in Table 5 is all treated using WSD methods, whereas stormwater in the two urban sub-catchments is either discharged directly to streams or via stormwater pond overflow with no trickle irrigation through forest. SQMCIsb values, indicative of stream ecosystem health, for the Regis streams are significantly higher than those for the two urban streams. The urban sub-catchments have both higher housing densities and poorer or no stormwater treatment than the Regis sub-catchments. Previous analysis of stream health at these two urban sites makes it probable that degradation is caused by stormwater discharges rather than due to higher density housing.

An observation unrelated to the set research questions is that, more than half of the streams monitored for this research are intermittent, and the ecosystems in these streams are at least as healthy, as indicated by SQMCIsb, as the perennial streams, even during the driest summer season. This adds to Auckland Regional Council (2006) research that supports equal protection and riparian corridor revegetation for intermittent streams and perennial streams during urbanisation.

5. Conclusions

For two of the three greenfield residential urban case studies examined, the simultaneous implementation of most of the ‘building block’ methods common to ‘Water Sensitive Design’ resulted in significantly healthier stream ecosystems than those of specific case study streams in a conventionally developed catchment where these building blocks have not been applied.

The differences, as indicated by SQMCIsb, in stream ecosystem health in Water Sensitive Design sub-catchments versus conventional development sub-catchments are greater and more statistically significant at urban densities compared with countryside living densities. However, this may change as developments mature and stabilise.

Countryside living sub-catchments (countryside living 5000 m^2 lots), do not always have healthier stream ecosystems than urban sub-catchments (urban 500 m^2 lots). Regardless of residential density, the failure to apply all ‘building block’ methods in some case study catchments demonstrates significantly different and degraded aquatic ecosystem health as measured by macroinvertebrate community indices. Even where most building block methods were applied, stream ecosystem degradation occurred in the absence of at-source stormwater treatment, or in the presence of septic tanks and online stormwater pond overflows.

If stormwater ponds are installed within urban residential catchments, priority should be given to offline ponds on valley slopes with overland (level spreader) trickle discharge, rather than online ponds (even with stream diversion) with direct overflow discharge to streams. Care is needed to ensure that stormwater devices, installed for hydrological or chemical improvements, do not create ecological harm that may go undetected. As noted above the Auckland Council has changed its policy on the location and function of ponds because of the adverse ecological effects.

Riparian forests are essential for stream health regardless of urban density, but they by themselves are not a guarantee of aquatic ecosystem health. Hydrological, physiochemical, and effluent discharge conditions must also be appropriate. The presence of excellent riparian forests at Jeffs Lower Norwood and Tiffany are insufficient when accompanied, respectively, by stormwater and/or septic tank effluent discharges, for the creation of a suitable instream habitat for most sensitive macroinvertebrate species.

Equal protection and riparian corridor revegetation for intermittent streams and perennial streams should be ensured during urbanisation. This research provides evidence that intermittent and perennial streams are equally valuable for stream invertebrate biodiversity.

This research demonstrates the difficulties of unravelling the multiple causes of the degradation of the health of stream ecosystems health degradation during urbanisation. A wide mix of priority conditions need to be present if the health of streams is to be maintained. However, this research adds insights into what those necessary conditions or 'building blocks' of Water Sensitive Design need to be. Urban planners and urban designers could provide leadership in standardising the urban form of greenfield and brownfield residential developments of all densities to achieve these outcomes.

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Author contribution statement

Marjorie Ruth van Roon: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data will be made available on request.

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The authors declare no conflict of interest.

Additional information

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