POINTING THE WAY TO REDUCING STORMWATER IMPACTS ON URBAN STREAMS

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ABSTRACT

Traditionally, urbanization results in increased areas of impervious surface that radically alter the hydrological regime. Urban development also leads to a loss of stream channels and associated aquatic and riparian habitat through piping and lining of channels to improve hydraulic efficiency. Four catchments representative of different urban and peri urban land covers in Waitakere City are being studied to quantify the impacts of urbanization and evaluate the benefits of improved stormwater management practices. This paper assesses the impacts of urbanization, and in particular catchment imperviousness, on streamflow regimes and aquatic ecosystem health.

The study confirms that increased areas of impervious surface and man-made drainage networks have increased storm discharges and reduced the sustainability of baseflows. Degraded water quality and reduced aquatic biodiversity of urban streams are also shown to be directly related to the percentage impervious cover of the study catchments. This suggests that although degradation of the urban environment is often observed in riparian margins, and in particular within the stream channel, the root cause of this problem is the modification of the hydrological cycle through construction of impervious surfaces, stormwater drainage and the increased availability of contaminants (i.e. the root cause is land manegment). This points to the need for truly integrated catchment management, with practitioners adopting an ecosystems approach to urban design to ensure each component of the urban environment complements and supports the sustainability of the entire system.

KEYWORDS

urban, stormwater, impervious, impacts, planning, management

1 INTRODUCTION

Research over the past 30 years has clearly demonstrated and quantified the impacts of impervious surfaces on the hydrological responses of urban streams in terms of changes to both streamflow (Leopold, 1968) and water quality (Sartor and Boyd, 1972). These changes are largely attributed to the increased percentage of impervious surface that generate greater volumes of storm runoff (Scheuler, 1994). Risks of flooding from increased urban runoff are typically mitigated through the construction of hydraulically efficient drainage systems that convey stormwater to the nearest natural watercourse. A significant proportion of the urban impervious surface comprises roads that are also a source of contaminants from vehicle emissions. These largely comprise hydrocarbons and heavy metals (Duncan, 1999). Zinc, one of the more problematic heavy metals within the urban environment, is also derived from the deterioration of zinc coated or galvanized iron pipes, roofs and fences (Makepeace et al., 1995). These contaminants are transported to the receiving environment either in solution or attached to sediment particles, with finer sediments carrying a larger proportion of the contaminated load (Lau and Strenstrom, 2001; Wong et al., 1999).

Although the RMA (1991) provides a legislative framework for managing our environment, and engineers and planners increasingly talk of integrated catchment management, aquatic ecosystems within our towns and cities continue to be degraded through increased peak flows, less-sustained based flows, and elevated contaminant loads. Although not quantified, observations suggest that the total impervious surface is expanding through green field developments and within the existing built environment. Expanding imperviousness within the built environment, known as impervious creep, is linked to urban renewal, increased intensification or infilling of housing, and the construction of paved utility areas such as public and private parking and paving.

This paper assesses the impacts of urbanization, and in particular imperviousness, on streamflow regimes and aquatic ecosystem health within four catchments representative of different urban and peri-urban land covers in Waitakere City. Loss of aquatic habitat and degraded streams are related to catchment imperviousness, and development of stormwater drainage systems. The impacts of these traditional urban design and stormwater management practices within the study catchments highlight the need for a more integrated ecosystem-based approach to urban design. It is suggested that recent developments in urban design coupled with improved technologies for managing stormwater runoff provide an exciting opportunity to set new goals for our urban environments and to build a more sustainable future.

2 METHODOLOGY

Water quality and aquatic macroinverebrate data were collected at 17 sites throughout four catchments representative of urban and peri-urban land covers within the Titirangi – Glen Eden area of Waitakere City. Streamflow from three of these catchments has been monitored continuously since July 2002. These data are assessed to demonstrate the impacts of urbanization on streamflow and aquatic health. In particular, the assessment sets out to demonstrate that traditional urban design and stormwater management practices lead to significant changes to the water cycle and are key factors in the degradation of urban aquatic ecosystems. This points to the need for urban planners and engineers to adopt more integrated ecosystem-based approaches to urban design and stormwater management.

2.1 STUDY CATCHMENTS

The four study catchments comprise the Cantwell, Hibernia, Waikumete and Tangutu catchments that are 76, 146, 54, and 84 ha in area respectively (Figure 1). Topography of the study area comprises rolling hill country in the lower catchment areas and steeper hill country in catchment headwaters located on the slopes of the Waitakere Ranges. Mean annual rainfall increases with elevation from approximately 1100 mm near Glen Eden to more than 1700 mm near Titirangi township. Soils mainly comprise poorly drained clays, with those under urban land cover often being highly modified during urban construction. This typically results in reduced infiltration and water storage capacity, making them more prone to generating stormwater runoff.

The Cantwell catchment is representative of pasture and regenerating native bush land cover. The Tangutu catchment comprises low to medium density housing with significant sections of its channel now piped or

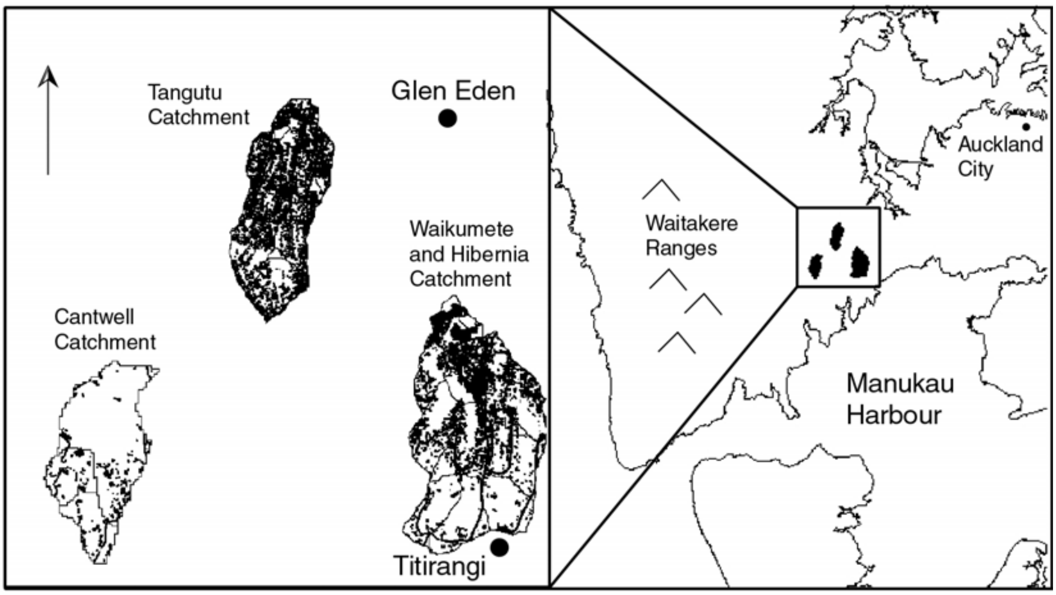

Figure 1 Location of the four study catchments, with impervious surfaces shaded

contained within lined channels. The Waikumete catchment comprises low- to medium-density housing in its lower reaches, low-density housing with regenerating bush riparian margins in its middle reaches, and regenerating native bush in its headwaters. Land cover of the Hibernia catchment is very similar to that of the

Waikumete catchment, with low- to medium-density housing in its lower reaches, low-density housing with extensive riparian buffers in its middle reaches, and regenerating native bush in its headwaters. The major difference between the Waikumete and Hibernia catchments is that stormwater from Titirangi township is piped directly into the headwaters of the Waikumete catchment, while the headwaters of the Hibernia catchment have minimal direct urban stormwater inflow. Also of note, the lower 0.4 km of the Hibernia catchment is piped, creating a potential barrier to native fish reaching the upper catchment.

Urban development within these catchments mainly comprises low- to medium-density residential housing that was initially developed in the lower catchment areas and along prominent ridgelines. Development is now moving up catchment, especially in the Tangutu catchment. Extensive public stormwater drainage networks have been constructed in the lower catchment areas where development is most intense, with stormwater discharged directly into the stream network. There are less intense drainage networks in the middle reaches of the developed catchments, discharging stormwater from roads directly into the stream system and minimal public drainage in the upper catchment areas. Stormwater systems within Waitakere City are designed to carry 1:5 year events, with larger events flowing overland, typically down roads to the nearest stream channel.

2.2 DATA COLLECTION

Digital elevation models were developed for each of the four study catchments to define their catchment boundaries and those of the 17 subcatchments surveyed for this study. Impervious surfaces within the subcatchments were mapped using Ikonos satellite imagery. Information on stormwater reticulation was supplied in GIS format by Waitakere City. The extent of stream channels lost to urban development is determined by comparing perennial channels mapped on NZMS 2 (Dept of Lands and Survey, 1942) with those identified in the catchments today.

Streamflows discharged from the Cantwell, Waikumete and Tangutu catchments have been continually monitored since July 2002. A survey of water quality, aquatic macroinvertebrates and fish was undertaken at the outlet of each subcatchment on 17 September 2002. The water samples were analyzed for total dissolved and suspended solids, nutrients, and heavy metals at Landcare Research's IANZ accredited water laboratory in Palmerston North. *In situ* field measurements of dissolved oxygen and water temperature were also recorded during this survey. However, only variations in total zinc and dissolved oxygen are assessed in this paper. All macoinvertebrate taxa were identified and Macroinvertebrate Community Index (MCI) scores determined as a measure of the ratio of "sensitive" to "tolerant" macroinvertebrates present at each site (Stark, 1998). Although this index was initially developed to assess the fauna of stony bottom streams, it has also become widely used to assess the ecology of soft-bottom streams throughout New Zealand. Generally, stony-bottom sites with MCI scores greater than 100 are regarded as being of high quality; between 100 and 80 often represent sites of good quality; between 80 and 60 often represents sites of fair quality, and sites below 60 are usually regarded as poor.

3 RESULTS AND DISCUSSION

3.1 HYDROLOGICAL IMPACTS

Continuous stream flow records for the Cantwell, Waikumete and Tangutu catchments for the period July 2002 to February 2003 were assessed to determine differences in their hydrological regimes. Although these records are for less than 1 year, comparison of the respective flow duration curves (Figures 2 and 3) clearly demonstrates differences in their hydrological responses. Peak flows are shown to be elevated, and base flows less sustained from the more impervious Tangutu and Waikumete catchments (Figure 2). For the predominantly bush and pasture Cantwell catchment, that was only 6% impervious, base flow discharges were sustained at above 3 $l.s^{-1}$. For the Waikumete catchment, with 16% imperviousness, baseflows decreased to 1 $l.s^{-1}$, while that from the 33%-impervious Tangutu catchment ceased flowing for 15 days during the study period. The reduced rates of base flow discharged from the Tangutu and Waikumete catchments reflect the reduced infiltration of rain water into soil and groundwater storages due to their impervious surface cover. Sustained flows from these storages are essential for maintaining streamflows and aquatic habitats during periods of little rainfall.

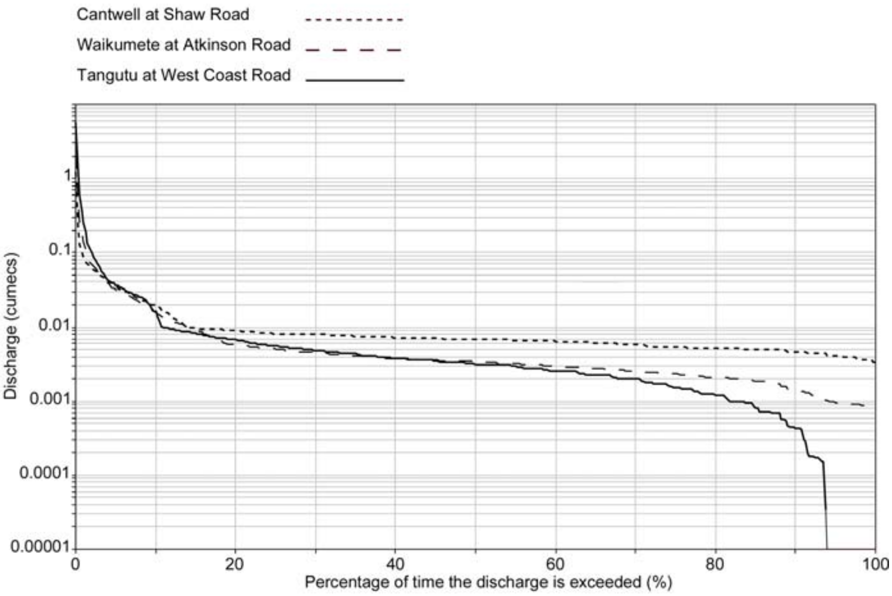

Figure 2 Flow duration curves for the Cantwell, Waikumete and Tangutu catchments

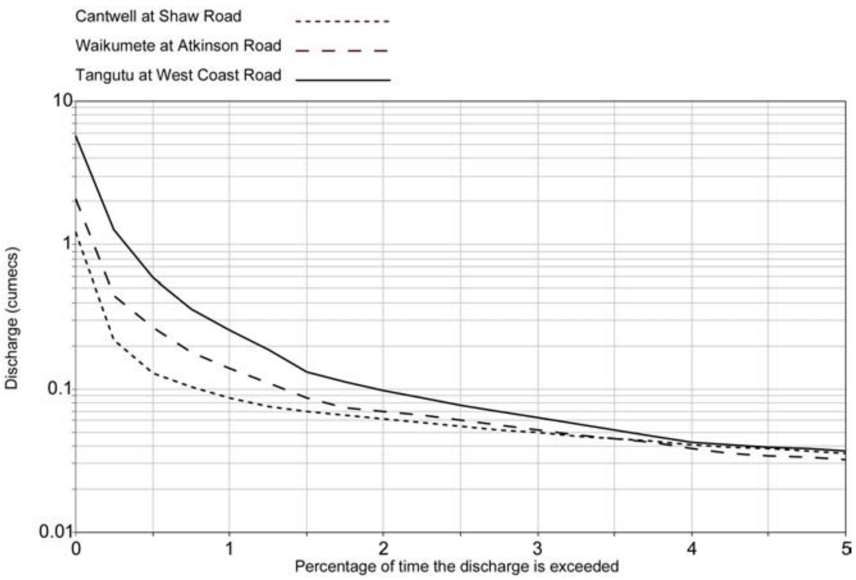

Figure 3 Flow duration curves for largest 5% of flows from the Cantwell, Waikumete and Tangutu catchments

Figure 3 compares stream flows exceeded for less than 5% of the study period. Clearly, stormflows discharged from the more impervious Tangutu and Waikumete catchments are substantially greater than those discharged from the pasture and regenerating bush-covered Cantwell catchment. The greatest discharge recorded from the Tangutu catchment during the study period was 6.7 m^3 s^{-1} compared with 2.1m^3 s^{-1} and 1.2 m^3 s^{-1} from Waikumete and Cantwell catchments respectively. The elevated peak discharges of the Tangutu and Waikumete catchments are in response to their imperviousness and stormwater drainage systems, which are designed to convey stormwater rapidly to the stream channel.

Traditionally, flood risk management within the urban environment is reliant on constructed drainage systems for the collection and discharge of stormwater to the nearest stream channel. These stormwater networks become larger and more intensive as urban areas become more impervious. Figure 4 illustrates this phenomenon, indicating that public drainage increases to nearly 160 m per hectare for subcatchments in the study catchments with more than 50% impervious cover. These stormwater drainage systems typically discharge directly into the nearest stream channel, resulting in increased volumes of runoff, elevated peak flows, and less sustained base flows.

Increased peak flows lead to increased channel erosion and sedimentation (Bledsoe and Watson, 2002), resulting in further degradation of aquatic ecosystems. To cope with the increased stormflows and to reduce bank and channel erosion, urban streams are often lined or piped to increase their hydraulic efficiency. The Tangutu catchment and lower reaches of the Hibernia catchment, with 0.4 km of its main channel now in pipe, are good examples of this traditional approach to stormwater management. By replacing stream channels with hydraulically efficient pipe networks, peak discharges are increased, due to their hydraulic efficiency, and aquatic habitat is lost. To measure this direct loss of aquatic habitat within the study catchments, perennial channels mapped in 1942 (Dept of Lands and Survey, 1942) are compared with those still present today. This comparison shows that approximately 50% of perennial stream channel length within the 34% impervious Tangutu catchment has been lost through piping and channel lining. The less impervious Waikumete and Hibernia catchments have lost 15 and 18% of their perennial channels respectively, while there has been no significant loss of stream channels within the Cantwell catchment.

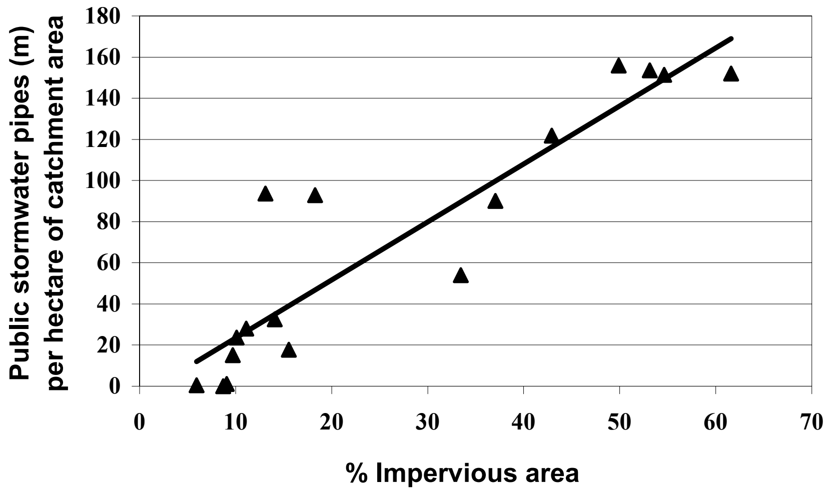

Figure 4 Length of public stormwater drainage per hectare and percent impervious surface area in subcatchments of the Cantwell, Hibernia, Waikumete, and Tangutu catchments

3.2 URBAN AQUATIC ECOSYSTEM HEALTH

Baseflow concentrations of total zinc, which in urban runoff is usually associated with disolved solids, was found to increase as the percentage impervious area increased (Figure 5). The lowest concentrations of total zinc, less than 7 µg/L, were analysed for baseflows discharged from the Cantwell catchment and headwaters of the Hibernia catchments. These catchment areas are less than 10 percent impervious. The highest concentration of total zinc (110 µg/L) was recorded for a tributary in the lower Tangutu catchment. This 66% impervious subcatchment comprised mainly low density residential land cover. Typically, sources of zinc in the urban environment comprise wear and tear of tyres and brake pads, and corrosion of galvanised roofs, roadside fittings, pipes and other metal objects (Makepeace et al., 1995). As vehicle traffic within this subcatchment is limited to local low volume roads, the elevated concentration of total zinc is mainly attributed to non-vehicle sources. Although not formally surveyed, galvanised iron roofs, garages, garden sheds, and fences are very common in this predominantly lower socio-economic area of the Tangutu catchment. Many are unpainted and in a poor state of repair, with the presence of rust suggesting their galvanised coating is now contaminating the local environment. This observation – that poorly maintanied zinc-coated building materials are more prevalent in areas of lower valued housing – suggests socio-economic considerations and building materials need be considered when developing effective policies to improve water quality and environmental health.

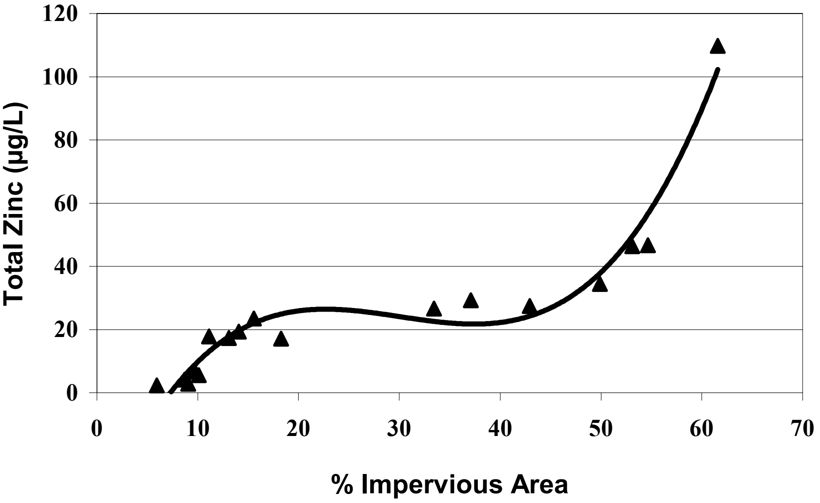

Figure 5 Base flow Concentrations of total zinc and percent impervious area of subcatchments in the Cantwell, Hibernia, Waikumete and Tangutu catchments

Results of the aquatic macroinvertebrate survey demonstrate how sites influenced by urban stormwater, as indicated by elevated baseflow concentrations of total zinc, comprise a greater abundance of less sensitive taxa. MCI scores for sites with total zinc concentrations greater than 10 µg/L generally declined to less than 100 (Figure 6). This indicates a decrease in the proportion of sensitive taxa with increasing concentrations of total zinc. However, it should be noted that elevated concentrations of total zinc are not identified as the key factor causing reductions in sensitive aquatic fauna and therfore lower MCI values. The decline in the ratio of sensitive to tolerant taxa is most likely driven by a number of factors including changes to the flow regime, degraded water quality due to a cocktail of urban contaminants, and degraded physical habitat. Two outliers to this trend are the headwaters of the Tangutu and Waikumete catchments, with MCI scores of 109 and zinc concentrations of 29 µg/L and 18 µg/L respectively. The upper Waikumete catchment, comprised mostly of regenerating native bush, was subject to direct inflows of stormwater from Titirangi township. Few sensitive macro-invertebartes were found in this subcatchment, with the MCI score elevated in the upper catchment by the occurrence of a few sensitive species. The 34% impervious headwaters of the Tangutu catchment, which comprised a substantial riparian buffer, is also influenced by direct discharges of urban runoff. As with the upper Waikumete stream, the MCI score in this subcatchment was elevated due to the presence of a few indivuals of some sensitive species. At the time of the field survey this subcatchment was undergoing further development, with signs of increased sedimentation likely to degrade this stream further.

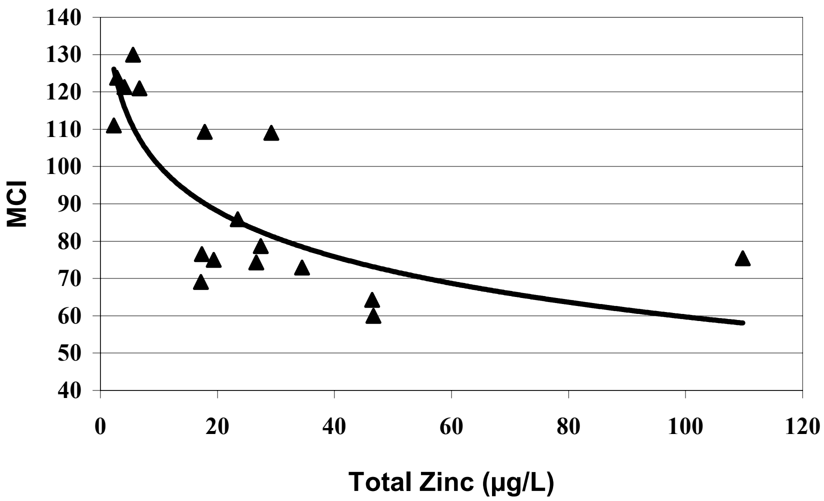

Figure 6 MCI scores and baseflow concentrations of total zinc for subcatchments in the Cantwell, Hibernia, Waikumete and Tangutu catchments

With the exception of one subcatchment, the headwaters of the Tangutu Stream, subcatchments with MCI scores greater 100, were less than 12% impervious. These communities included more sensitive species such as mayflies, stoneflies and caddisfies.With increasing imperviousness of between 12 and 20%, MCI scores decrease to a cluster of values between 69 and 86. This inicates a significant degrading of stream habitat. The communities at these sites included fewer sensitive species and an increased abundance of those more tolerant of degraded conditions. With further increases in percentage impervious surface, MCI values remain in a range between 60 and 80, with tolerant taxa dominating these communities. These sites were characterised by varying abundances of less sensitive taxa, including *Potamopyrgus antipodarum* (pond/mud) snail, oligochaete worms flatworms and midges.

Concentrations of disolved oxygen also decrease with increasing percent impervious area from over 10 mg/l in the upper Cantwell, Hibernia and Tangutu catchments to 7 mg/l in the lower Tangutu (Figure 8). This reduction

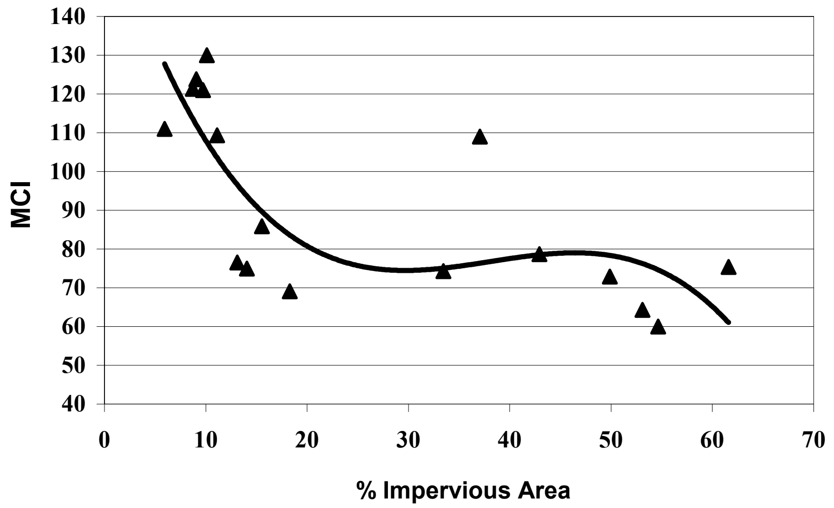

Figure 7 MCI scores and percent impervious areas for subcatchmentsin the Cantwell, Hibernia, Waikumete and Tangutu catchments

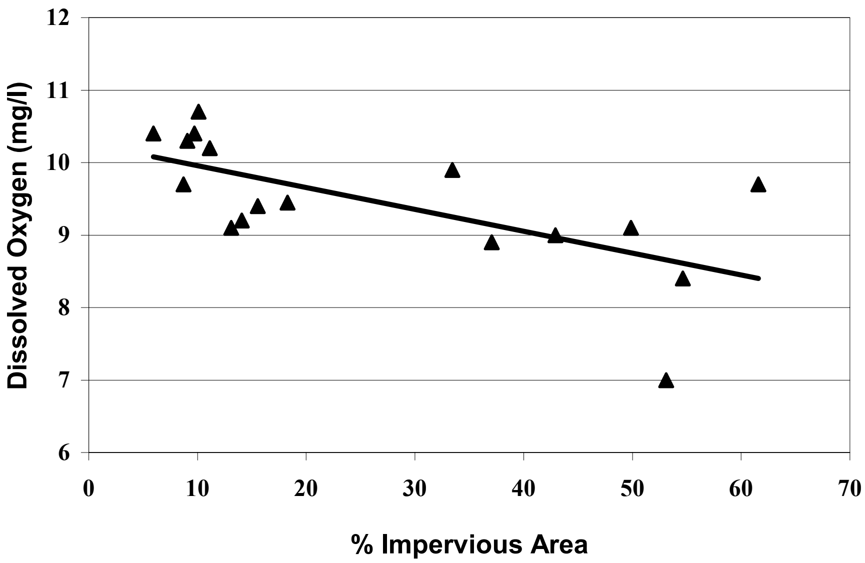

Figure 8 Dissolved oxygen and percent impervious area for subcatchment of the Cantwell, Hibernia, Waikumete and Tangutu catchments

is attributed to the higher biological and chemical oxygen demand (BOD and COD) of urban streams due to contaminants from road runoff and possible sewer misconnections, overflows and exfiltration. Without a more detailed assessment it is not possible to be more specific on the likely sources of BOD and COD that may have reduced concentrations of disolved oxygen in the more impervious subcatchments. Slower current speeds and warmer water temperatures are also likely to contribute to lower dissolved oxygen concentrations, which in turn lead to lower MCI scores.

In summary, aquatic ecosystem health within the study area is degraded with inflows of stormwater, especially when the impervious surface exceeds 12% of the total catchment area. It is important to note that catchments of regenerating native bush and those with substantial riparian buffers are also degraded when urban stormwater is discharge directly into their stream channel. However, a positive observations was that banded Kokopu were found in the headwaters of the Tangutu, Waikumete and Hibernia catchments. To reach these headwaters this native fish, which returns to the sea for part of its life cycle, must pass through the degraded water and habitat of the lower and middle reaches of these catchments, including significant lengths of linned channel and culverting. In the case of the Hibernia catchment, banded Kokopu swim through 0.4 km of culverted channel to reach the catchment headwaters.

3.3 POINTING THE WAY

This assessment demonstrates the impacts of traditional urban design and stormwater management practices on stream flows and aquatic biota in four urban and peri urban catchments in Waitakere City. The study area is typical of New Zealand's urban landscape, with low- to medium-density, single-unit residential housing, and stormwater drainage systems that drain directly into the nearest stream channel. Streams influenced by stormwater runoff, as indicated by elevated concentrations of total zinc, are shown to be subject to increased peak flows, reduced base flows, and degraded communities of aquatic invertebrate fauna. These streams not only included those draining areas of predominantly urban landcover, but also subcatchments of regenerating bush and significant riperian buffers where road and roof runoff is piped directly to the stream channel.

Although stream restoration projects often comprise revegetation of riparian margins and reconstruction of pools and riffles in the stream channel (Palmer et al., 1997), the likely root cause of the degradation is modification to the hydrological cycle through construction of impervious surfaces, stormwater drainage systems and the increased availability of contaminants. Successful stream and riparian restoration must therefore comprise more than the reintroduction of physical habitat to the channel and its riparian margin. To succeed we must manage the generation and contamination of stormwater over the entire catchment. Restoration projects that ignore these catchment-wide processes are doomed to failure, or at best, may only improve the aesthetics and ammenity value of the riparian margin.

Improved, water-sensitive, urban design concepts (Wong, 2001) that reduce the volume and rate of stormwater runoff are being developed, as are technologies for the removal of contaminants from stormwater. There are increasing international examples where impacts of urban runoff are reduced through on-site storage and use of stormwater, including that for domestic supply and irrigation (Lloyd, 2001; Shirley-Smith, 2002). In Australia, pipeless residential subdivisions have been constructed where all stormwater is discharged into biofilters that provide both attenuation and treatment (Lloyd et al., 2001). Within New Zealand, treatment wall technologies are being developed that remove more than 90% stormwater contaminants (Pandey et al., 2003). Information is available on the implementation low-impact stormwater management devices (ARC, 2003). There is also a move towards financial incentives to facilitate more sustainable stormwater management. Schedule 3 of the Local Government (Rating) Act (2002) identifies land within rating units that is "sealed, paved or built on" as a factor to be used in calculating liability for targeted rates. North Shore City is offering financial incentives for residents to install rain tanks for garden irrigation to reduce rates of stormwater discharge.

Although the impacts of traditional urbanization as demonstrated in this study have been recognised for many years, and information on improved stormwater management practices is available, practitioners are reluctant to implement truly integrated ecosystem-based urban design and catchment management. The way forward is for roading, water and drainage engineers to work together with environmental scientists and urban planners to gain a better understanding of the interrelationships between their respective fields of expertise. It is only through this process that the impacts and true costs of current urban design practices can be understood and the benefits of water-sensitive urban design appreciated. In other words, these practitioners must adopt an ecosystems approach to urban design and stormwater management that will ensure each component of the urban environment complements and supports the sustainability of the entire system.

Waitakere City is providing leadership in this direction with its planning of the Northern Strategic Growth Area (NOSGA). Development of this area, comprising the Hobsonville, Whenuapai and Red Hills area of Waitakere City, is currently being planned for the next 50 years. This planning includes studies of integrated supply and management of potable waste and stormwater. Included in these investigations is the compilation of an environmentally sentitive area map (Herald et al., 2003) that integrates development constraints and opportunities to ensure optimum use of available land in terms of achieving development goals and environmental protection. Through this approach, planners, engineers, and environmental scientests are now working to develop common goals based on a truly integrated approach to urban design and stormwater management.

4 CONCLUSIONS

This study confirms that traditional urban design and catchment management practices, characterized by extensive areas of impervious surface and stormwater drainage networks, which discharge directly into stream channels, led to substantial degradation of aquatic ecosystems. This degradation, as measured by aquatic macroinvertebrate community composition, is shown to increase rapidly as imperviousness increases beyond 12 percent of the catchment area. Construction of stormwater drainage systems within the study area has also led to a substantial loss of aquatic habitat through piping and lining of stream channels. The study confirms that if urban aquatic ecosystems are to be successfully restored and preserved then new water-sensitive urban design strategies need to be implemented that focus on stormwater management.

As part of this process it is essential for urban planners to adopt truly integrated planning appoaches that are not discipline- or function-based, as is currently practised. No longer can water, drainage and roading engineers, and urban and environmental planners work in isolation. These practitioners must jointly adopt an ecosystems-based approach to urban design that will ensure each component of the urban environment complements and supports the sustainability of the entire system. With the development of new urban design and stormwater management practices, these practitioners are in an ideal position to set new, more challenging goals to impove the quality of our towns and cities through implementation of water sensitive urban design.

ACKNOWLEDGEMENTS

This research is part of Landcare Research's FRST funded Living Urban Environments research programme. I would like to thank: Waitakere City for their support in providing aerial photography and information on stormwater infrastructure; Stephen Moore for assistance with surveying and analysis of macroinvertebrate data; Brian Daly and his team for analysing the water samples; and Janice Willoughby and Heather North for their remote sensing and GIS analysis.

REFERENCES

ARC (2003) 'Stormwater treatment devices: design guidelines manual' Technical Publication 10, Auckland Regional Council, Auckland, New Zealand.

Bledsoe B. P. and Watson C.C. (2002) 'Effects of urbanization on channel instability' J. of the American Water Resources Association, 37(2), 255–270.

Department of Lands and Survey (1942) 'Titirangi Sheet' New Zealand Map Series 2, 1:25,000 scale, NZ Govt. Printers, Wellington.

Duncan H.P. (1999) 'Urban stormwater quality: A statistical overview' Cooperative Research Centre for Catchment Hydrology, Report No. 99/3.

Herald, J.R., Luckman, P. and Miguel, T. (2003) 'Integrated thinking to improve stormwater management' Proceedings of the 3rd South Pacific Conference on Stormwater and Aquatic Resource Protection, Auckland, New Zealand, 14–16 May 2003, In press.

Lau, S.L., and Strenstrom, M.K. (2001) 'Metals and PAHs absorbed to street particles' Proceedings of the 2nd South Pacific Stormwater Conference, Auckland, New Zealand, 27–29 June 2001, pp. 122–134.

Leopold L.B. (1968) 'Hydrology for urban land planning – a guide-book on the hydrologic effects of urban land use' U.S. Geol Survey, Circular No. 554.

Lloyd, S.D. (2001) 'Water Sensitive urban design in the Australian context' Synthesis of a conference held 30-31 August 2000, Melbourne, Australia, CRC for Catchment Hydrology, TR 01/7, September 2001, pp. 26.

Lloyd S.D., Wong, H.F. and Chesterfield C.J. (2001) 'Opportunities and implementation to water sensitive urban design in Australia' Proceedings of the 2nd South Pacific Stormwater Conference, Auckland, New Zealand, 27–29 June 2001, pp. 302–309.

Local Government (Rating) Act 2002 'Local Government (Rating) Act 2002' Wellington, New Zealand.

Makepeace D.K., Smith D.W. and Stanley S.J. (1995) 'Urban stormwater quality: Summary of contaminant data, critical review' Environmental Science Technology, 25(2), 93–139.

Palmer M.A., Ambrose R.F., and Poff N.L. (1997) 'Ecological theory and community restoration. Restoration Ecology, 5, 291–300.

Pandey S. Taylor, M., Shaver, E. and Lee, R (2003) 'Reducing road runoff contaminants through low-cost treatment wall (filter) systems' Proceedings of the 3rd South Pacific Conference on Stormwater and Aquatic Resource Protection, Auckland, New Zealand, 14–16 May 2003, In press.

RMA (1991) 'The Resource Management Act 1991' Wellington, New Zealand.

Sartor J.D. and Boyd G.B. (1972) Water pollution aspects of street surface contaminants' Environmental Protection Service, EPA – R2/72-081, U.S. EPA, Office Resource Monitoring, Washington, D.C.

Scheuler T.R. (1994) 'The importance of imperviousness' Water Protection Technology 1(3), 100–111.

Shirley-Smith C. (2002) 'Integrating water management as a tool for sustainable urban regeneration' The Sustainable City 11, 117–131.

Stark, J.D. (1998) 'SQMCL: a basic index for freshwater macroinvertebrates coded-abundance data' New Zealand Journal of Marine and Freshwater Research, 32, 55-66.

Wong, T.H.F. (2001) 'A changing paradigm in Australian urban stormwater management' Proceedings of the 2nd South Pacific Stormwater Conference, Auckland, New Zealand, 27–29 June 2001, pp. 302-309.

Wong, T.H.F., Breen, P.F. and Somes, N.L.G. (1999) 'Ponds vs wetlands – performance considerations in stormwater quality management' Proceedings of the 1st South Pacific conference on conprehensive stormwater and aquatic ecosystem management, Auckland, New Zealand, 22–26 February 1999, Vol 2, pp. 223–231.