Factors limiting the capacity of stormwater control measures to protect stream ecosystems

Facteurs limitant le rôle des techniques alternatives pour la protection des cours d'eau

Samantha J. Imberger[1], Christopher J. Walsh[1], Tim D. Fletcher[1], Darren G. Bos[1] and Matthew J. Burns[1]

[1]School of Ecosystem and Forest Sciences, The University of Melbourne, Australia.

RÉSUMÉ

Les programmes de restauration des cours d'eau urbains se focalisent souvent sur l'échelle du tronçon, et pourtant les eaux pluviales sont la cause majeure de dégradation du milieu récepteur à l'échelle du bassin versant. Les recherches ont montré que ces restaurations localisées n'améliorent pas ou peu l'état écologique du cours d'eau, car elles ne traitent pas la cause de la dégradation. Dans cette étude, 620 techniques alternatives ont été implémentées sur six bassins versants avec pour objectif le retour au bon état écologique des cours d'eau. L'objectif est de diminuer l'eau ruisselée et de revenir à un cycle de l'eau pré-urbanisation. Un modèle hiérarchique spatialisé a été utilisé pour prédire l'effet des techniques alternatives à partir de mesures de débits et de la qualité des cours d'eau. Les résultats ont montré que le nombre d'ouvrages installés n'apportent pas la capacité de rétention suffisante pour atteindre les objectifs hydrologiques prévus. Les deux facteurs de limitation principaux étaient le manque de foncier disponible pour installer d'autres ouvrages, et une demande insuffisante de réutilisation des eaux pluviales.

ABSTRACT

While stormwater runoff, a widely reported degrading agent of receiving waters, acts at the catchment scale, urban stream restoration has often been undertaken at isolated reach-based scales. Evidence is mounting that such small-scale activities fail, primarily because they do not address the catchment-wide driver of degradation. In this experiment, we aimed to improve the hydrology, water quality and ecosystem structure and function of several small urban streams via the catchment-scale installation of stormwater control measures (SCMs). We installed over 620 dispersed SCM projects to treat runoff from 6 urban 'intervention' catchments, with the aim of reducing stormwater runoff. We used a nested network model to predict our intervention effect over time and measured in-stream flow and water quality in our intervention streams and several other reference and control streams. Despite the extensive implementation, the SCMs did not achieve sufficient runoff retention in all catchments due to constraints on available space and demand for captured stormwater. The results highlight the limiting factors which must be overcome if a pre-urban hydrologic state is to be achieved with the aim of restoring stream ecosystems.

KEYWORDS

Restoration, Stormwater, Stormwater control measures (SCMs), Urban drainage design, Water-use

INTRODUCTION

Stream ecological structure and function are degraded by urban stormwater runoff. While the pervasive catchment-scale impacts of stormwater runoff are widely recognised in the scientific literature, urban stream restoration is frequently undertaken with a focus on reach features such as channel reconfiguration and bank stabilisation (Palmer et al. 2014). Evidence is mounting, however, that this mismatch between the scale of restoration action and the scale of the major degrading agent is hampering the success of such approaches. Many studies have shown the use of stormwater control measures (SCMs) can reduce pollutant loads and peak flows at the scale of individual systems (Hatt et al. 2009, Zhang et al. 2014). Fewer have empirically assessed their effects on runoff quality and quantity when dispersed across an entire catchment (however examples incl. Bedan et al. 2009, Line et al. 2011); and only one study has investigated the effects on receiving waters when dispersed at the catchment scale (Shuster et al. 2013, Roy et al. 2014). Given the large investments worldwide in SCMs, there is an urgent need to test whether their catchment-wide application has a positive impact on urban streams.

METHODS

We aimed to restore the hydrology, water quality and ecosystem structure and function of several small urban streams via the catchment scale retrofit of stormwater infrastructure. We selected 10 small first-order perennial streams located in and around the Dandenong Ranges to the east of Melbourne, Victoria, Australia. Our study was loosely based on a Beyond Before-After-Control-Impact experimental design, where we monitored stream hydrology and water quality intermittently in 3 forested reference streams, 2 urban control streams (i.e. no SCM intervention) and 6 ‘intervention’ streams before, during and after SCM installation. Over 8 years, beginning in 2009, we installed over 620 dispersed SCMs projects to treat runoff from 4 km^2 of urban development in the intervention catchments. We installed SCM technologies which aimed to improve water quality and, in contrast to more traditional load reduction technologies, also aimed to restore important elements of the natural flow regime. These included raingardens, biofilters, swales and rainwater tanks which were designed and optimized to reduce contaminated stormflows via infiltration, harvesting and evapotranspiration. SCM ‘projects’ were made up of one or more SCMs installed in series, but funded as a single project. We modelled the individual performance of SCM projects and their nested spatial and temporal installation in order to quantify their hydrological performance as a predictor of our stormwater intervention (Figure 1). When generating this predictor we used a simplistic best-case scenario measure of SCM performance we termed Effective Imperviousness$_S$ (EI$_S$). This measure of catchment effective imperviousness, provided an estimate of the proportion of the catchment covered by impervious surfaces that were directly connected to streams via the stormwater drainage network; assuming that all impervious areas upstream of an SCM were *completely disconnected* (i.e. best-case). We also calculated a more realistic estimate of SCM performance based on the system’s capacity to reduce runoff volumes, termed Volume Reduction efficiency (VR eff.). This was calculated as the product of the runoff volume sub-index described by Walsh et al. (2015), multiplied by 100 and divided by the impervious catchment area (m^2).

RESULTS

Stormwater control measures were installed opportunistically in partnership with local communities and ranged in size from small domestic tanks treating impervious areas of 20 m^2, to large precinct scale harvesting systems treating impervious areas of 55,000 m2 (Table 1). Individual SCMs were designed in consultation with key stakeholders (i.e. home owners or local council) with the aim of maximising stormwater retention and the resultant ‘environmental benefit’ index (see Walsh et al. 2015). Given the unique spatial arrangement of engaged landholders and existing stormwater infrastructure, SCMs were unevenly distributed across intervention catchments (Figure 1 and Table 1).

We installed 41–161 SCM projects per catchment (24–234 SCMs/km^2) (Table 1). Catchment LIS0001 had the greatest density of SCMs, followed by LSS0001, LSN0001 and DBS0004. The median SCM size across catchments ranged from a treated impervious area of 205 m^2 to 0.012 km^2; while the largest ranged from 776 m^2 to 0.055 km^2 (Table 1). Private SCM’s included internally plumbed rainwater tanks installed in series with either leaky tanks, subsurface infiltration or raingardens. These private systems were installed in greater numbers, but were smaller than the public SCMs, with the largest private systems across catchments treating only 314–1076 m^2 (Table 1). Catchment LIS0001 displayed the greatest density of private SCMs, followed by LSS0001 and LSN0001. Conversely our public SCMs were fewer, but included large screetscape stormwater harvesting tanks and raingardens. The largest public SCM in each catchment treated an impervious area of 0.012 km^2 to 0.055 km^2; which was on average 40 times the size of the corresponding private SCM's (Table 1). Similar to private SCMs, catchment LIS0001 had the greatest density of public SCMs, followed by LSS0001 and LSN0001. Interestingly our small private SCMs exhibited greater volume reduction efficiencies than our larger public SCMs, more so when tanks were internally plumbed to hot water services. However public SCMs treated larger areas and therefore had a larger effect on Ei_s, even though they were likely to be less effective control measures.

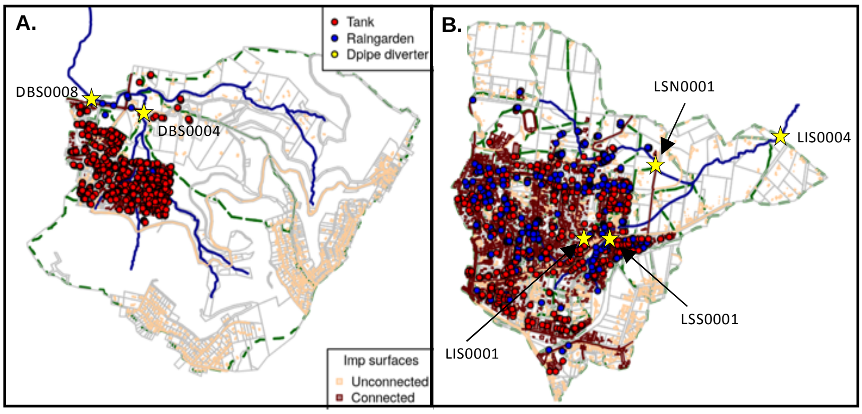

Figure 1. Intervention catchments showing impervious areas and the nested distribution and type of installed SCMs. A. Dobsons Creek catchment including DBS0008 and DBS0004; B. Little Stringybark Creek catchment including LSN0001, LIS0001, LSS0001 and LIS0004.

Table 1. SCM installation, design and performance statistics across our intervention catchments. Where EI_{start} refers to the catchment effective imperviousness (EI) at the start of the experiment. For DBS0008 and LIS0004, catchment statistics are calculated only for the areas not covered by upstream catchments.

Catchment	Area (km_2)	EI_{Start} (prop.)	EI_s change (prop.)	SCM No.	Treated area max (m^2)	Treated area median (m^2)	SCM No. private	Treated area private max (m^2)	Vr Eff. private median (%)	SCM No. public	Treated area public max (m^2)	Vr Eff. public max (%)
DBS0008	4.39	0.015	0.007	105	34364	325	78	481	0.63	7	34364	0.35
DBS0004	3.55	0.022	0.008	161	19498	11901	101	314	0.66	2	19498	0.21
LIS0001	0.67	0.222	0.033	157	11690	205	125	513	0.67	17	11690	0.24
LIS0004	1.33	0.092	0.042	41	776	215	36	776	0.64	0		
LSN0001	1.5	0.047	0.045	70	30265	296	53	1076	0.51	17	30265	0.18
LSS0001	0.97	0.110	0.084	86	54720	221	67	623	0.52	17	54720	0.78

The installation of SCMs reduced EI_s in our intervention catchments by between 0.7 % and 8.4 %: LSS0001 had the greatest reduction in EI_s, followed by LSN0001 and LIS0004 (Table 1, Figure 2). Trends in EI_s through time showed a slight countering effect of urban growth, however net decreases were strongly influenced by SCM number, size and water demand. While the reduction in EI_s through time is an important predictor of our stormwater intervention effect, the EI_{start} value is also critical. Low EI_{start} values at DBS0004 and DBS0008 mean that while changes in EI_s through time were small (0.8 % and 0.7 % respectively) the final EI_s values were low (Figure 2). Our results thus indicate that substantial declines in effective imperviousness, where the final EI_s was less than 3%, could only be achieved in 4 of our 6 intervention catchments; DBS0008, DBS0004, LSN0001 and LSS0001 (Figure 2).

DISCUSSION

Improvements in water quality and biological indicators are only like to be observed if EI is reduced below ~3% (Walsh et al., 2005). Despite substantial efforts over 8 years, including the installation of over 620 SCM projects which treated considerably greater catchment area than any previous research, we were unable to achieve substantial declines in EI_s in 2 of our 6 intervention catchments.

While catchments DBS0004 and DBS0008 showed substantial declines in EI below 3 %, this was largely driven by low EI starting values and only moderate/low declines in EI_s due to the installation of SCMs.

Conversely, substantial changes in EI_S in catchments LSS0001 and LSN0001 were driven by SCM implementation. Catchments LSS0001 and LSN0001 both contained several large public SCMs (> 0.03 km^2) in the lower part of their catchment. These public SCMs treated large areas of impervious surfaces, but their efficiency in reducing and treating stormwater flows varied with available space, and harvesting demand. The public SCMs in LSS0001 were likely to have little effect, as a result of their small size (relative to their catchments) and lack of harvesting; while the large public system in LSN0001 had a high irrigation demand over summer which increased its Volume Reduction index and its expected performance.

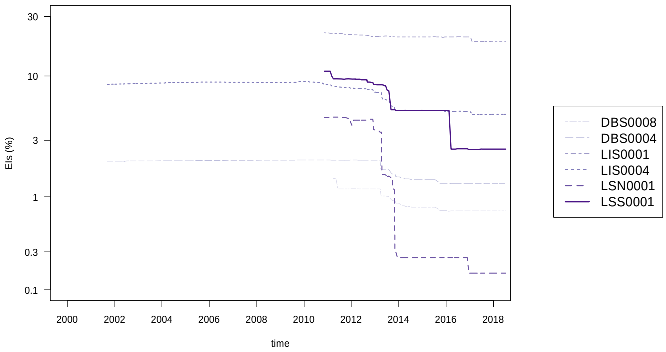

Figure 2. Temporal trends in intervention catchment EI_S; Highlighting urban growth and variation in stormwater intervention effects between catchments.

Catchment LIS0001 had a high density of both public and private SCMs, but lacked usable space near the outlets of larger stormwater pipes which hampered the installation of large public SCMs of a similar magnitude to that installed in LSS0001 and LSN0001. Catchment LIS0004 lacked the density of private SCMs seen in LIS0001 or even LSN0001 and contained no larger public systems due to insufficient space for installation.

While we were unable to achieve sufficient retention in all intervention catchments in this study; our success in 4 of 6 catchments was primarily driven by SCM density and access to sufficient space to implement large public SCMs with high demand for water. Our study suggests that dispersed stormwater control is only likely to successfully protect or restore stream ecosystems where there is sufficient demand for the stormwater retained in the SCMs, along with space for stormwater infiltration systems.

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