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Publication Date
2019-03-01

DOI
10.1016/j.jenvman.2018.12.023

Peer reviewed

Can catchment-scale urban stormwater management measures benefit the stream hydraulic environment?

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Cite as: Anim, D. O., Fletcher, T. D., Pasternack, G. B., Vietz, G. J., Duncan, H. P., & Burns, M. J. (2019). Can catchment-scale urban stormwater management measures benefit the stream hydraulic environment? *Journal of Environmental Management*, *233*, 1-11

https://doi.org/10.1016/j.jenvman.2018.12.023

Abstract

The potential for catchment-scale stormwater control measures (SCMs) to mitigate the impact of stormwater runoff issues and excess stormwater volume is increasingly recognised. There is, however, limited understanding about their potential in reducing in-channel disturbance and improving hydraulic conditions for stream ecosystem benefits. This study investigates the benefits that SCM application in a catchment have on in-stream hydraulics. To do this, a two-dimensional hydraulic model was employed to simulate the stream hydraulic response to scenarios of SCM application applied in an urban catchment to return towards pre-development hydrologic pulses. The hydraulic response analysis considered three hydraulic metrics associated with key components of stream ecosystem functions: benthic mobilization, hydraulic diversity and retentive habitat availability. The results showed that when applied intensively, the developed SCM scenarios could effectively restore the in-stream hydraulics to close to natural levels. Compared to an unmanaged urban case (no SCMs), SCM scenarios yielded channels with reduced bed mobility potential, close to natural hydraulic diversity and improvement of retentive habitat availability. This indicates that mitigating the effect of stormwater driven hydrological change could result in significant improvements in the physical environment to better support ecosystem functioning. We therefore suggest that intensive implementation of SCMs is an important action in an urbanizing catchment to maintain the flow regime and hydraulic conditions that sustain the 'natural' stream habitat functioning. We propose that stormwater management and protection of stream ecosystem processes should incorporate hydraulic metrics to measure the effectiveness of management strategies.

Keywords: Urbanization, Stormwater management, Stream, Hydraulics, Stormwater runoff, Urban hydrology

1. Introduction

Stream ecosystems are characterised by complex and dynamic ecosystem functions directly governed by the hydraulic regime (Statzner & Higler, 1986; Kemp et al., 2000; Anim et al., 2018a). In turn, patterns of hydraulic characteristics are determined by the interactions of flow (i.e. magnitude, frequency, duration, rate of change and timing) and channel form (i.e. nested features of topographic structure) (Jacobson & Galat, 2006). As a result, ecologists and river scientists generally recognize the interactions between flow and form as a controlling template for fluvial ecological processes (Townsend et al., 1997; Emery et al., 2003; Wallis et al., 2012; Yarnell et al., 2015). Stream ecological integrity relies on the presence of natural dynamic behaviour expressed through the hydraulic conditions (Statzner et al., 1988; Brooks et al., 2005). Therefore, to sustain healthy natural stream ecosystem functioning, it is important to maintain ecologically relevant hydraulic conditions that are similar to those in a naturally functioning stream system.

When a catchment is urbanized, the sealing of native soils with impervious surfaces drastically alters the water balance. Fluxes of evapotranspiration and infiltration are reduced and matched by an increase in the surface runoff (i.e. urban stormwater) (Haase, 2009; Burns et al., 2013; Fletcher et al., 2013). This excess water is typically managed by connecting impervious surfaces to hydraulically efficient stormwater drainage systems which convey runoff directly to streams draining the catchment (Roy et al., 2008; Walsh et al., 2012). When urban stormwater runoff is directed to streams, many changes occur, including hydrological alteration (Burns et al., 2012), water quality impairment (Brabec et al., 2002) and channel alterations (Vietz et al., 2015). These changes to the flow regime and channel form unequivocally alter the stream's hydraulic regimes (Jacobson & Galat, 2006; Anim et al., 2018a), resulting in ecological degradation (Walsh et al., 2005; Paul & Meyer, 2008). Stormwater runoff is thus a primary source of stress to stream ecosystems (Walsh, 2004; Ladson et al., 2006; Mallin et al., 2009; Vietz et al., 2014; McIntyre et al., 2015).

To address this, increasing efforts have centred on stormwater management approaches that aim to holistically mimic natural hydrological processes at the catchment-scale and treat polluted runoff as well as deliver other benefits (e.g. improved amenity). Burns et al (2012) coined such an approach the 'flow-regime stormwater management'. This approach emphasizes the protection, restoration or mimicking of natural hydrological process at small scales within the catchment, using stormwater control measures (SCMs), with the aim of restoring natural flow regimes at larger scales downstream (Burns et al., 2012; Fletcher et al., 2014). This catchment-focused approach agrees with the core principle of process-based restoration that emphasize on addressing the root causes or source of degradation (Kondolf et al., 2006; Beechie et al., 2010), such as urban stormwater runoff. Mitigating stormwater runoff impacts requires that hydrologic objectives be specified, including 1) reducing the volume of stormwater runoff, 2) restoring lost infiltration, and 3) returning the runoff response of impervious surfaces towards the pre-development condition (Ladson et al., 2006; Walsh et al., 2012; Burns et al., 2014). Such objectives can be achieved using specifically-designed SCMs that are based on retention, detention, infiltration and harvesting of stormwater (e.g. DeBusk et al., 2010a; Hunt et al., 2011; Li et al., 2017).

Several studies have tested and shown the potential hydrological performance of flow regime-focused approaches to maintain or return the pre-development hydrological regime (e.g. Damodaram et al., 2010; DeBusk et al., 2010b; Jenkins et al., 2012; Loperfido et al., 2014; Burns et al., 2015a). For instance, stormwater bioretention systems (a common SCM) have been tested and found to mimic pre-developed hydrologic performance (DeBusk et al., 2010b; Davis et al., 2011), mitigating peak flows and total runoff volume (Winston et al., 2016; Liu & Fassman-Beck, 2017). Jenkins et al. (2012) also showed that the hydrologic performance of constructed stormwater wetlands led to significant runoff interception and mitigated total runoff reaching the stream. The use of retention systems (e.g. rainwater tanks) has been found to achieve stormwater retention performance comparable to pre-developed conditions by reducing the frequency and volume of stormwater run-off from a site (Burns et al., 2015a).

Exactly how well the hydrologic outcomes of SCMs translate to the hydraulic needs of the receiving stream ecosystem remains poorly understood. While understanding the hydrologic outcome is important, it is critical to understand the anticipated translation into hydraulic characteristics such as depth and velocity, which provide an explicit link to the habitat and ecosystem functioning of the receiving streams (Clarke et al., 2003; Rosenfeld et al., 2011a). Such consideration accounts for the interplay of streamflow dynamics with channel morphology (Anim et al., 2018b), which drive habitat quality (Clarke et al., 2003; Escobar-Arias & Pasternack, 2010). In particular, whilst bankfull discharge is often considered as driving geomorphic change, it is increasingly recognised that the more subtle initial changes of bed disturbance should be targeted for flow-regime strategies focused on the physical and ecological changes of concern (Vietz & Hawley, 2018). Environmental flow management approaches for sustaining stream ecosystem arguably have a better chance of maintaining healthy ecological functioning when they are based on the mechanistic relationships between flow and channel form (Clark et al., 2008; Yarnell et al., 2015). Therefore, an understanding of how flow regime-focused approaches can protect or maintain the hydraulic conditions at or near their natural levels is useful to inform strategies for urban stormwater management.

In this study we ask if flow regime-based stormwater management can restore in-stream hydraulics to near their natural conditions. To test this, we used a two-dimensional (2D) hydraulic model to simulate and examine the stream hydraulic responses to flow-regime management strategies using different SCM scenarios applied in an urbanizing catchment. Managing excess stormwater runoff as driver of stream ecosystem degradation is not particularly a new thinking, but the novelty of this work is underpinned on the scope to investigate the in-stream hydraulic outcomes of alternative approaches towards stormwater management. More specifically, we aim to evaluate the effectiveness of the applied management strategies to sustain the stream hydraulic conditions required for ecosystem functioning in an urban catchment. To achieve this, the study first adopted a case-study natural stream (with typical natural hydrology and channel form) in a natural catchment with no development. Subsequently, various urban development scenarios with or without stormwater management were explored.

2. Methods

2.1 Experimental design

To answer the study question, we formulated a modelling method made up of five parts (Fig. 1). Firstly, we adopted a case-study stream setting (with a typical natural hydrology and channel form) in a natural catchment with no development. Secondly, a representative digital terrain model (DTM) of the stream corridor topography was developed using existing field channel reach parameters data and the synthetic river valley (SRV) methodology of Brown et al. (2014). Thirdly, hydrological models were developed to produce different flow-regime scenarios based on the (i) natural catchment with no development and (ii) developed catchment with and without management (applied SCM alternatives). Fourthly, a 2D hydraulic model was used to simulate the ecologically relevant hydraulic conditions delivered by each flow regime scenario in the channel. Finally, temporally varying hydraulic patterns represented by metrics of known link to relevant ecosystem functions were evaluated under each flow regime scenario. We characterised the hydraulic patterns using three ecologically relevant hydraulic characteristics: benthic disturbance; hydraulic diversity and retentive habitat availability, all of which are important aquatic ecosystem drivers (Paterson & Whitfield, 2000; Brooks et al., 2005; Vanzo et al., 2016). Details of each part are presented below.

2.2 Case study setting: McMahons Creek catchment

McMahons Creek catchment is located 90 km east of Melbourne (145.937'E, 37.821'S) with a catchment area of 40 km^2. The catchment is forested throughout, mostly by mountain ash (*Eucalyptus regnans*), with the lower slopes occupied by mixed species eucalypt forest and riparian vegetation amounts to several percent of the total catchment area (Land Conservation Council of Victoria, 1973). This remote catchment is not proposed for development but has good flow records and is in close to natural condition. Physiography can be characterised by steep terrain with partly confined channels (only pockets of floodplain within the valley sides). Geologically, the catchment is largely covered by Devonian granites and sandstones, overlaid by red and brown soils (Land Conservation Council of Victoria, 1973). The selected case-study segment of the creek length has an intact and complex naturally meandering, pool-riffle channel morphology comprised of well-sorted coarse-grained sediments with sand, gravels and some boulders. Stream banks are commonly clay/silt with interbedded gravels between the clay/silt layers. The channel morphology is comparable to typical naturally occurring shallow streams in forested catchments in the Melbourne region. Rainfall pattern is fairly evenly distributed over the year with an annual catchment rainfall averaging ~1000mm/year.

2.3 Synthetic channel morphology

An archetypal stream channel was designed for the McMahon Creek catchment in this study using RiverBuilder package (version 0.1.0), an emerging technique of synthesizing channel topography for science and engineering applications (Pasternack & Arroyo, 2018). Based on the SRV mathematical framework of Brown et al. (2014), RiverBuilder is an open-source, free R package capable of procedurally rendering a digital terrain model from user-selected geometric functions that describe subreach topographic variability and associated parameter values at reach and subreach scales. Methodological details are available in Brown et al. (2014), and the information used to create the specific DTM used in this study is described here, focusing on the two key steps at the reach and subreach scales.

2.3.1 Reach-average parameters

The SRV approach first creates a generic reach-average topography scaled by reach-average bankfull depth (H_{bf}) and width (W_{bf}), with median particle size (D_{50}), slope (S), sinuosity, floodplain width, and floodplain lateral slope as user-defined input parameters (Brown et al., 2014). Existing topographic data for the study stream segment in McMahons Creek provided reach-scale parameter values required to synthesize archetypal morphology (Table 1).

2.3.2 Channel variability parameterization

From the initial reach-average values above, RiverBuilder incorporates subreach-scale topographic variability using combinations of geometric functions at the user's expert discretion. The sub-reach variability for this study was created in the model according to Eq (1) and (2) such that the local bankfull width and bed elevation of the thalweg was estimated as

$$z_t(x_i) = \left(\overline{H_{bf}} f(x_i) + \overline{H_{bf}}\right) + S(\Delta x_i) + Z_d \tag{1}$$

$$W_{bf}(x_i) = \left(\overline{W_{bf}} f(x_i) + \overline{W_{bf}}\right) \tag{2}$$

where $z_t(x_i)$ and $W_{bf}(x_i)$ are local bed elevation and bankfull width at location x_i respectively. Z_d is the user-defined datum. The term $f(x_i)$ is the user-selected subreach variability function. Several possible functions are available in River Builder, such as linear, sinusoidal, and sine squared, depending on archetypal characteristics for a given class of stream. The general sinusoidal model was used to achieve the variability of W_{bf} and Z_t about the reach-averaged values by a control function $f(x_i)$ nested in Eqs. 2 and 3. The $f(x_i)$ was modelled as Eq (3):

$$y(x_i) = a_s sin(b_s x_r + \theta_s) \tag{3}$$

where y_i is the dependent control function values, a_s, b_s, and θ_s as the amplitude, angular frequency and phase for the sinusoidal competent and x_r is the Cartesian stationing in radians (Brown et al., 2014). The resulting DTM of the channel morphology and the longitudinal profile is shown in Fig. 2.

Table 1. Channel reach-average and variability geomorphic attributes used in the design of the synthetic DTM. Reach channel parameters are field derived average values scaled from the case-study reach segment channel morphology.

Reach channel parameters	
Bankfull width ($\boldsymbol{W_{bf}}$) (m)	6.5
Bankfull depth ($\boldsymbol{H_{bf}}$) (m)	0.8
Median particle size ($\boldsymbol{D_{50}}$) (m)	0.006
Slope ($\boldsymbol{S}$)	0.01
Vertical datum ($\boldsymbol{Z_d}$) (m)	1000
Floodplain width (m)	10
Floodplain lateral slope	0.005
Channel length (m)	150
Sinuosity	1.1

Variability parameters	a_s	b_s	θ_s
Bankfull width	0.25	2	0
Planform	10	1	0
Bed elevation	0.25	2	0
Floodplain outline	5	1	3.14

2.4 Model development

Hydrologic modeling was performed using the Model for Urban Stormwater Improvement Conceptualisation (MUSIC) (eWater, 2015). MUSIC is commonly used for modeling stormwater flow and quality using continuous simulation (Schubert et al., 2017). In its default mode, MUSIC source nodes (which represent the catchments) use three rainfall-runoff stores: an impervious area store (describe by initial loss), a soil store (a linear reservoir described by infiltration and storage properties), and a groundwater store (a linear reservoir described by initial depth and daily rates of recharge, baseflow and seepage) (Hamel & Fletcher, 2014). MUSIC can model various SCM interventions such as rainwater tanks, infiltration and bioretention systems.

The model was first calibrated to observed flows under the current natural conditions. Model parameters were then adjusted to simulate fully urbanized land use on the same catchment with or without stormwater management (applied SCM alternatives) as described below. Further details of model structure are reported in the Supplementary Material. This study used the July 2006 to July 2013 water years' data, which provides a good representation of dry, normal and wet year conditions. Flow data, at a 6-minute timestep, were obtained from the McMahon's Creek gauge (229106A) operated by Melbourne Water, while rainfall data were obtained from the closest gauge (229102A) at Upper Yarra Dam. Calibration was undertaken for a range of flow metrics covering the magnitude, timing and duration of flows, based on the approach described by Hamel and Fletcher (2014). The model calibration is described in detail in Duncan et al. (2016). After model calibration, the model scenarios were developed to represent different cases of SCM implementation as described below

Natural (pre-development) scenario: This scenario represents the existing natural conditions in the case study catchment. It forms the baseline for assessing the performance of the SCM implementation strategies.

Urban base scenario: We then developed a model to simulate complete urbanisation of the catchment according to typical urbanisation guidelines and practices in Melbourne (see Duncan et al, 2016) without stormwater mitigation measures. In this scenario the impervious area comprised 68% of the total catchment area, containing housing, roads and associated impervious areas.

SCM implementation scenarios: Stormwater management scenarios were applied in MUSIC to the urban base-case scenario with the aim of moving the flow regime back towards its pre-development conditions. Management actions explored include diversion of ground-level impervious runoff to bioretention systems, domestic and non-domestic water use from rainwater tanks, diversion of tank overflow and controlled low-flow 'leaks' to bioretention and harvesting of water from stormwater pipes upstream of watercourses for off-stream storage and non-potable uses (e.g. landscape irrigation). We adopted three basic SCM scenarios, herein labelled SCM30, SCM45 and SCM65, where the numbers (30, 45, 65) represent the target percentage reduction in runoff volume). The overarching design objective was based on total runoff volume reduction in comparison to the urbanised base case without SCM implementation (Table 2). Scenario SCM30 uses only bioretention and rainwater tanks to achieve a total 30% volume reduction. All ground level impervious runoff in this scenario was directed to bioretention systems, while household roof runoff was directed to rainwater tanks which had a controlled slow-release to bioretention. Scenario SCM45 uses the same measures as SCM30, and in addition models the removal of additional 20% of the remaining runoff from stormwater pipes upstream of the watercourse, representing use for a range of non-potable purposes such as landscape irrigation, industry or agriculture. This scenario targeted an overall reduction in runoff volume of 45%. Scenario SCM65 uses the same measures as SCM45 but increases additional flow removal from 20% to 50% of runoff from stormwater pipes in every time step, thus achieving a total runoff volume reduction of 65%. Such a scenario might represent the case where stormwater was harvested, and treated, before being stored and used in the potable supply, as is already being trialled in some locations (e.g. McArdle et al., 2011) .

The MUSIC model outputs include flow time-series at 6-minute timestep, representing the flow regime of each modelled scenario (Fig. 3). Further details of the flow regimes of modelled hydrological scenarios are reported in the Supplementary Material.

Table 2. Volume reduction scenarios and pairs of basic SCMs used to retain volume reduction. See text for definition of scenarios acronyms.

Flow regime scenario	Volume reduction (%)	SCMs used to retain volume reduction
Natural	Natural	None
Fully urban	0	None (surface runoff directed to stream via stormwater pipes upstream of watercourse)
SCM30	30	Tanks and bioretention
SCM45	45	As FRM1 and 20% runoff removal from stormwater pipes
SCM65	65	As FRM2 and 50% runoff removal from stormwater pipes

2.5 Hydraulic modeling and scenarios

TUFLOW Classic is a numerical model that solves the full 2D (depth-averaged) momentum and continuity equations for free surface flow (Syme, 2001). It was used to simulate the spatially explicit hydraulic patterns of the five flow regimes delivered from each of the hydrological scenarios described above. A square grid computational mesh was elevated with the RiverBuilder's DTM data points generated for the channel reach, with 150 longitudinal nodes spaced at 0.5 m (~1/16 W_{bf}). The default TUFLOW Smagorinsky viscosity was used for turbulence closure with coefficient value of 0.5 and constant value of 0.005m^2/s suitable for shallow waters (e.g. Anim et al., 2018a). Manning's n was set to 0.05, representing typical unvegetated coarse-grained (gravel/boulders) surface roughness (Arcement and Schneider, 1989). Typical of published exploratory numerical modeling studies, calibration of bed roughness or eddy viscosity was not possible as the study uses numerical models of theoretical channel archetypes in purely exploratory mode (e.g., Pasternack et al., 2008; Brown et al., 2016; Lane et al., 2018).

Model simulation input and exit boundary conditions included 10 flow stage and corresponding discharge (Q), ranging from 0.2-2.0x the bankfull flow (Q_{bkf}) stage (Table 3). Q_{bkf} stage is the water surface elevation (WSE) at which flow overtops the banks. Manning's equation was used to estimate the discharge values associated with the modelled flow stage based on representative cross-sections of the synthetic DTM (Table 3). Bankfull stage and wetted perimeter were calculated manually from the cross-sections and cross-sectional area determined using the parabolic approximation. These hydrological values used are scaled to the synthetic DTM to associate each modelled flow stage in the hydraulic model. We emphasize that these are estimates and should not be considered as utmost targets to inform management. 2D model outputs include hydraulic rasters of depth-averaged velocity in the direction of flow, water depth, bed shear stress (τ_b) and WSE. ArcGIS (Esri ArcGIS desktop 10.2) was used to process and analyze these outputs to evaluate each investigated scenario.

Table 3. Channel archetype discharge values simulated for 0.2-2.0 times bankfull stage estimated using Manning's equation

Fraction of $\boldsymbol{Q_{bkf}}$ stage	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Simulated $\boldsymbol{Q}$ (m^3/s)	0.18	0.73	1.64	2.62	3.83	5.86	8.35	10.90	13.17	17.15

2.6 Ecologically relevant hydraulic metrics

This study considered three eco-hydraulic relevant metrics associated with key components of stream ecosystem functions: variation of benthic disturbance that affect bed mobilization and drift of benthic biota that lives in them (e.g. Gibbins et al., 2010); variation of hydraulic diversity (e.g. Gostner et al., 2013); and physical habitat availability (e.g. Vietz et al., 2013). Quantitative hydraulic performance metrics related to these ecosystem functions used includes: (i) established near-bed Shield stress thresholds as indicators of bed mobility, (ii) a measure of spatial heterogeneity of flow depth and velocity that reflects overall reach hydraulic diversity and (iii) a measure of retentive habitat area that quantifies availability of slow and shallow depth water. We examined these hydraulic functions using an ArcGIS decision tree that enabled rapid evaluation of the hydraulic model raster outputs over specific defined threshold bounds.

2.6.1 Benthic disturbance

Benthic space is naturally disturbed by bed material movement in unaltered hydrological regime reaches on a periodic basis, but this process has been shown to increase in magnitude, frequency and duration with urbanization. This increases streambed instability and degradation (e.g. Hawley and Vietz, 2016; Anim et al., 2018a) and impacts biota (Hawley et al., 2016). The non-dimensionalized bed shear stress known as Shields stress (τ^*) was used to quantify the bed mobility potential of the channel in each grid cell of the model. The shields stress was calculated as:

$$\tau * = \frac{\tau_b}{D_{50}(\gamma_s - \gamma_w)} \tag{4}$$

where τ_b is bed shear stress and γ_s and γ_w are the unit weight of bed particle and water respectively. In this study, τ^* values where classified based on established bed particle mobility threshold, where $\tau^* < 0.03$ indicates stable bed or no mobility, $0.03 < \tau^* < 0.06$ indicates partial mobility (i.e. incipient motion of finer particles at the bed surface) and $\tau^* > 0.06$ indicate full bed mobility (i.e. persistent movement of a sheet of bed particles) (Wilcock and McArdell, 1993; Buffington and Montgomery, 1997; Sawyer et al., 2010). The mobility performance was then quantified as the cumulative proportion of the channel bed experiencing the different levels of mobility as defined by the threshold. The results were then binned for comparison purposes such that low, medium, and severe disturbance are associated with 0-20%, 20-50% and above 50% proportion of the channel bed experiencing at least partial bed mobility respectively. For instance, above 50% of the channel bed area must be experiencing at least partial or full bed mobility to be considered severe disturbance.

2.6.2 Hydraulic diversity

Varying patterns of flow velocity and depth have been recognized as part of the stream heterogeneity key to ecosystem integrity (Rosenfeld et al., 2011b). Hydraulic variability supports differentiation of species' life history strategies (Verberk et al., 2008; Braun and Reynolds, 2014). We used the hydro-morphological index of diversity (HMID) developed by Gostner et al. (2013) to quantify the overall hydraulic diversity in the channel for a given discharge. The HMID is based on the reach-scale coefficient of variation (CV) of flow velocity (u) and water depth (d) estimated as:

$$HMID_{channel} = (1 + CV_u)^2 + (1 + CV_d)^2 \quad (5)$$

where $CV = \sigma/\mu$, σ and μ are the standard deviation and mean value respectively. Results were binned to reflect Gostner et al. (2013) proposal such that HMID <5 assumes low diversity; 5 < HMID < 9 assumes medium or transitional diversity; HMID > 9 assumes high diversity.

2.6.3 Retentive habitat availability

Shallow slow-water habitat (SSWH) area was used to evaluate the relative habitat availability for explored scenarios. SSWH are vulnerable to an altered hydrological regime. Decreases in SSWH area impact fish abundance, macroinvertebrates that rely uses such habitat for refugia, and organic matter retention (Schiemer et al., 2001; Vietz et al., 2013). SSWH (total area per channel length) was estimated from the model flow depth and velocity raster using an ArcGIS python script that processes water depth and velocity outputs to locate cells with joint velocity and depth values of 0-0.2 m/s and 0-0.3 m respectively. This depth and velocity criteria is particularly preferred by fish (Milhous and Nestler, 2016) and benthic macroinvertebrates (Shearer et al., 2015) in streams.

2.7 Hydraulic regime performance analysis

An approach that blends hydrological time series with functional hydraulic performance was employed to evaluate the hydraulic response of each explored flow regime scenario. First, functional relationships were developed for the full range of flows modelled (Table 3) for each hydraulic metric investigated. Then the functional relationships were integrated with flow time series of each hydrologic scenario to yield hydraulic metric time series. The resulting annual time series represent the temporal pattern of the hydraulic response under each hydrologic scenario. The relative influence of each flow scenario to maintain or restore stream hydraulics regime was evaluated by quantitively characterizing and comparing the temporal variation in each explored hydraulic metrics to the pre-development conditions. This approach employed simple descriptive statistics, where the statistical analysis of the time-series of each metric aimed to evaluate the relative percent change of the various aspects of the hydraulic behaviour. This includes frequency, magnitude and duration, which are key elements of the hydraulic template (Poff and Ward, 1990). The analysis also considered the increase or decrease of the metrics as a function of discharge relative to the explored scenarios where the degree of change was examined corresponding to the defined thresholds.

3. Results

3.1 Variability of hydraulic metrics with discharge

The model results showed a decrease in the portion of the channel benthic area experiencing no bed mobility ($\tau^*<0.03$) beginning as the flow reaches approximately 0.4 Q_{bkf} (Fig. 4a). This represents flows of 65% and 85% exceedance for both developed and pre-developed mean daily flow regime respectively. A slight decrease was then observed as flows near 0.9 Q_{bkf} and tends to stop as flows spills over the banks reaching a constant 15% with over 50% of the channel bed under partial or full mobility. A predicted ~75% of the wetted channel bed area experienced either partial or full bed mobility at bankfull flow.

The HMID values invariably decreased as flow increased and eventually stabilised once flow spilled over the banks (Fig. 4b). HMID was substantially higher at baseflows (< 0.2 Q_{bkf}) than higher flows (> 0.5 Q_{bkf}), with baseflow values about 4x as high. Above 0.2 Q_{bkf}, the HMID values reduce and attains medium values (5 < HMID < 9). It then transitions from medium to low values (HMID <5) as flows reaches 0.5 Q_{bkf} and tends to stop around an approximately constant value of HMID = 2 for very high flows. Here, larger flow depth and velocity CV for flows below 0.2 Q_{bkf} was observed. Generally, mean flow velocities and water depth ranged from 0 to 1.1 m/s and 0 to 0.83 m respectively. At Q_{bkf}, maximum velocity and depth were 1.5 m/s and 1.28 m respectively. The water depth was observed to change rapidly at low flow variations (<0.3 Q_{bkf}), whereas the flow velocity was sensitive to variations in high flows (>0.5 Q_{bkf}).

The SSWH area initially increased gradually with complete wetting conditions of the active channel bed topography as flow increased (Fig. 4c). This was associated with low flows up to 0.2 Q_{bkf}, beyond which the SSWH area diminished rapidly and was near zero at Q_{bkf}. Once flows overtopped the banks, there was a substantial increase in SSWH area as floodplains were inundated.

3.2 Hydrologic scenarios comparisons

3.2.1 Benthic disturbances

The urban baseline scenario produced the most unstable bed within the channel, dominated by increased periods of the channel bed experiencing either partial or full mobility (Fig. 5). The predicted frequency and magnitude of portion of the benthic space that was exhibiting severe benthic disturbance (period that over 50% of the channel bed area shows partial or full bed mobility) were substantially greater. The influence of flow alteration in the urban hydrological regimes was revealed in the frequency and duration of the severe disturbance (Fig. 6a and 6b). For example, comparing the natural flows and urban flows the frequency (number of days) that channel bed areas experience severe disturbance under urban scenario was about 50x that of the natural (pre-developed) state. This was estimated to be 217 days for the study period, averaging 37 days/year. This represents ~8% of the total study period compared to 0.1% for the natural. It reflected the increased frequent-high magnitude storm flows with the altered hydrology. In other words, almost all the estimated days of channel experiencing severe disturbance under urban scenario were associated with flows occurring ~40% of the time. In contrast, the natural flow regime resulted in predominantly stable bed most of the year, averaging 2 days/year of severe disturbance, with approximately 85% and 14% of low and moderate disturbance respectively.

The different SCM approach interventions (SCM30, SCM45, SCM65) showed reduced potential benthic disturbance compared to the fully urban. The observed periods of severe disturbance compared to the urban scenario were substantially improved particularly for SCM65 which showed a benthic disturbance regime close to the natural scenario. The estimated period under severe disturbance plummeted from 8% under urban scenario to 5%, 2.7% and 0.4% under SCM30, SCM45 and SCM65 respectively. More importantly, the temporal analysis revealed that, the continuous duration of the channel bed exhibiting severe disturbance of greater than 2 days was substantially reduced with SCMs applied (Fig. 6b). Similar to the natural scenario, the duration of period of severe disturbance in the channel bed under SCM65 was short-lived, mostly within 0-2 days. Here, the period of severe disturbance was only larger for long duration-high magnitude flows occurring ~3% of the time of the flow regime.

3.2.2 Reach hydraulic diversity

The temporal hydraulic diversity pattern was highlighted by the HMID exceedance curves for all investigated scenarios (Fig. 7). For all scenarios, HMID values were within moderate to high bins about 75% of the time. The natural scenario produced higher HMID values for most of the year showing higher temporal persisting diverse in-channel hydraulics, with values within medium to high performance equalled or exceeded ~95% of the time. Under urban scenario, high HMID values (>9) occurred only 20% of the time with marginally higher (>11) values compared to all other hydrologic scenarios exceeded 10% of the time. This is related to the extended lower summer and winter baseflows under urban scenario. For flow regimes under SCM intervention scenarios (SCM30, SCM45, SCM65), HMID values showed some improvement in the temporal hydraulic diversity compared to urban scenario, particularly for SCM65 (which yielded an HMID regime close to that of natural scenario).

The natural scenario shows consistently high HMID values across the year, particularly during winter period (June-August) when frequent storms flows are expected (Fig. 8). SCM65 exhibited a similar HMID pattern to natural scenario. Sensitivity of the hydraulic diversity to frequent flow alteration was illustrated for urban scenario, when HMID values fluctuated rapidly between low, medium and high performance.

3.2.3 Retentive habitat availability

SSWH area exceedance curves revealed a substantial reduction of the temporal persistence of SSWH availability in the channel under the urban flow regime (Fig. 9). This was up to about 3x less relative to the natural scenario for the total study duration, particularly for flows between 40-60% exceedance. Considering the median of these flow regimes (Table 4), the urban scenario reduces SSWH availability on average by approximately 30-45% annually for the study period. As low flows produce higher SSWH availability in general, it is unsurprising that urban scenario exhibited slightly higher SSWH areas occurring about 20% of the time, related to the extended lower baseflows.

The influence of flow alteration in the urban flow regimes was also revealed in the frequency distribution of SSWH availability per unit 150 m over the study duration (Fig. 10). For example, comparing natural and urban scenarios showed a reduction in the frequency (number of days) of larger areas of SSWH (>200 m^2/150 m). Under natural scenario, diversity in the SSWH areas is greatest with larger areas of SSWH frequently present. Smaller areas of SSWH (< 100 m^2/150 m) are most common under altered hydrological regimes particularly for the urban scenario which skews the distribution further. Overall, reductions of SSWH availability was minimized by the alternative SCM scenarios (SCM30, SCM45 and SCM65). The applied SCMs appropriately improved the totally skewed to very little SSWH areas commonly occurring under urban scenario towards the natural scenario. This improvement was most evident for SCM65, which retained a total SSWH areas close to the natural scenario, with only marginal reduction in the magnitude and duration of SSWH areas. Conversely SCM30 had little effect on the frequency and magnitude of larger SSWH areas.

Table 4. SSWH area of each modelled scenario at median flows

Modelled scenario	Flow (m^3/s)	SSWH area (m^2)
Natural	0.188	240.6
SCM65	0.177	255.2
SCM45	0.247	161.2
SCM35	0.294	143.3
Urban	0.381	130.0

4. Discussion

4.1 Hydraulic effects of an urban-induced altered hydrologic regime

As demonstrated in this study, the altered flow regime that results from urbanization drives fundamental deleterious changes to the natural hydraulic regime of the stream ecosystem. This coincides with widely recognized arguments made by researchers that urban stormwater runoff is a major stressor to urban stream ecosystems (Brabec et al., 2002; Walsh, 2004; Ladson et al., 2006; Burns et al., 2012; Vietz et al., 2014). In turn, this is a primary contributor to decreased ecological health often observed in streams draining urban catchments (Wenger et al., 2009; Groffman et al., 2014).

The results suggest that the urban flow regime could lead to the channel experiencing substantially higher bed mobility, making the channel bed highly unstable, the first stage to channel incision (Hawley and Vietz, 2016). Full transport defined by Sawyer et al. (2010) as persistent entrainment of a sheet of bed particles will occur more frequently and for longer durations following urbanization, given that urban hydrology is characterized by increased frequency, magnitude and volume of storm flows (Anim et al., 2018b). This means acceleration of channel evolution processes, including deleterious positive feedback such as containment of greater volumes of streamflow once channel capacity increases (Vietz and Hawley, 2018).

Increased frequency, duration, and spatial extent of bed mobility in this degradation mechanism translates to ecological impacts via regular disturbance of physical habitat (Francoeur and Biggs, 2006) and eventually habitat loss, limiting benthic refuge space (Negishi et al., 2002). Benthic disturbance dynamics is a key factor in the distribution, abundance and diversity of benthic biota (Townsend et al., 1997). This type of disturbance does not yield a consistent regime that species can adapt or acclimatise to.

Sensitivity of spatial and temporal hydraulic diversity to the flow alteration after urbanization has relevant implications for biodiversity and ecosystem functioning. While the channel maintained temporal persistence of high range and coefficient of variation of depth and velocity for the most part, altered hydrology in the urban case increases the magnitude and frequency of higher discharge events. This renders the channel liable to frequent fluctuations of hydraulic diversity, with limited temporal persistence of the larger range and covariance of depth and velocity. Gostner et al. (2013) argued that for channels experiencing such rapid fluctuations, the chances of maintaining a healthy biotic stream community are limited. While a higher hydraulic diversity alone does not necessarily yield a healthy stream or suitable ecological performance, it is expected to impact the longitudinal distribution and assemblages of biota (Elosegi et al., 2010; Lane et al., 2018).

In addition, retentive habitat availability under the urban hydrological regime is low, limiting opportunities for biotic refuge. Persistent limited availability of SSWH can reduce breeding and rearing habitat and refuge which could be a major factor for local extinction and reduced assemblages and diversity of biota (Poznańska et al., 2009; Wenger et al., 2009; Koperski, 2010).

These factors suggest that appropriate urban flow regime stormwater management is a likely requirement to protect the hydraulic conditions of streams. Excess stormwater runoff volume needs to be prevented from becoming streamflow to have a chance of sustaining the ecosystem functioning.

4.2 Can catchment-scale application of SCMs restore a more natural hydraulic condition?

Our results demonstrate that a high level of SCM implementation is necessary to maintain in-stream hydraulic conditions close to pre-development levels in urban catchments. Similar to what is proposed to restore and/or protect geomorphic form (Vietz et al., 2015), water quality (Fletcher et al., 2014) and ecology (Walsh et al., 2015). The hydraulic performance of the SCM scenarios (SCM30, SCM45, SCM65), compared with the natural scenario suggest that protecting or restoring ecologically relevant aspects hydraulic regime through catchment-scale application of SCMs is feasible, but requires relatively high levels of SCM intervention. The hydraulic behaviour of adopted hydraulic performance metrics showed that the three designed SCM scenarios could potentially reduce the impact of stormwater runoff on the stream ecosystem. The volume reduction achieved is an important surrogate predictor of the changes to each of hydraulic metrics, with the most effective scenario being SCM65. The SCM30 scenario provided only marginal improvement of the hydraulic conditions.

The observation that intensive application of SCMs is necessary to fully protect the hydraulic environment has important implications for stormwater management. In reality, achieving such volume reductions will need to involve significant harvesting; relying on infiltration or evapotranspiration alone will not be sufficient (Walsh et al. 2016). In essence, the design stormwater control measures should have the capacity to retain rainfall up to the amount that would have caused widespread surface runoff under natural catchment conditions (Burns et al., 2015b). As an example, in south-eastern Australia, this amount has been calculated as being around 25 mm (Hill et al., 1996).

Several authors have demonstrated that achieving such an outcome requires that SCMs be applied at or near source throughout the catchment (e.g. Meyer and Wallace, 2001; Burns et al., 2015a; Walsh et al., 2016), as this provides greater opportunity to mimic natural flow paths and restore a natural water balance. By this reasoning, we posit that, it is possible for urbanization to be managed with suitable infrastructure to avoid significant impact on the in-stream hydraulic conditions. Management interventions to achieve such large volume reduction include diversion of ground level impervious runoff to bioretention systems, domestic and non-domestic water use from rainwater tanks, diversion of tank overflow and controlled low-flow ‘leaks’ to bioretention and harvesting of water from stormwater pipes upstream of the stream for offstream storage and use (e.g. DeBusk et al., 2010a; Burns et al., 2015a).

Our modelling suggests that lower levels of implementation of SCMs are unlikely to provide the natural hydraulic conditions, as demonstrated by the SCM30 scenario. This suggests that partial hydrological regime restoration in an established urbanized catchment may not be enough to protect the hydraulic environment.

4.3 Challenges of appropriate scale for flow-regime stormwater management

Achieving high levels of volume reduction could be challenging, especially in an established urban catchment, due to space constraints and limited demand for alternative water supplies (Hamel et al., 2013; Walsh et al., 2016). In a retrofit situation, there will be a large cost required for retention and storage (see for example Burns et al., 2015a; Li et al., 2017), but it is worth noting that such strategies also bring other benefits such as improving urban amenity through increased social values and enhancing the urban microclimate (Roehr and Fassman-Beck, 2015; Kuller et al., 2017). Considering these challenges, it is clear that implementation will be most feasible when it is planned at the development phase, where there is the potential to incorporate the required SCMs and water harvesting as part of the construction phase, both reducing net cost and maximising the other secondary benefits provided (Walsh et al., 2016).

4.4 Opportunities for management to protect stream ecosystem

The results of this study suggest that the definition of urban stormwater management for stream protection should require meeting objectives that maintain the natural hydraulic regime of receiving streams. In this context, hydraulic performance metrics provide useful and specific design objectives for SCM implementation. Recent studies have contended that streamflow considerations should go beyond hydrologic assessment and include hydrogeomorphic evaluations that provide a better understanding of the effects of intended management actions (Wohl et al., 2015; Yarnell et al., 2015; Stone et al., 2017). Hydraulic conditions provide an explicit mechanistic linkage between exogenous variables and ecological responses and are associated with key components of stream ecosystem integrity: hydrogeomorphic processes and aquatic habitat (Kemp et al., 2000; Escobar-Arias and Pasternack, 2010; Vanzo et al., 2016). This is in line with the guidance of Walsh et al. (2016), who argue that a target for the ecological state of the stream ecosystem to be protected should be identified and used to set performance objectives for catchment-wide stormwater management.

5. Conclusions and future works

Stream ecosystem processes are substantially governed by their hydraulic regime, which in turn is driven substantially by catchment hydrology. This study examined how catchment-wide application of stormwater control measures implemented focused on restoring more natural flow regimes in an urbanizing catchment could maintain or restore in-stream hydraulics towards their pre-development conditions. By investigating quantitative eco-hydraulic metrics, we were able to evaluate the hydraulic response to changes in the hydrological regimes. Comparing the performance of these metrics suggested that SCM implementation is a prerequisite to sustaining the hydraulics at pre-development levels to protect the ecological structure and function.

The results highlighted that stormwater management that maximises the retention, harvesting and infiltration of surface runoff would have noticeable impact if applied intensively throughout the catchment, such that the runoff volume approaches that which would have occurred prior to urbanisation. Given that the managed flow regimes should result in suitable hydraulic conditions for ecosystem functioning, we propose that stormwater management and protection of stream ecosystem processes should target strategies for and incorporate anticipated effects on stream hydraulics. Our study provides a novel framework for more quantitative assessment of the effectiveness of stormwater management strategies, using hydraulic metrics associated with key elements of stream ecosystem functions.

Our study has emphasized the need for a large proportion of surface runoff to be prevented from becoming streamflow. We acknowledge this will be challenging in terms of the space required, cost, and finding demand for the harvested stormwater, particularly for an established urban catchment. Such challenges should be weighed up, however, against the range of other benefits to urban amenity that result from returning a more natural water balance in urban landscapes.

Further work is needed to identify specific hydraulic metrics that could guide design in particular streams, based on channel form, substrate composition, or ecological values to be protected. In addition, in cases of established urban catchments, where restoring altered flow regimes is difficult, further research would be useful to understand how the target stream's channel form influences the effect of altered hydrology on key stream ecosystem functions. Understanding the template of hydraulic conditions that results from the interplay between channel form and flow could help to design complementary channel modification. Independent adjustment of flow and channel form might give managers additional flexibility for ecologically successful restoration and protection of streams in urban catchments.

Acknowledgements

This work was funded by a University of Melbourne Research Scholarship and undertaken through the Waterway Research Practice Partnership, supported by Melbourne Water. T.D Fletcher was supported by ARC project FT100100144 during part of this work. The manuscript benefited greatly from comments from two anonymous reviewers.

References

Anim, D. O., Fletcher, T. D., Vietz, G., Pasternack, G., & Burns, M. J. (2018a). Effect of urbanization on stream hydraulics. *River Research and Applications*, 1-14. doi: 10.1002/rra.3293

Anim, D. O., Fletcher, T. D., Vietz, G., Pasternack, G., & Burns, M. J. (2018b). Restoring in-stream habitat in urban catchments: modify flow or the channel? *Ecohydrology,* e2050. doi: doi.org/10.1002/eco.2050

Arcement, G. J., & Schneider, V. R. (1989). Guide for selecting Manning's roughness coefficients for natural channels and flood plains: US Government Printing Office Washington, DC.

Beechie, T. J., Sear, D. A., Olden, J. D., Pess, G. R., Buffington, J. M., Moir, H., . . . Pollock, M. M. (2010). Process-based principles for restoring river ecosystems. *BioScience, 60*(3), 209-222. doi:10.1525/bio.2010.60.3.7

Brabec, E., Schulte, S., & Richards, P. L. (2002). Impervious surfaces and water quality: a review of current literature and its implications for watershed planning. *Journal of planning literature, 16*(4), 499-514. doi:10.1177/088541202400903563

Braun, D. C., & Reynolds, J. D. (2014). Life history and environmental influences on population dynamics in sockeye salmon. *Canadian Journal of Fisheries and Aquatic Sciences, 71*(8), 1198-1208. doi: 10.1139/cjfas-2013-0326

Brooks, A. J., Haeusler, T., Reinfelds, I., & Williams, S. (2005). Hydraulic microhabitats and the distribution of macroinvertebrate assemblages in riffles. *Freshwater biology, 50*(2), 331-344. doi:10.1111/j.1365-2427.2004.01322.x

Brown, R., Pasternack, G., & Wallender, W. (2014). Synthetic river valleys: Creating prescribed topography for form–process inquiry and river rehabilitation design. *Geomorphology, 214*, 40-55. doi:10.1016/j.geomorph.2014.02.025

Brown, R. A., Pasternack, G. B., & Lin, T. (2016). The topographic design of river channels for form-process linkages. *Environmental management, 57*(4), 929-942. doi:10.1007/s00267-016-0663-9

Buffington, J. M., & Montgomery, D. R. (1997). A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers. *Water Resources Research, 33*(8), 1993-2029. doi:10.1029/96WR03190

Burns, M. J., Fletcher, T. D., Duncan, H. P., Hatt, B. E., Ladson, A. R., & Walsh, C. J. (2015a). The performance of rainwater tanks for stormwater retention and water supply at the household scale: an empirical study. *Hydrological Processes, 29*(1), 152-160. doi:10.1002/hyp.10142

Burns, M. J., Fletcher, T. D., Walsh, C. J., Ladson, A., & Hatt, B. (2013). Setting objectives for hydrologic restoration: from site-scale to catchment-scale. *NOVATECH 2013*.

Burns, M. J., Fletcher, T. D., Walsh, C. J., Ladson, A. R., & Hatt, B. E. (2012). Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform. *Landscape and Urban Planning, 105*(3), 230-240.

Burns, M. J., Fletcher, T. D., Walsh, C. J., Ladson, A. R., & Hatt, B. E. (2014). Flow-Regime Management at the Urban Land-Parcel Scale: Test of Feasibility. *Journal of Hydrologic Engineering, 20*(12), 04015037.

Burns, M. J., Schubert, J. E., Fletcher, T. D., & Sanders, B. F. (2015b). Testing the impact of at-source stormwater management on urban flooding through a coupling of network and overland flow models. *Wiley Interdisciplinary Reviews: Water, 2*(4), 291-300.

Clark, J. S., Rizzo, D. M., Watzin, M. C., & Hession, W. C. (2008). Spatial distribution and geomorphic condition of fish habitat in streams: an analysis using hydraulic modelling and geostatistics. *River Research and Applications, 24*(7), 885-899.

Clarke, S. J., Bruce-Burgess, L., & Wharton, G. (2003). Linking form and function: towards an eco-hydromorphic approach to sustainable river restoration. *Aquatic Conservation: Marine and Freshwater Ecosystems, 13*(5), 439-450.

Damodaram, C., Giacomoni, M. H., Prakash Khedun, C., Holmes, H., Ryan, A., Saour, W., & Zechman, E. M. (2010). Simulation of combined best management practices and low impact development for sustainable stormwater management. *JAWRA Journal of the American Water Resources Association, 46*(5), 907-918.

Davis, A. P., Traver, R. G., Hunt, W. F., Lee, R., Brown, R. A., & Olszewski, J. M. (2011). Hydrologic performance of bioretention storm-water control measures. *Journal of Hydrologic Engineering, 17*(5), 604-614.

DeBusk, K. M., Hunt, W. F., Hatch, U., & Sydorovych, O. (2010a). Watershed retrofit and management evaluation for urban stormwater management systems in North Carolina. *Journal of Contemporary Water Research & Education, 146*(1), 64-74.

DeBusk, K. M., Hunt, W. F., & Line, D. E. (2010b). Bioretention outflow: Does it mimic nonurban watershed shallow interflow? *Journal of Hydrologic Engineering, 16*(3), 274-279.

Duncan, H. P., Fletcher, T. D., Vietz, G., & Urrutiaguer, M. (2016). The feasibility of maintaining ecologically and geomorphically important elements of the natural flow regime in the context of a superabundance of flow: Stage 2 – McMahons Creek Study. Melbourne Waterway Research-Practice Partnership Technical Report 16.1.

Elosegi, A., Díez, J., & Mutz, M. (2010). Effects of hydromorphological integrity on biodiversity and functioning of river ecosystems. *Hydrobiologia, 657*(1), 199-215.

Emery, J. C., Gurnell, A. M., Clifford, N. J., Petts, G. E., Morrissey, I. P., & Soar, P. J. (2003). Classifying the hydraulic performance of riffle-pool bedforms for habitat assessment and river rehabilitation design. *River Research and Applications*, *19*(5-6), 533-549.

Escobar-Arias, M., & Pasternack, G. B. (2010). A hydrogeomorphic dynamics approach to assess in-stream ecological functionality using the functional flows model, part 1—model characteristics. *River Research and Applications, 26*(9), 1103-1128.

eWater. (2015). MUSIC - Model for Urban Stormwater Improvement Conceptualisation - User Guide 4. *eWater Cooperative Research Centre, Canberra, Australia*.

Fletcher, T., Andrieu, H., & Hamel, P. (2013). Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. *Advances in Water Resources, 51*, 261-279. doi:10.1016/j.advwatres.2012.09.001

Fletcher, T. D., Vietz, G., & Walsh, C. J. (2014). Protection of stream ecosystems from urban stormwater runoff The multiple benefits of an ecohydrological approach. *Progress in Physical Geography*, 38(5), 543-555.

Francoeur, S. N., & Biggs, B. J. (2006). Short-term effects of elevated velocity and sediment abrasion on benthic algal communities *Advances in Algal Biology: A Commemoration of the Work of Rex Lowe* (pp. 59-69): Springer.

Gibbins, C., Batalla, R. J., & Vericat, D. (2010). Invertebrate drift and benthic exhaustion during disturbance: Response of mayflies (Ephemeroptera) to increasing shear stress and river-bed instability. *River Research and Applications, 26*(4), 499-511.

Gostner, W., Parasiewicz, P., & Schleiss, A. (2013). A case study on spatial and temporal hydraulic variability in an alpine gravel-bed stream based on the hydromorphological index of diversity. *Ecohydrology, 6*(4), 652-667. doi:10.1002/eco.1349

Groffman, P. M., Cavender-Bares, J., Bettez, N. D., Grove, J. M., Hall, S. J., Heffernan, J. B., . . . Neill, C. (2014). Ecological homogenization of urban USA. *Frontiers in Ecology and the Environment, 12*(1), 74-81.

Haase, D. (2009). Effects of urbanisation on the water balance–A long-term trajectory. *Environmental impact assessment review, 29*(4), 211-219.

Hamel, P., Daly, E., & Fletcher, T. D. (2013). Source-control stormwater management for mitigating the impacts of urbanisation on baseflow: A review. *Journal of Hydrology, 485*, 201-211.

Hamel, P., & Fletcher, T. D. (2014). Modelling the impact of stormwater source control infiltration techniques on catchment baseflow. *Hydrological Processes*, *28*(24), 5817-5831.

Hawley, R., & Vietz, G. (2016). Addressing the urban stream disturbance regime. *Freshwater Science, 35*(1), 278-292.

Hawley, R. J., Wooten, M. S., MacMannis, K. R., & Fet, E. V. (2016). When do macroinvertebrate communities of reference streams resemble urban streams? The biological relevance of Q critical. *Freshwater Science, 35*(3), 778-794.

Hill, P., Maheepala, U., Mein, R., & Weinmann, P. (1996). Empirical analysis of data to derive losses for design flood estimation in South-Eastern Australia. *Cooperative Research Centre for Catchment Hydrology, Monash University, Clayton, Victoria. Report, 96*(5).

Hunt, W. F., Davis, A. P., & Traver, R. G. (2011). Meeting hydrologic and water quality goals through targeted bioretention design. *Journal of Environmental Engineering, 138(6),* 698-707.

Jacobson, R. B., & Galat, D. L. (2006). Flow and form in rehabilitation of large-river ecosystems: an example from the Lower Missouri River. Geomorphology, 77(3), 249-269.

Jenkins, G. A., Greenway, M., & Polson, C. (2012). The impact of water reuse on the hydrology and ecology of a constructed stormwater wetland and its catchment. *Ecological Engineering, 47*, 308-315.

Kemp, J. L., Harper, D. M., & Crosa, G. A. (2000). The habitat-scale ecohydraulics of rivers. *Ecological Engineering, 16*(1), 17-29.

Kondolf, G., Boulton, A., O'Daniel, S., Poole, G., Rahel, F., Stanley, E., . . . Cristoni, C. (2006). Process-based ecological river restoration: visualizing three-dimensional connectivity and dynamic vectors to recover lost linkages. *Ecology and society, 11*(2).

Koperski, P. (2010). Urban environments as habitats for rare aquatic species: The case of leeches (Euhirudinea, Clitellata) in Warsaw freshwaters. *Limnologica-Ecology and Management of Inland Waters, 40*(3), 233-240.

Kuller, M., Bach, P. M., Ramirez-Lovering, D., & Deletic, A. (2017). Framing water sensitive urban design as part of the urban form: A critical review of tools for best planning practice. *Environmental Modelling & Software, 96*, 265-282.

Ladson, A. R., Walsh, C. J., & Fletcher, T. D. (2006). Improving stream health in urban areas by reducing runoff frequency from impervious surfaces. *Australian Journal of Water Resources, 10*(1), 23-33.

Land Conservation Council of Victoria. (1973). Report on the Melbourne Study Area. *Land Conservation Council of Victoria, Melbourne*.

Lane, B. A., Pasternack, G. B., & Sandoval-Solis, S. (2018). Integrated analysis of flow, form, and function for river management and design testing. *Ecohydrology*, e1969.

Li, C., Fletcher, T. D., Duncan, H. P., & Burns, M. J. (2017). Can stormwater control measures restore altered urban flow regimes at the catchment scale? *Journal of Hydrology, 549*, 631-653.

Liu, R., & Fassman-Beck, E. (2017). Hydrologic experiments and modeling of two laboratory bioretention systems under different boundary conditions. *Frontiers of Environmental Science & Engineering, 11*(4), 10.

Loperfido, J. V., Noe, G. B., Jarnagin, S. T., & Hogan, D. M. (2014). Effects of distributed and centralized stormwater best management practices and land cover on urban stream hydrology at the catchment scale. *Journal of Hydrology, 519*, 2584-2595.

Mallin, M. A., Johnson, V. L., & Ensign, S. H. (2009). Comparative impacts of stormwater runoff on water quality of an urban, a suburban, and a rural stream. *Environmental Monitoring and Assessment, 159*(1-4), 475-491.

McArdle, P., Gleeson, J., Hammond, T., Heslop, E., Holden, R., & Kuczera, G. (2011). Centralised urban stormwater harvesting for potable reuse. *Water Science and Technology, 63*(1), 16-24.

McIntyre, J., Davis, J., Hinman, C., Macneale, K., Anulacion, B., Scholz, N., & Stark, J. (2015). Soil bioretention protects juvenile salmon and their prey from the toxic impacts of urban stormwater runoff. *Chemosphere, 132*, 213-219.

Meyer, J., & Wallace, J. (2001). Lost linkages and lotic ecology: rediscovering small streams. *Ecology: Achievement and challenge, 295317*.

Milhous, R. T., & Nestler, J. (2016). *On history of habitat criteria in instream flow studies. Part I.* Paper presented at the 11th International Symposium on Ecohydraulics (ISE 2016).

Negishi, J., Inoue, M., & Nunokawa, M. (2002). Effects of channelisation on stream habitat in relation to a spate and flow refugia for macroinvertebrates in northern Japan. *Freshwater biology, 47*(8), 1515-1529.

Pasternack, G., & Arroyo, R. (2018). RiverBuilder: River Generation for Given Data Sets. *R package version 0.1.0*.

Pasternack, G. B., Bounrisavong, M. K., & Parikh, K. K. (2008). Backwater control on riffle–pool hydraulics, fish habitat quality, and sediment transport regime in gravel-bed rivers. *Journal of Hydrology, 357*(1-2), 125-139.

Paterson, A., & Whitfield, A. (2000). Do shallow-water habitats function as refugia for juvenile fishes? *Estuarine, Coastal and Shelf Science, 51*(3), 359-364.

Paul, M., & Meyer, J. (2008). Streams in the Urban Landscape. In J. Marzluff, E. Shulenberger, W. Endlicher, M. Alberti, G. Bradley, C. Ryan, U. Simon & C. ZumBrunnen (Eds.), *Urban Ecology* (pp. 207-231): Springer US.

Poff, N. L., & Ward, J. (1990). Physical habitat template of lotic systems: recovery in the context of historical pattern of spatiotemporal heterogeneity. *Environmental management, 14*(5), 629.

Poznańska, M., Kobak, J., Wolnomiejski, N., & Kakareko, T. (2009). Shallow-water benthic macroinvertebrate community of the limnic part of a lowland Polish dam reservoir. *Limnologica-Ecology and Management of Inland Waters, 39*(2), 163-176.

Roehr, D., & Fassman-Beck, E. (2015). *Living roofs in integrated urban water systems*: Routledge.

Rosenfeld, J., Hogan, D., Palm, D., Lundquist, H., Nilsson, C., & Beechie, T. J. (2011a). Contrasting landscape influences on sediment supply and stream restoration priorities in Northern Fennoscandia (Sweden and Finland) and coastal British Columbia. *Environmental management, 47*(1), 28-39.

Rosenfeld, J. S., Campbell, K., Leung, E. S., Bernhardt, J., & Post, J. (2011b). Habitat effects on depth and velocity frequency distributions: Implications for modeling hydraulic variation and fish habitat suitability in streams. *Geomorphology, 130*(3-4), 127-135.

Roy, A. H., Wenger, S. J., Fletcher, T. D., Walsh, C. J., Ladson, A. R., Shuster, W. D., . . . Brown, R. R. (2008). Impediments and solutions to sustainable, watershed-scale urban stormwater management: lessons from Australia and the United States. *Environmental management, 42*(2), 344-359.

Sawyer, A. M., Pasternack, G. B., Moir, H. J., & Fulton, A. A. (2010). Riffle-pool maintenance and flow convergence routing observed on a large gravel-bed river. *Geomorphology, 114*(3), 143-160.

Schiemer, F., Keckeis, H., Reckendorfer, W., & Winkler, G. (2001). The" inshore retention concept" and its significance for large rivers. *Arch. Hydrobiol.(Suppl.)(Large Rivers), 135*(2), 509-516.

Schubert, J. E., Burns, M. J., Fletcher, T. D., & Sanders, B. F. (2017). A framework for the case-specific assessment of Green Infrastructure in mitigating urban flood hazards. *Advances in Water Resources, 108,* 55-68.

Shearer, K., Hayes, J., Jowett, I., & Olsen, D. (2015). Habitat suitability curves for benthic macroinvertebrates from a small New Zealand river. *New Zealand journal of marine and freshwater research, 49*(2), 178-191.

Statzner, B., Gore, J. A., & Resh, V. H. (1988). Hydraulic Stream Ecology: Observed Patterns and Potential Applications. *Journal of the North American Benthological Society, 7*(4), 307-360. doi: 10.2307/1467296

Statzner, B., & Higler, B. (1986). Stream hydraulics as a major determinant of benthic invertebrate zonation patterns. *Freshwater biology, 16*(1), 127-139.

Stone, M. C., Byrne, C. F., & Morrison, R. R. (2017). Evaluating the impacts of hydrologic and geomorphic alterations on floodplain connectivity. *Ecohydrology*.

Syme, W. (2001). *TUFLOW-Two & Onedimensional unsteady flow Software for rivers, estuaries and coastal waters.* Paper presented at the IEAust Water Panel Seminar and Workshop on 2d Flood Modelling, Sydney.

Townsend, C. R., Scarsbrook, M. R., & Dolédec, S. (1997). The intermediate disturbance hypothesis, refugia, and biodiversity in streams. *Limnology and oceanography, 42*(5), 938-949.

Vanzo, D., Zolezzi, G., & Siviglia, A. (2016). Eco-hydraulic modelling of the interactions between hydropeaking and river morphology. *Ecohydrology, 9*(3), 421-437.

Verberk, W. C., Siepel, H., & Esselink, H. (2008). Life-history strategies in freshwater macroinvertebrates. *Freshwater biology, 53*(9), 1722-1738.

Vietz, G. J., & Hawley, R. J. (2018). Protecting and managing stream morphology in urban catchments. In T. G. A. Sharma, D. Begbie, eds. (Ed.), *Approaches to water sensitive urban design* (pp. 626): Woodhead Publishing, Elsevier.

Vietz, G. J., Sammonds, M. J., & Stewardson, M. J. (2013). Impacts of flow regulation on slackwaters in river channels. *Water Resources Research, 49*(4), 1797-1811.

Vietz, G. J., Sammonds, M. J., Walsh, C. J., Fletcher, T. D., Rutherfurd, I. D., & Stewardson, M. J. (2014). Ecologically relevant geomorphic attributes of streams are impaired by even low levels of watershed effective imperviousness. *Geomorphology, 206*, 67-78.

Vietz, G. J., Walsh, C. J., & Fletcher, T. D. (2015). Urban hydrogeomorphology and the urban stream syndrome Treating the symptoms and causes of geomorphic change. *Progress in Physical Geography, 40*(3), 480-492.

Wallis, C., Maddock, I., Visser, F., & Acreman, M. (2012). A framework for evaluating the spatial configuration and temporal dynamics of hydraulic patches. *River Research and Applications, 28*(5), 585-593.

Walsh, C. J. (2004). Protection of in-stream biota from urban impacts: minimise catchment imperviousness or improve drainage design? *Marine and Freshwater Research, 55*(3), 317-326.

Walsh, C. J., Booth, D. B., Burns, M. J., Fletcher, T. D., Hale, R. L., Hoang, L. N., . . . Scoggins, M. (2016). Principles for urban stormwater management to protect stream ecosystems. *Freshwater Science, 35*(1), 398-411.

Walsh, C. J., Fletcher, T. D., Bos, D. G., & Imberger, S. J. (2015). Restoring a stream through retention of urban stormwater runoff: a catchment-scale experiment in a social–ecological system. Freshwater Science, 34(3), 1161-1168.

Walsh, C. J., Fletcher, T. D., & Burns, M. J. (2012). Urban stormwater runoff: a new class of environmental flow problem.

Walsh, C. J., Roy, A. H., Feminella, J. W., Cottingham, P. D., Groffman, P. M., & Morgan II, R. P. (2005). The urban stream syndrome: current knowledge and the search for a cure. *Journal of the North American Benthological Society, 24*(3), 706-723.

Wenger, S. J., Roy, A. H., Jackson, C. R., Bernhardt, E. S., Carter, T. L., Filoso, S., . . . Martí, E. (2009). Twenty-six key research questions in urban stream ecology: an assessment of the state of the science. *Journal of the North American Benthological Society, 28*(4), 1080-1098.

Wilcock, P. R., & McArdell, B. W. (1993). Surface-based fractional transport rates: Mobilization thresholds and partial transport of a sand-gravel sediment. *Water Resources Research*, *29*(4), 1297-1312.

Winston, R. J., Dorsey, J. D., & Hunt, W. F. (2016). Quantifying volume reduction and peak flow mitigation for three bioretention cells in clay soils in northeast Ohio. *Science of the Total Environment*, *553*, 83-95.

Wohl, E., Lane, S. N., & Wilcox, A. C. (2015). The science and practice of river restoration. *Water Resources Research*, *51*(8), 5974-5997.

Yarnell, S. M., Petts, G. E., Schmidt, J. C., Whipple, A. A., Beller, E. E., Dahm, C. N., . . . Viers, J. H. (2015). Functional flows in modified riverscapes: hydrographs, habitats and opportunities. *BioScience*, *65*(10), 963-972.

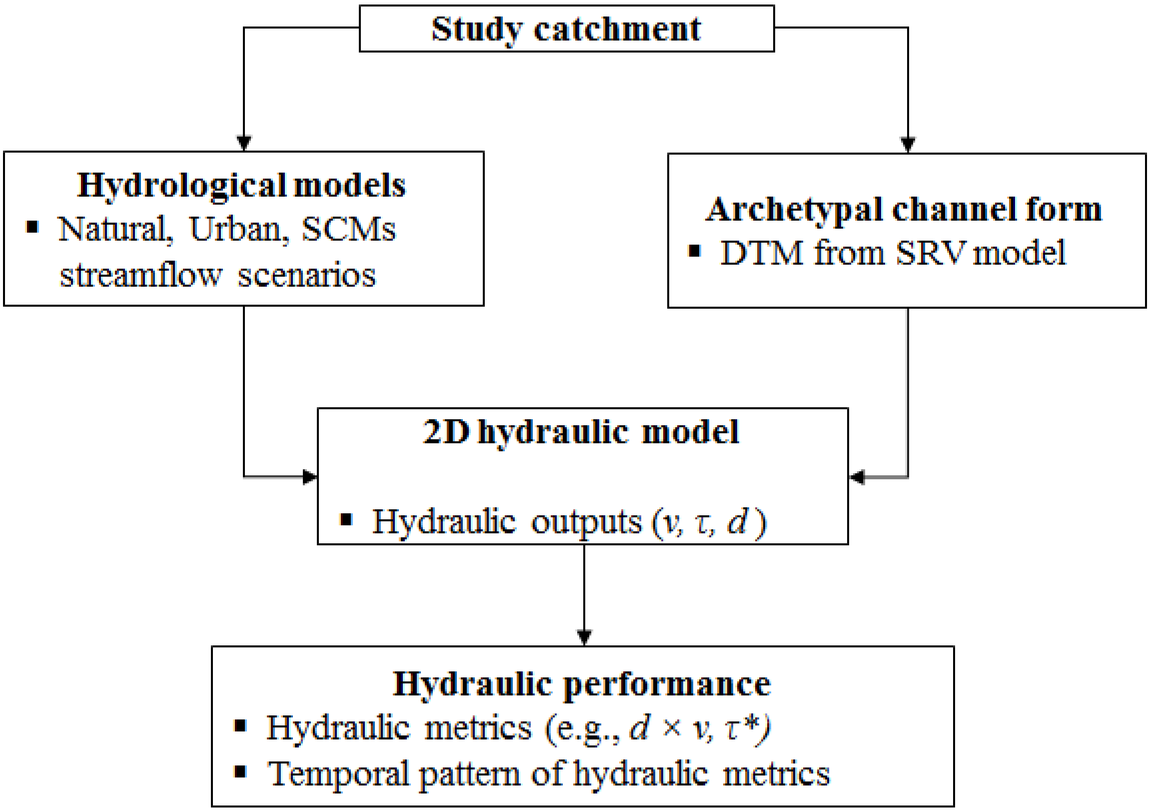


Fig. 1. Steps followed to quantify hydraulic performance of each explored flow-channel form scenario

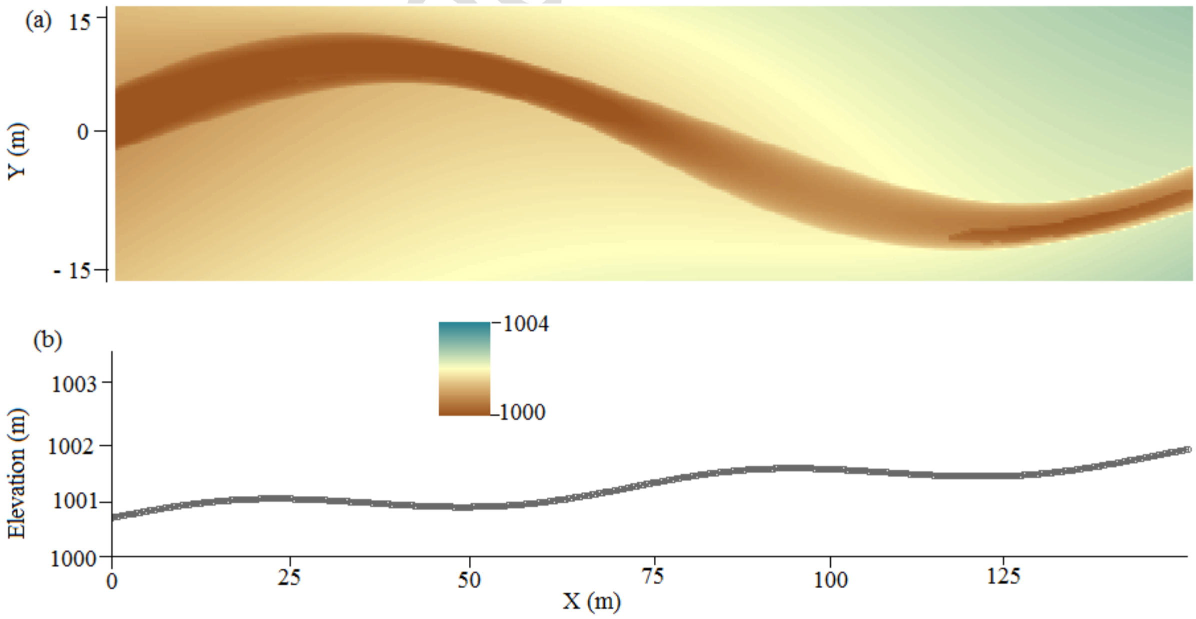
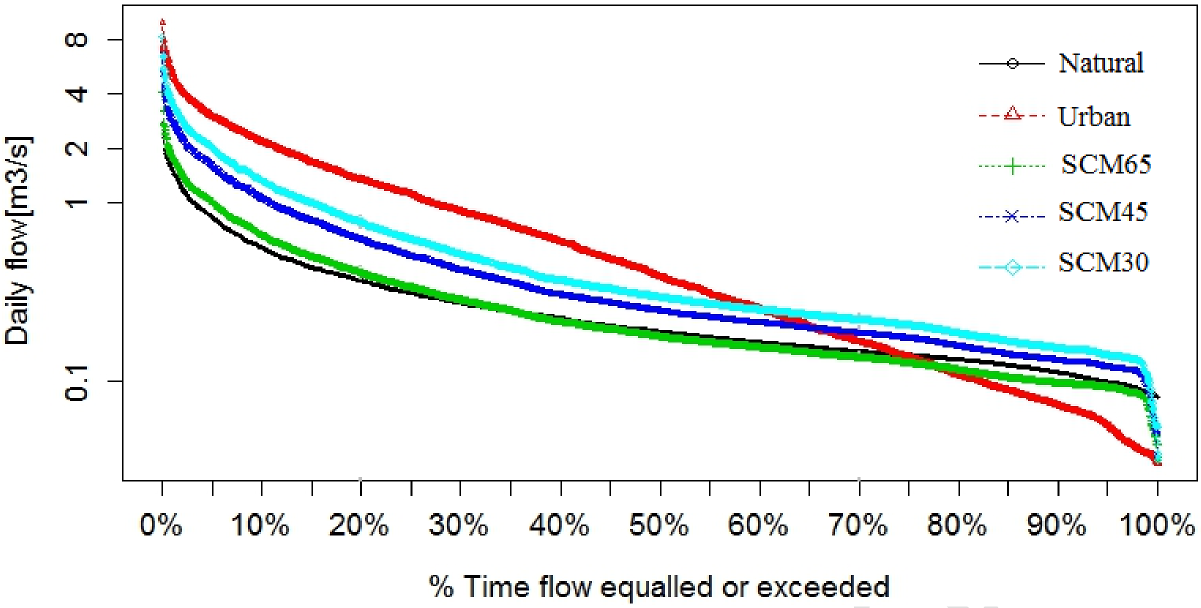


Fig. 2. (a) The synthetic DTM and (b) the longitudinal profile of the thalweg.



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879 Fig. 3. Flow duration curves that summarised the modelled time-series (daily) for each
880 scenario.

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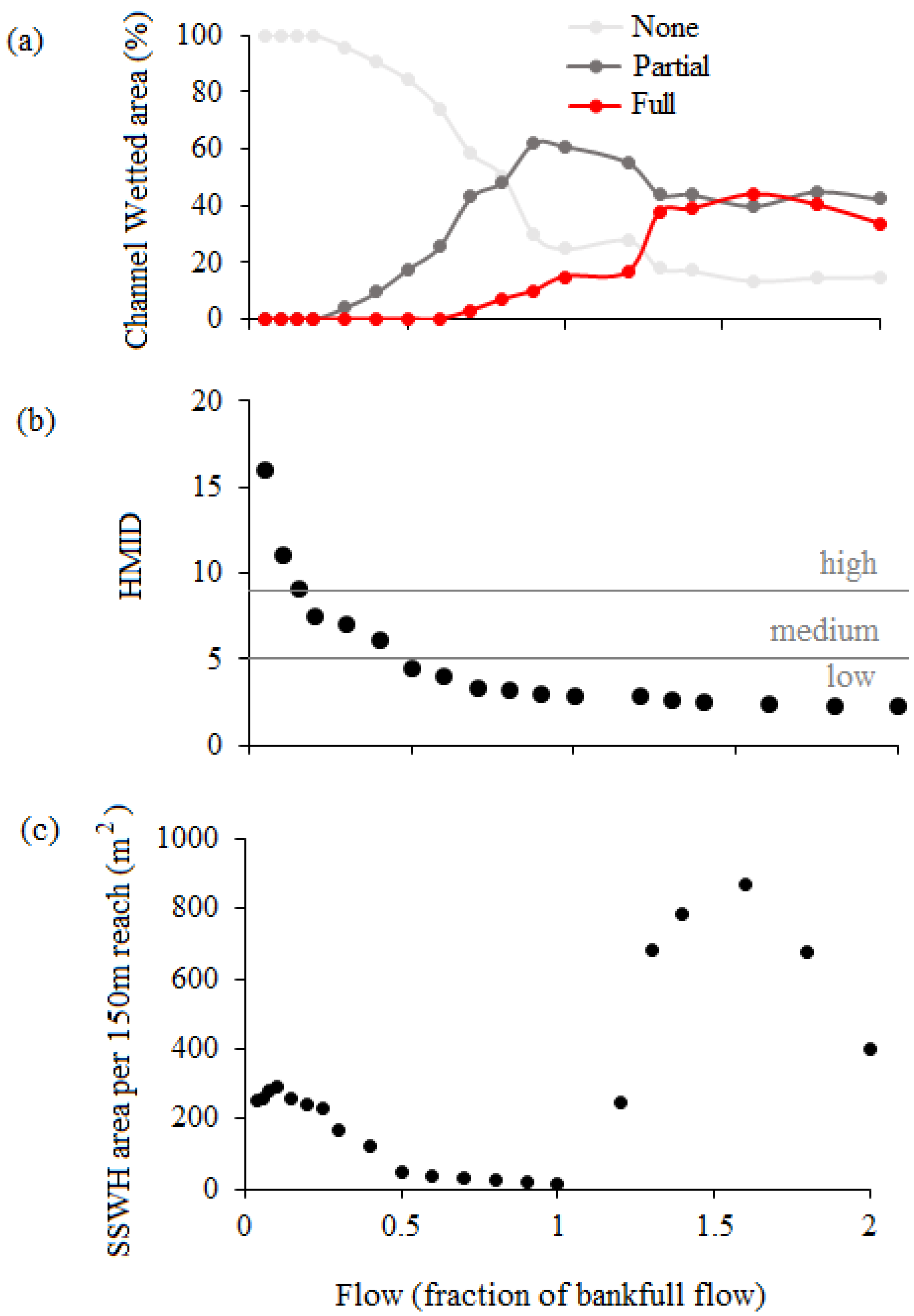

Fig. 4. Relationship between discharge (as a fraction of bankfull flow) and hydraulic metrics. (a) Proportion of the wetted channel bed area under different classification of sediment mobility, (b) HMID values, and (c) SSWH area values.

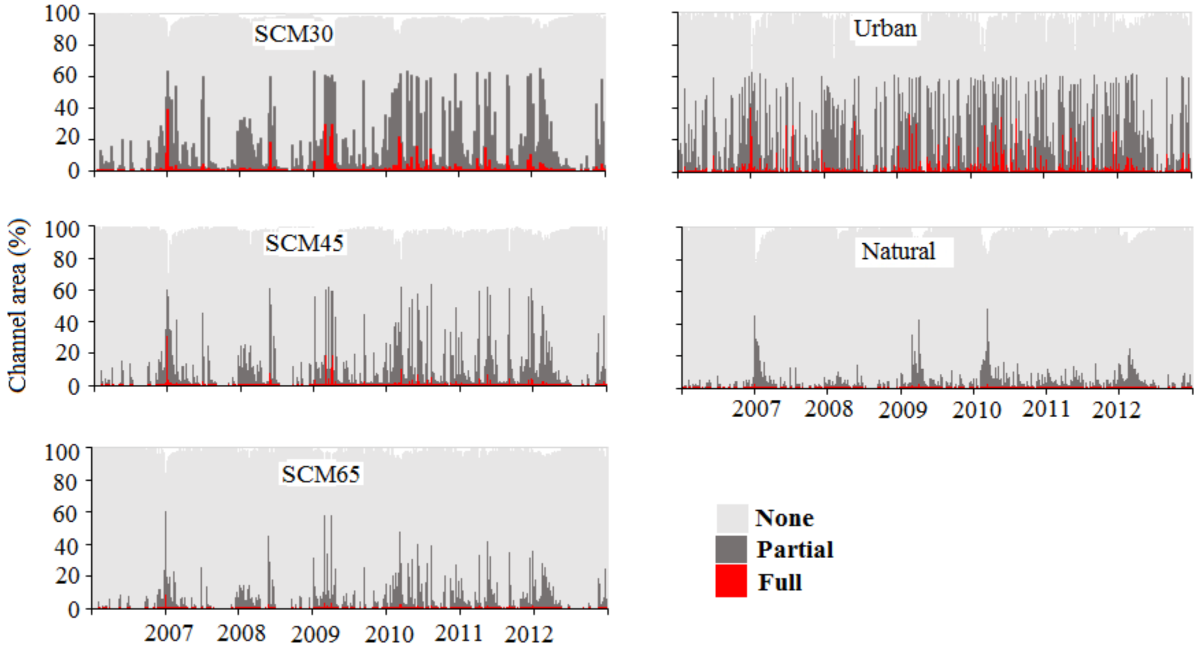

Fig. 5. Time series of the daily proportion of the wetted channel bed area under each classification of sediment mobility, for each modelled scenario considered over the study period.

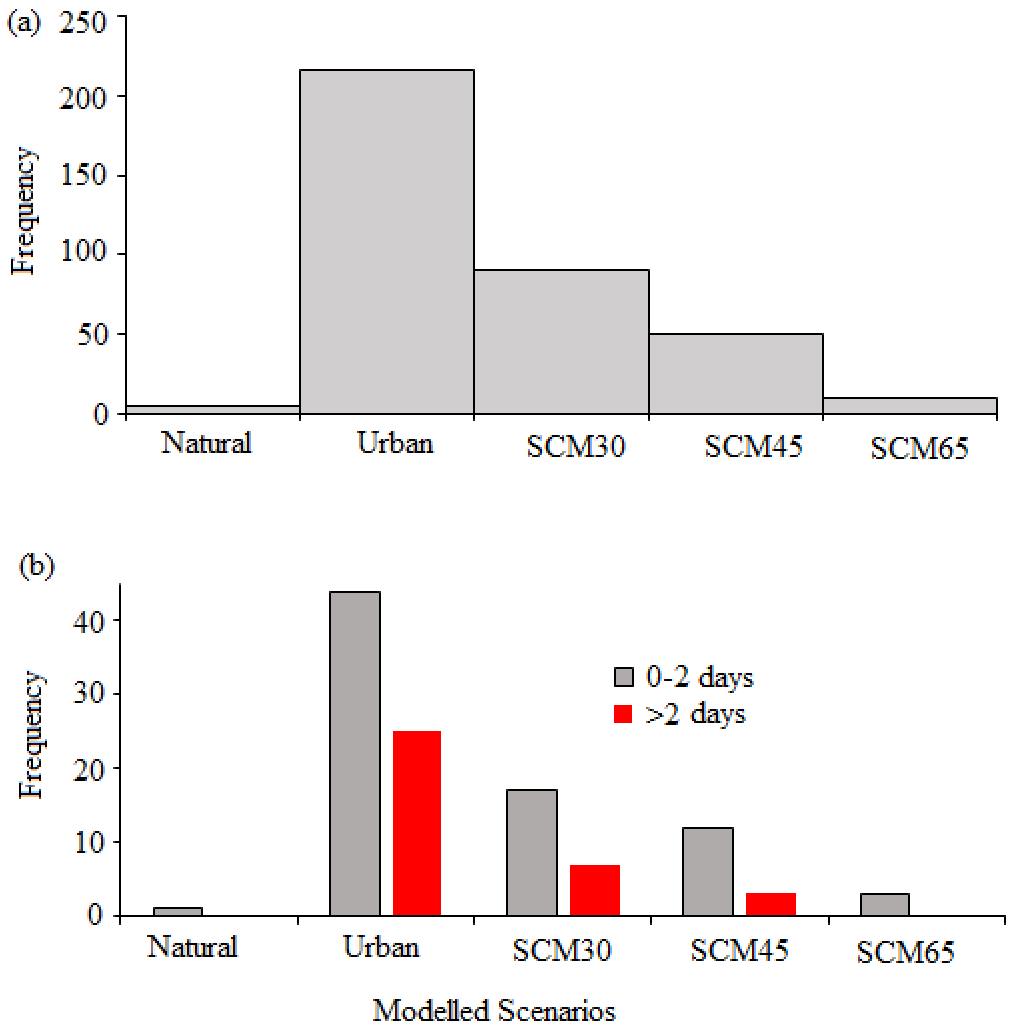

Fig. 6. (a) Frequency (in days) that at least 50% of the wetted channel bed area exhibiting atleast partial bed mobility (i.e. severe disturbance); (b) continuous duration of severe disturbance of each modelled scenario considered over the study period.

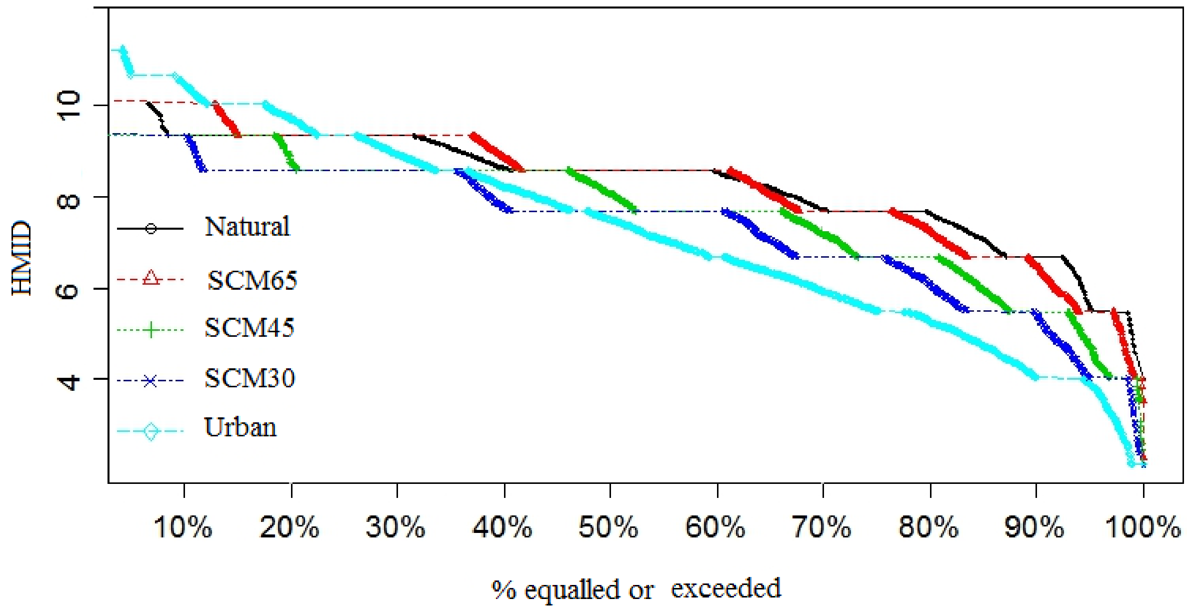

Fig. 7. Hydromorphic index of diversity (HMID) percent exceedance curves for each modelled scenario considered over the study period.

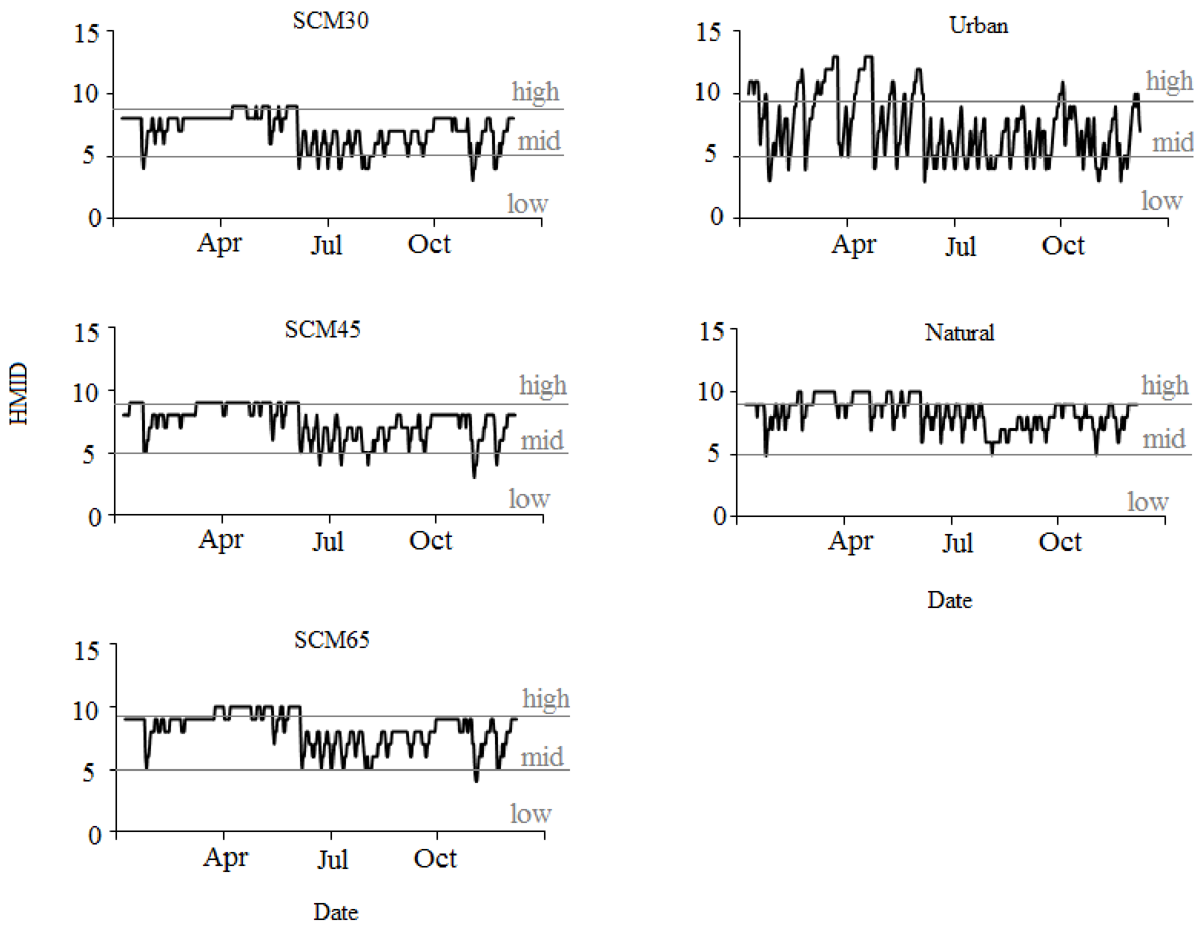

Fig. 8. Time series of daily HMID values for each modelled scenario showing periods of low, medium (mid) and high hydraulic diversity over a year.

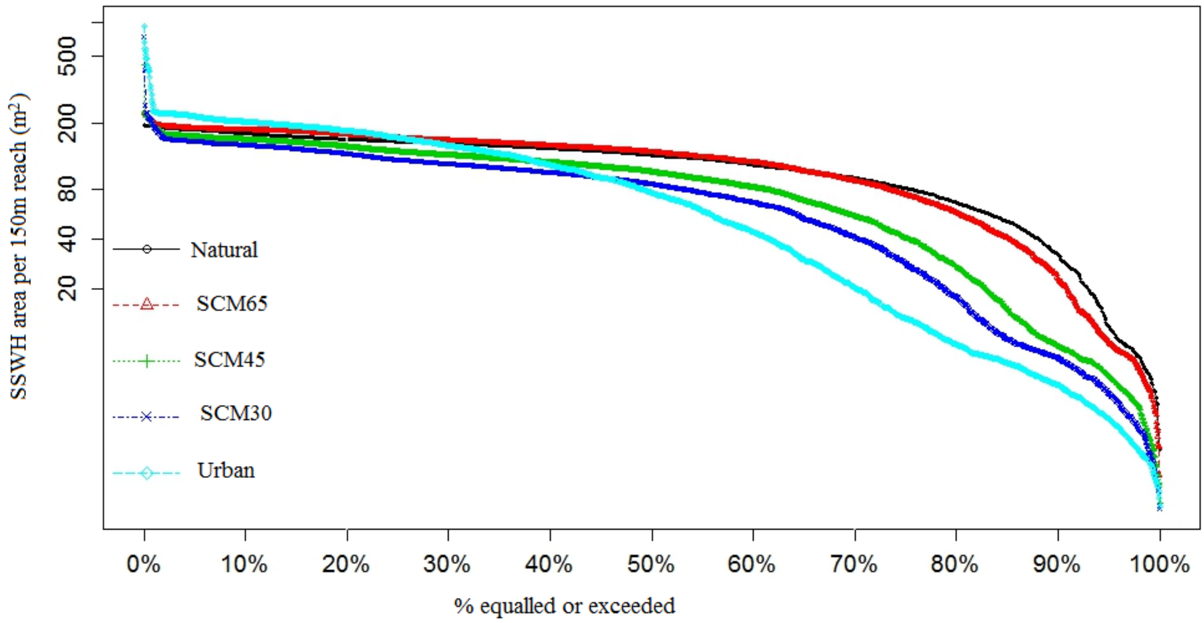

Fig. 9. SSWH area percent exceedance curves for each modelled scenario considered over the study period.

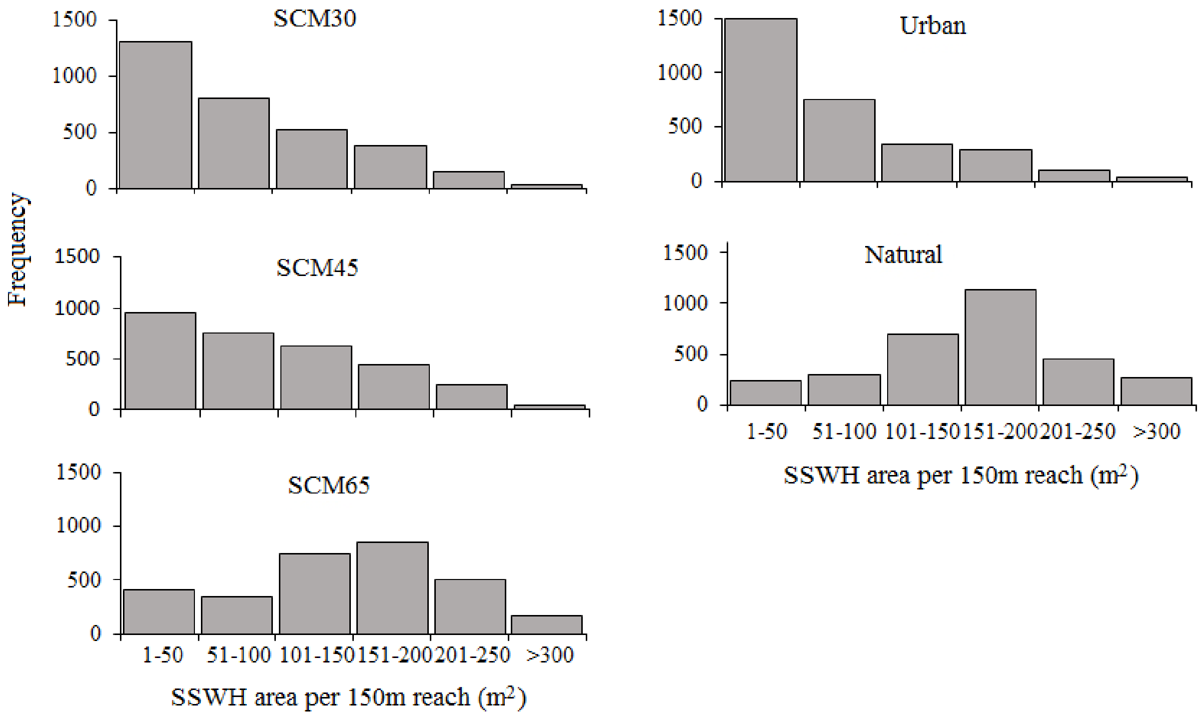

Fig. 10. Distribution of daily values of SSWH area for each hydrologic scenario considered over the study period.