Managing urban streams: change the channel or change the flow?

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Key Points

- Urbanization usually results in degradation of instream habitat
- Management efforts often focus on restoring the flow or the channel form
- The relative importance of restoring the flow or the channel form is poorly understood
- This study uses hydraulic modelling to examine the relative relevance of altered flow and form in addressing the stream degradation
- Stream managers need to protect channel before they degrade to have better chance of maintaining natural instream habitat health

Abstract
Urbanization and the role of urban stormwater runoff as a degrader of streams are well known, but how changes to flow with resulting channel change, impact stream hydraulics is poorly understood. To improve instream habitat for ecosystem health, it is helpful to understand the relative importance of modifying the flow, or modifying the channel. We used two-dimensional (2D) hydraulic modelling to compare and contrast the relative effects of channel morphology and flow in setting hydraulic conditions. We explored different test scenarios of urban and natural channel with urban and natural flow and compared them for their habitat value and for its susceptibility to bed movement. Modelling results from the examined scenarios suggest that: 1) both hydrological regime and channel form modification play a key role in altering the instream hydraulics, and 2) for a fundamentally modified channel, addressing just the flow regime is unlikely to restore the hydraulic habitat conditions. This highlights the importance of protecting channels from excess stormwater runoff before geomorphic change occurs, to have a chance of maintaining natural channel hydraulics. Without a natural-like morphology, restoration efforts that only target a natural flow regime are unlikely to achieve appropriate hydraulic conditions, and ecological benefits may thus be unlikely.

Keywords
Urbanization, altered flow regime, channel morphology, stream hydraulics, hydraulic modelling, stream restoration.

Introduction
Streams are often physically and ecologically degraded due to the impact of urbanization (Paul & Meyer, 2008; Vietz et al., 2014). These consequently lead to declines in the stream ecosystem health (Walsh et al., 2005). Stormwater runoff input, a byproduct of urbanization from impervious surfaces has been identified as the primary driver of observed degradation (Walsh, 2004; Vietz et al., 2015). Protection and/ or restoration efforts by stream managers usually involves two key approaches. The first approach, traditionally hinged on ensuring stream stability which was characterised by physical intervention such as channelization, channel straightening and recently channel design actions that seek to create a natural-like morphology (Chin & Gregory, 2009; Vietz et al., 2016). The second approach includes actions to restore altered hydrology to near pre-development levels

(Ladson et al., 2006; Burns et al., 2014). This has a primary goal to minimize and attenuate excess runoff input in the streams (Walsh et al., 2012) catchment-scale mitigation interventions(Burns et al., 2014; Li et al., 2017).

However, it is important that restoration goals are directly linked to the needs of the receiving stream ecosystem particularly considering ecosystem functioning (Clarke et al., 2003; Anim et al., 2018). It is argued that the stream hydraulics which forms the mechanistic mediator between the flow and channel form is a key controlling driver of the stream ecosystem functioning (Emery et al., 2003; Anim et al., 2018). Ecologist and river scientists generally recognised that the stream hydraulics forms the key coordinating template for aquatic ecosystem functioning (Townsend et al., 1997; Järvelä & Helmiö, 2004). Thus, management approaches employed towards restoration must have the objective of maintaining ecological important hydraulic conditions to have a better chance of successful restoration particularly to observe ecological benefits.

Therefore, opportunities for addressing urban stream degradation will be greatly limited without an improved understanding of how the approach used (i.e. changes made to hydrology and/ or channel form) influence the hydraulic habitat template for ecosystem functioning. An improved understanding of how these actions impact the stream hydraulics will inform management strategies particularly in setting restoration goals. The application of two-dimensional (2D) hydraulic modeling was therefore used to examine the relative importance of restoring the channel form and flow in impacting the instream hydraulics. Modeling approach explored different test scenarios of urban and natural channel with urban and natural flow and compared them for their habitat value and for its susceptibility to bed movement using hydraulic metrics: Shields stress and slackwater habitat (SWH) areas.

Methods

Study sites

The study used the same two sites (Figure 1) that were investigated by Anim et al. (2018) in the Cardinia Shire catchment. The range of these sites represents a gradient of urbanisation from almost completely undeveloped (“non-urban site) to peri-urbanization (“urban site”. The sites were originally selected to focus the major anthropogenic disturbance to catchment urbanization and the role of stormwater runoff input from stormwater drainage system. See Anim et al. (2018) for further site details.

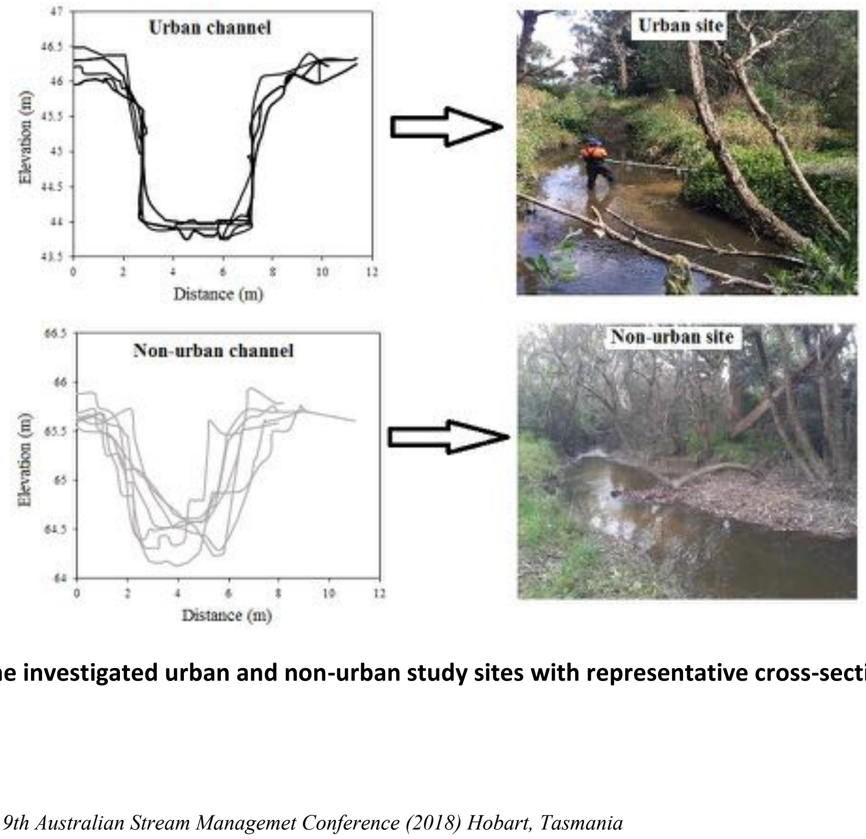

Figure 1. The investigated urban and non-urban study sites with representative cross-sectional survey

Data collection

Detailed channel topographic data of the channel bathymetry was collected as well as hydrological data sampled at each site from January to December 2015 (Figure 2). See Anim et al. (2018) for further details in data collection.

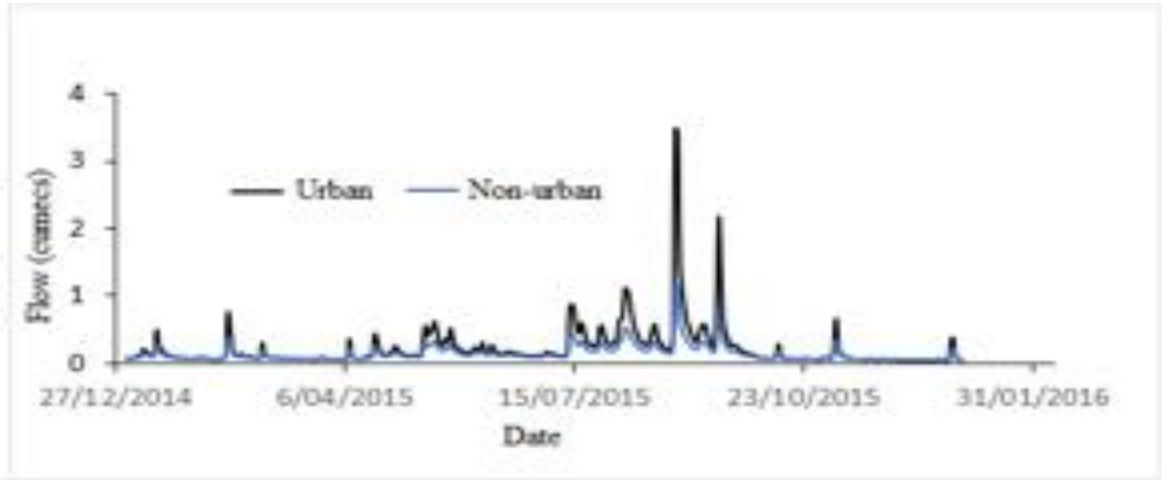

Figure 2. Mean daily streamflow for the urban and non-urban site

Hydraulic modeling and scenarios investigated

Scenarios

Four flow and form combinations scenarios were explored using the urban and non-urban channel form as well as the urban and non-urban flow regimes (Figure 3). Scenario QnCn and QuCu explored the current condition in the non-urban and urban site whereas QnCu and QuCn conceptually examined the management approach of either addressing hydrology or channel form. Qn and Qu represent the non-urban and urban hydrology respectively. Cn and Cu represent the non-urban and urban channel respectively

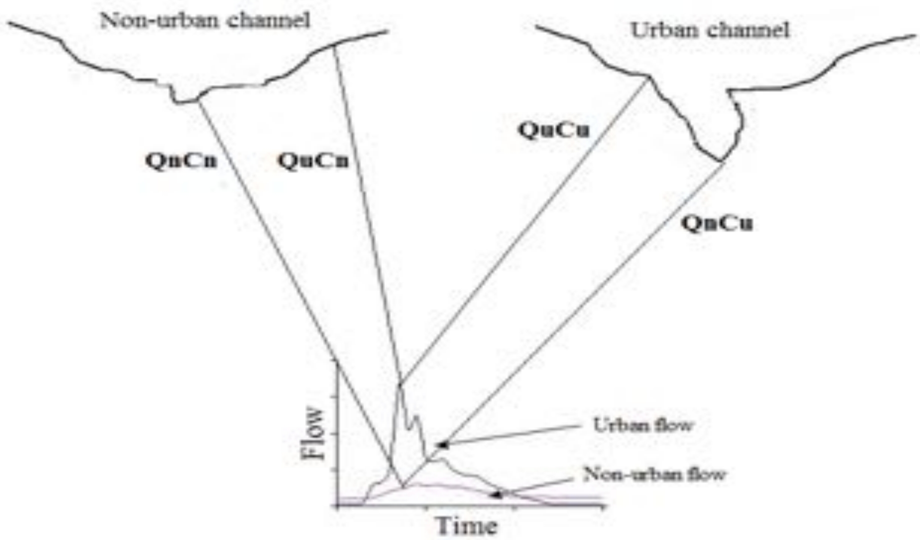

Figure 3 Schematic representation of flow-form scenarios explored (see text for definition of scenario codes).

Hydraulic modeling

2D hydraulic models for each flow-form scenario was performed using TUFLOW 2D (Syme, 2001). A computational mesh with internodal spacing of 0.3 m was generated for each channel using topographic survey. Model runs were done in a steady-state mode based on representative flows observed for each site corresponding to 1-95% of time flow exceedance. Model calibration was achieved by manipulation of the Manning's n values to match observed water surface elevation profiles. See Anim et al. (2018) for detailed model calibration and validation approach used. Model outputs include hydraulic rasters (e.g. water depth, bed shear stress, flow velocity).

Hydraulic metrics and data analysis

This study considered two hydraulic relevant characteristics linked with key components of stream ecosystem functions: variation of benthic disturbance that affect bed mobilization and drift of benthic biota living in them (Lobera et al., 2017); and retentive habitat availability (Vietz et al., 2013). The non-dimensionalized Shields Stress (τ_o^*) and slackwater habitat (SWH) area hydraulic metrics were used to quantitatively evaluate these hydraulic characteristics. The τ_o^* was estimated from TUFLOW's bed shear stress output which was used for analysis to evaluate each scenario and compare for its relative potential for bed mobilization as:

$$\tau_o^* = \frac{\tau_b}{g(p_s - p)D_{50}} \qquad (1)$$

where τ_b is the bed shear stress, D_{50} is the representative median particle size of the channel bed (D_{50}= 6mm), p_s and p are the unit weight of bed material and of water respectively. Critical mobility threshold (τ_c^*) of 0.045 (Lisle et al., 2000) was used. τ_b raster cells where τ_o^*>τ_c^* were where potential bed particles entrainment (herein benthic disturbance) are expected.

The velocity and water depth outputs were processed to examine the SWH area. For each simulated flow, composite grid cells of SWH areas were assessed by categorizing the grid cells that fell within a depth class of 0-0.3 m and velocity class of 0-0.2 m/s. this depth and velocity are considered to be particularly important for benthic macroinvertebrates in small streams (Shearer et al., 2015). Esri ArcGIS was used to process and analyze 2D model outputs to evaluate these two metrics for each investigated scenario.

By converting the flow series into an equivalent Shields stress and SWH area series, we could compare the relative effects of channel morphology and flow in setting hydraulic conditions. This was done by quantitatively characterizing the relative change in the regime for each explored scenario. The analysis aimed to look at the decrease or increase in magnitude, duration and frequency for each scenario explored.

Results and Discussions

Benthic disturbance

At low flows, the benthic disturbance patterns were similar for all explored scenarios, indicating stable conditions at the benthic space. However, substantial increase in bed mobility potential was observed as flow increases particularly for QuCu whereas marginal increases where observed for QuCn. High risk of bed mobility is likely in the urban channel at very high flows as flow approaches 0.4x bankfull discharge (Qbkf). Here, τ_o^* averages 0.05 over the summer high flows and 0.06 in the winter high flows, where an overturn of the bed is expected. Sawyer et al. (2010) referred to this condition as full transport. For a stream in urban catchment experiencing frequent altered hydrology characterised by elevated flows, the temporal persistence of benthic space available as refuge for biota is limited. In addition, frequent bed movement will lead to increased local extinction of sensitive biota as well as biota assemblages as they are drifted as particles move (Negishi et al., 2002). This also promotes incision of the channel (Hawley et al., 2012). In contrast, the non-urban channel showed a decrease in the frequency of the channel benthic area experiencing bed mobility. Compared to the urban channel the scenarios (QuCn and QnCn) illustrated low τ_o^* averaging 0.038 at very high flows all year suggesting a very stable bed with low potential of full bed movement. This indicate comparatively greater temporal persistence of benthic refuge for biota functioning that promotes biota diversity and abundance (Townsend et al., 1997). The results suggested that scenario QuCn significantly led to approximately 70% decreased in the frequency of benthic disturbance compared to QuCu. This indicate the ability of the natural channel morphology to minimize the impact of altered hydrology. Similarly, QnCn led to ~45% in the increased frequency of the channel bed experiencing bed movement compared to QuCu. While this is a considerable reduction, comparing that to QuCn, our results suggest channel form play relative important influence on the bed movement regime compared to altered flows. In addition, the relative difference comparing the above the threshold duration between the urban channel were larger for long occurring high flow events particularly QuCu. In contrast, the non-urban site demonstrated reduced duration of above threshold duration. This observation reflects the influence of the geomorphically dynamic channel bed on the benthic disturbance regime.

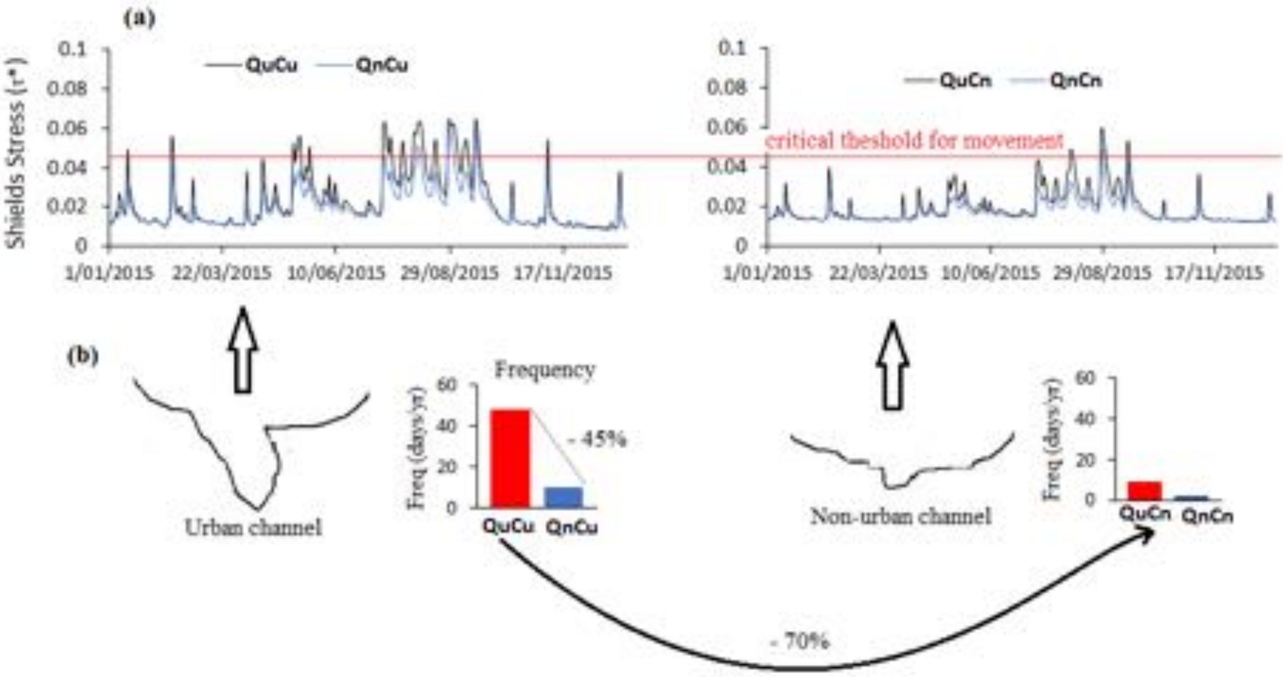

Figure 4. (a) Daily maximum Shield stress for the urban and non-urban sites for each explored scenario. (b) frequency (number of days per year) of shields stress was above critical threshold, i.e. $\tau_o^*>\tau_c^*$. Solid horizontal red line shows the critical Shields stress for bed particle mobilization (τ_c^* = 0.045).

Slackwater availability

The results show substantial reductions in SWH availability under the urban conditions particularly QuCu (Figure 5). Rapid decline was observed at moderately high flows where flow was deeper and faster SWH area was high at low flows. The non-urban channel maintained considerable greater availability of the SWH area even under urban flow conditions. Diversity in the SWH areas is greatest with larger areas of SWH frequently available all year compared to the urban channel even with the natural flow regime although the total annual availability was improved. Even under high flow conditions, natural morphology of the non-urban channel ensured persistence of relatively higher SWH area compared to the degraded urban channel. This has significant habitat implications for life stages of many biota (Vietz et al., 2013). However, in the urban channel, frequent elevated flows means plummeted SWH availability which when persist for extended period, have several ecological implications such as eliminating rearing and breeding habitat of biota like fish and macroinvertebrate (Nielsen et al., 2010).

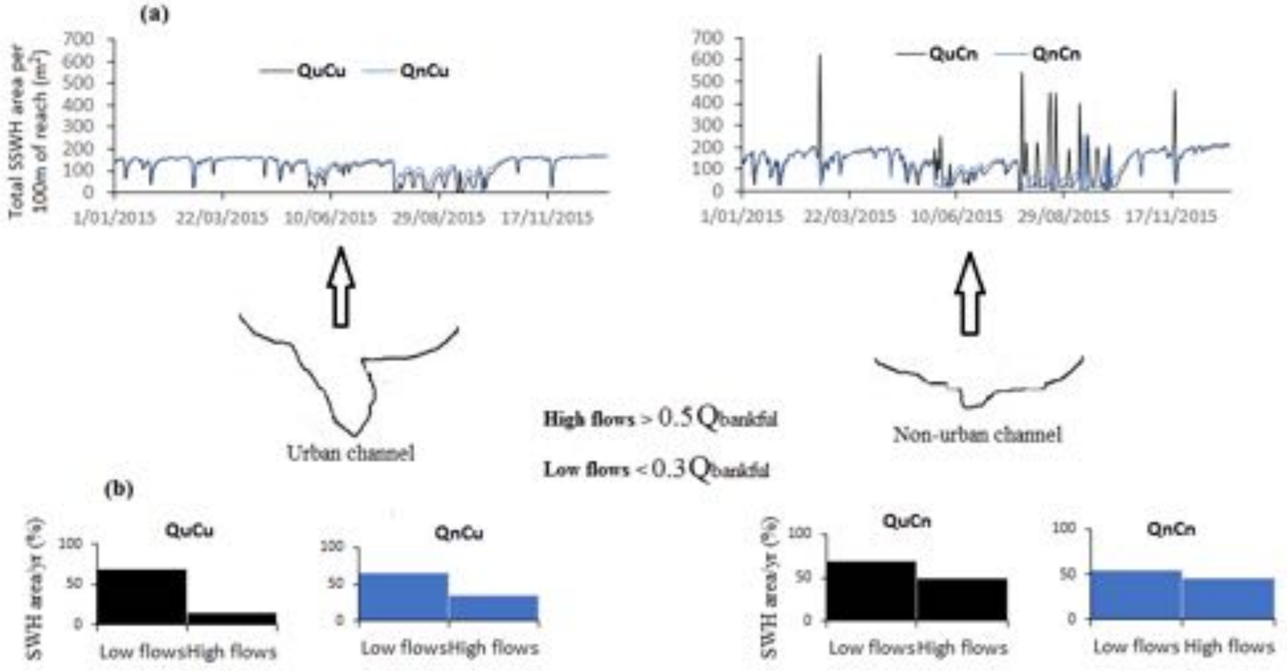

Figure 5. (a) Daily total SSWH area available per 100m of reach for the urban and non-urban sites for each explored scenario. (b) proportion of wetted channel available as SWH during both low and high flows for each explored scenario

Management implications and future research

Our study highlights that stream hydraulics are substantially influenced by the compounding contribution of both channel morphology and flow regimes. The results suggest stream hydraulics regimes are very sensitive to the channel morphology. 'Natural' dynamic channel morphology could potentially mitigate the benthic disturbance driven by altered urban hydrology as well as provide temporal persistence of habitat (SWH) availability. This indicate that a natural-like geomorphically dynamic is required to reduce the impact of altered flow regimes. This means a key future management challenge will be to mitigate the degradation of the channel morphology, requiring management efforts to aim at protecting channel morphology from urban-induced changes. Failure to do so will limit future efforts to address altered flow regimes to restore stream ecosystem health degradation. In the absence of a natural-like morphology, even achieving a natural flow regime pulses may not result to a natural hydraulic regime that support ecosystem functioning for ecological benefits.

Restoration actions, once both channel morphology and flow are altered will require an integrated strategy. For example, opportunities to combine catchment-scale hydrological alterations control measures with options that promote self-regeneration of the channel morphology such as self-organizing sediments (Wilcock, 2012) to minimize mobility could be encourage. However, future research to investigate the hydraulic performance of such management approach is required.

Conclusions

This paper evaluated the relative effects of addressing channel form and/ or flow in setting hydraulic conditions template that governs some key stream ecosystem functions by means of 2D hydraulic model simulations. We examined four hydrogeomorphic scenarios and compared them for their susceptibility to benthic disturbance and habitat value benefits.

The results demonstrated an increased altered hydraulic regime under urban-induced altered hydrological regimes and channel morphology. The examined scenarios suggested that the hydraulic conditions are more sensitive to channel morphology. We posit that restoring urban hydrology close to pre-development levels is unlikely to sustain 'natural' hydraulic conditions as measured by our adopted metrics when the channel is essentially modified. This requires stream managers to take protective measures to ensure stream channel form is prevented from degradation as in the case of most streams draining urbanized catchment. In particular, excess stormwater runoff input need to be prevented from becoming streamflow which has been recognized to drive channel evolution.

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