UNDERSTANDING STREAM HABITAT TO INFORM MANAGEMENT IN URBAN CATCHMENT

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It is commonly known that flow regimes of urban streams are altered due to urban development and excess stormwater runoff. This in turn alters the stream hydraulic conditions which can have greater effect on the ecological functioning of the stream ecosystem particularly through bed disturbance (the movement of the streambed materials), limiting refuge habitats. This study presents evidence of the effects of flow alteration due to urbanization on stream hydraulics by comparing the urban and natural reaches of the same stream. We characterize the degree and pattern of the hydraulic changes through 2D hydrodynamic modelling using ecologically relevant hydraulic metrics; Shields stress (τ^*) that evaluates the bed disturbance based on bed material entrainment and habitat availability measured by the slackwater habitat (SWH) area. The results show that urban-induced flow alteration substantially alters the hydraulic changes. The frequency and magnitude of bed disturbance over the study period were predicted to be substantially greater in the urban stream than the natural stream. The urban stream showed the most unstable bed with the relative percent area of channel bed likely to be entrained as flow nears bankfull about 3x higher compared to the natural stream. The SWH area rapidly diminishes in the urban stream as discharge increases. These results demonstrate changes in stream hydraulic regimes due to urbanization that may impact on physical habitat in urban streams which may have extensive and significant impact on aquatic biota and ecosystems functions. The findings underpin a better mechanistic insight of the link between urban-induced flow changes and degradation of stream physical habitat and thus help to inform of management protection actions.

1 INTRODUCTION

It is widely recognised that urbanization of catchments results in many impacts to the stream ecosystem [1, 2]. Common changes observed include frequent flow regimes and water quality disturbance as well as channel geomorphology changes. Thus, most streams in urban catchment shows signs of reduced ecological conditions [3, 4], termed as the urban stream syndrome [5].

While these multiple factors have been reported to be important drivers, frequent altered flow regimes because of regular delivery of stormwater runoff from urban upstream drainage area have been shown to be a key element influencing stream health [2, 5, 6]. This has resulted in urban stream degradation being considered a primarily hydrological problem, driving research to investigate the mechanisms driving degradation [1], and to inform protection and restoration approaches. However, while hydrology is key, it is how the hydrology is translated into hydraulic characteristics such as depth and velocity that has been shown to be relevant to ecosystem processes particularly stream communities function [7, 8]. The evidence found in previous studies [4, 9-11] directly linking hydrologic indicators to stream ecosystem impairment does not necessarily provide strong evidence of the direct causal mechanisms driving stream degradation. However, spatial and temporal changes in the hydraulic physical habitat have been directly linked to aquatic biota survival and mortality [12] as well as geomorphic process [13]. Studies have increasingly shown that while stream channels are naturally dynamic and complex, their form and functions are directly related to the hydraulic habitat conditions [14, 15]

This implies opportunities for addressing the ‘urban stream syndrome’ could be greatly limited without understanding the changes to the hydraulic habitat conditions. Directly linking hydrologic indicators to stream ecosystem degradation without considering hydraulics, fails to account for the direct causal physical mechanisms driving stream degradation and habitat quality [16]. However, there is a limited understanding of how urbanization through altered flow regimes impact hydraulics.

This study thus aimed to examine how urban-induced changes impact hydraulic conditions in urban streams. We used two-dimensional hydraulic modelling approach to characterise the hydraulic changes by comparing urban and natural stream. The degree of hydraulic change was explored using ecologically important hydraulic metrics including Shields Stress and Slackwater habitat (SWH) area which describe the stream bed disturbance, and retentive habitat availability respectively. These metrics have been shown to be relevant indicators for key aquatic ecosystem functioning [8, 17]. A better understanding of hydraulic changes to urban streams may highlight the need for management strategies that include the goal of restoring and/or protecting natural hydraulic regime.

2 METHODS

2.1 Study site

Two stream reaches were selected on the Cardinia Creek which drains the Cardinia Shire catchment in south-eastern Melbourne, Australia (Figure 1) in the Cardinia Shire basin. These selected reaches physically represent urban and non-urban/natural settings referred in this study as ‘urban’ and ‘natural’ site respectively. The natural sub-catchment is mainly occupied by forests and natural vegetation (50%) with pasture cover (43%) and very little impervious cover (4%). 0.1% of the impervious surface connected to the stream and the rest draining to impervious surfaces, thus significantly reducing any hydrological effect to the stream [18]. The urban reach located 6km downstream of the natural site drains an urbanized catchment that retains about 40% natural cover, with the rest of the surface area cleared for urban development. It has ~7% impervious cover with more than half (~3.5%) of this directly connected to the stream via stormwater drainage systems. The urban reach has a sand-gravel bed with a less complex, low gradient channel and a simplified planform and cross-profile morphology. The natural channel has a relatively complex, natural channel topography with a sand-gravel bed, riffle-pool sequence as well lateral benches and bars morphological features (Figure 1). Both reaches have similar rainfall pattern with an annual catchment rainfall averaging ~870 mm/year.

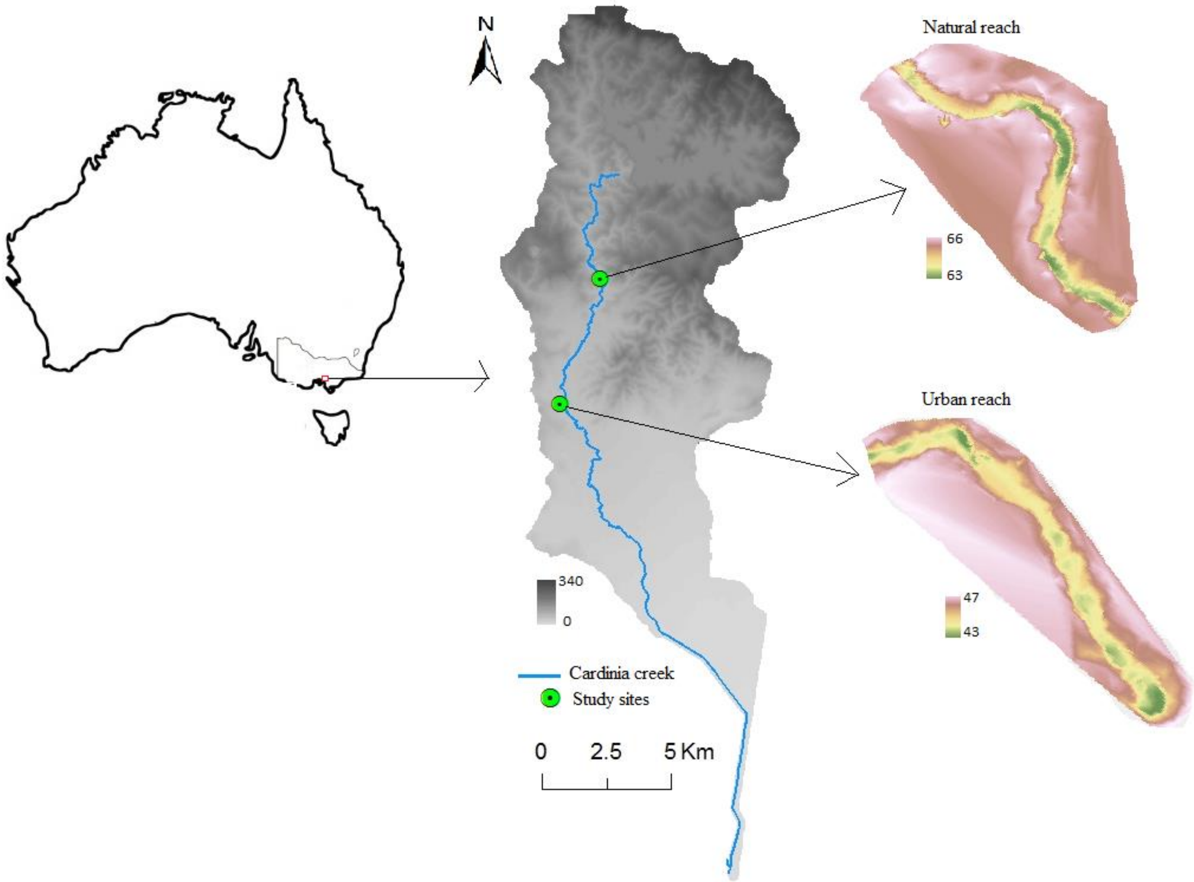

Figure 1. Location map of the Cardinia Creek in the Cardinia catchment showing the two study reaches.

2.2 Channel topography and flow

Each study reach extended 100m (~ 20x bankfull channel width). Detailed topographic and bathymetric data were collected to enable 2D modelling using Sokkia Set 5X total station covering the channel bed and banks, water surface elevation (WSE), wet/dry edge boundaries.

Water levels were monitored at the two study sites for two years (Jan 2015- Dec 2016) using capacitive water level sensors (ODYSSEY® MP System) which was converted to streamflow (Figure 2) using discharge rating curves specifically estimated for the two study reaches using direct gauging. The average daily flows during the study period was 0.31 m^3/s and 0.17 m^3/s for the urban and natural reach respectively. Maximum daily flows were 3.48m3/s and 1.15 m^3/s whereas minimum daily flows were 0.03 m^3/s and 0.04 m^3/s for the urban and natural reach respectively.

For each discharge gauging, WSE longitudinal profiling was done at 20 m intervals along both banks for each site. Like most streams draining urban catchments with some connected imperviousness [e.g. 11, 18, 19], the flow regimes of the urban reach have been significantly altered by frequent stormwater runoff input characterised by high magnitude flashy (short-lived) flows compared to smaller magnitude, persisting longer at the natural reach. Flow alteration has resulted in marked reduction in summer baseflows and increased frequency of winter/spring high flows including both extreme high flow events and mean daily flows during this period (Figure 2).

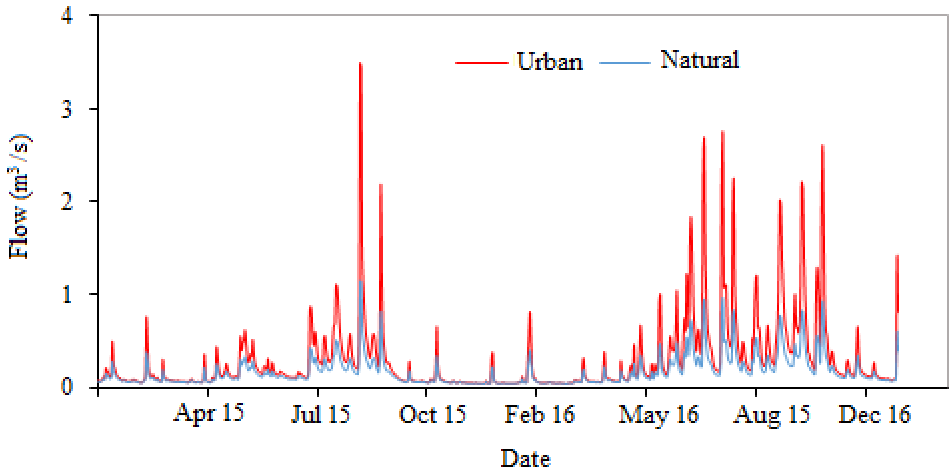

Figure 2. Mean daily streamflow for the urban and natural study reaches during study period.

2.3 Hydraulic modelling

TUFLOW 2D hydraulic model [20] was used for the simulations developed from the bathymetric survey data. Model simulation input and boundary conditions included inflow discharge and corresponding downstream WSE. The model was run in steady-state mode spanning the representative flow ranges for the hydrological data at each reach corresponding to 0.5-99 % of time discharge (Q) exceedance. All simulations were run until steady state flow was achieved where instantaneous flow at the downstream boundary matched the upstream inflow. Channel roughness were accounted for in each reach using the surface friction coefficient (Manning's n). Model were calibrated by adjusting Manning's n values for the channels to match observed WSE. A final Manning's n value of 0.035, which yielded the most satisfactory predictions where observed WSE agreed with the modelled WSE to within ±3 cm was used for all simulations.

2.4 Characterising the hydraulic conditions

We assessed the hydraulic conditions using model bed shear stress, velocity and water depth outputs. Model outputs were analysed in ArcGIS (Esri ArcGIS desktop 10.2). The bed shear stress in each grid cell was used to estimate the non-dimensionalized Shields Stress (τ*) as

$$\tau* = \frac{\tau_o}{D(\gamma_s - \gamma_w)} \quad (1)$$

where τ_o is the bed shear stress, D is the representative particle size of the channel bed (herein D_{50}) with a mean particle size (D_{50}) of 3mm and 6mm for the natural and urban reach respectively, γ_s and γ_w and γ_s are the unit weight of water and bed material respectively. Critical entrainment threshold (τ_c^*) of 0.045 [21, 22] to indicate potential bed movement. The SSWH areas were mapped by categorizing the grid cells that fell within a depth class of 0-0.3 m and velocity class of 0-0.2 ms^{-1} of composite grid maps of velocity-depth outputs. SSWH depth and velocity class considered here is reported to be preferred, particularly by benthic macroinvertebrates in small streams [23].

The impacts of urbanization were assessed by looking at the increase or decrease of metrics as a function of discharge relative to natural conditions. 2D maps corresponding to three Q, including low flow, mean and bankfull were generated to assess patch behaviour and evaluate the extent of any longitudinal changes of Shields stress, SWH.

3 RESULTS AND DISCUSSION

3.1 Channel bed disturbance

Both reaches showed increased values of τ* as flow increased. The patterns were similar at low flows but differed substantially as flow approaches bankfull discharge (Q_{bkf}) at the urban reach and marginally increased at the natural reach (Figure 3). The urban site τ* averages ~ 0.06 at very high flows and then averages 0.02 and 0.04 respectively at baseflows and recession periods respectively. This suggest that the urban reach would potentially experience substantially higher bed particle movement making the channel bed very unstable. An overturn of the bed is expected particularly at storm flows (> $0.5Q_{bkf}$) where τ* averages 0.061, a phenomenon Sawyer, et al. [22] described as full transport (movement of a sheet of bed material). Given that the urban reach flow regime is progressively characterized with increased frequency, magnitude and volume of storm flows, the bed disturbance process is expected to accelerate. In contrast, the natural reach showed comparatively stable bed with reach-average of 0.02 and 0.04 at peak flows.

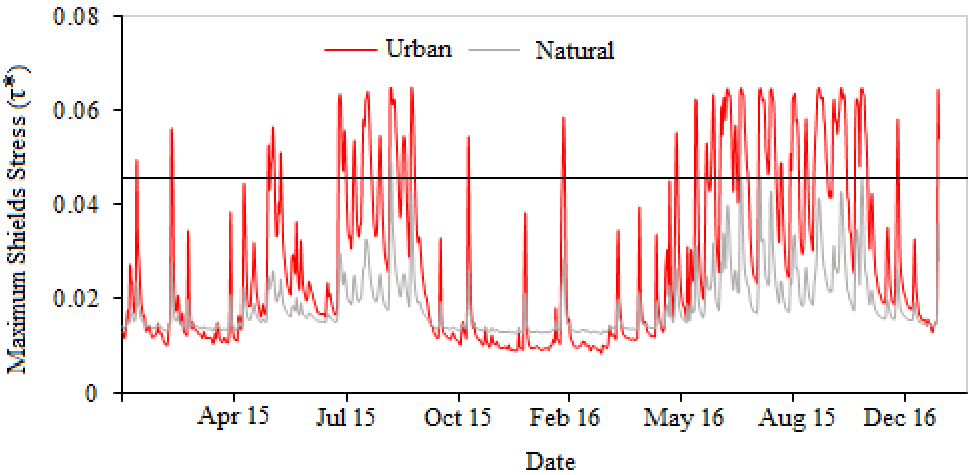

Figure 3 Daily maximum bed shear stress for the urban and natural reach for the study period. Horizontal black line indicates critical Shield stress, τ_c^*.

The frequency and magnitude of bed disturbance over the study period were predicted to be substantially greater in the urban site. The period that daily $\tau^* \geq \tau_c^*$ averages 98 days/year for compared to 15 days/year for the natural site. For these periods, the maximum τ* at the urban site increases by a factor of 2-4. This means bed mobility potential in the urban site will consequently increase channel movement efficiency over time. This is expected to regularly influence physical habitat adjustment or at worse eliminate important habitat features [24, 25]. The geomorphic and ecological consequence will be large as studies have shown that bed disturbance dynamics is a key geomorphic process in lotic habitats [26] and have impact on biota living in them [12] as a well a driver to channel incision [27].

In the natural channel, channel topographic complexity allowed areas of high τ^* were observed to shift as Q increased. The lack of variation in channel width and bed geometry in the urban channel resulted in reduced changes in the spatial location of high τ^* as flow increased, with areas simply extending longitudinally and laterally (Figure 4). This suggest channel morphological dynamism can steer flow such that the different topographic features turn on and off to create hydraulic diversity as flow increases [13].

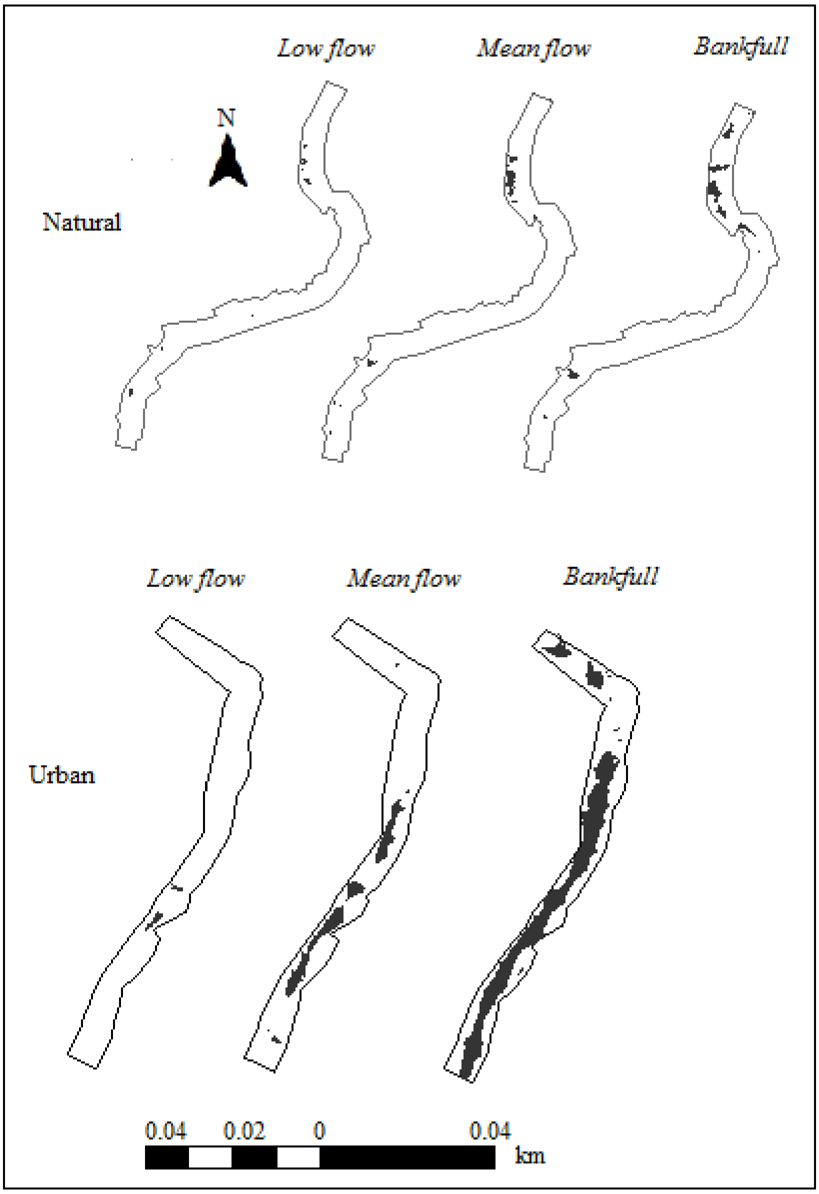

Figure 4. Planform maps of Shield stress pattern for low, mean and bankfull flow indicating spatial distribution of potential bed movement location as flow increases at each site. Shaded black represents area where Shield stress is above critical.

3.2 Physical habitat (SWH) availability

The total SSWH area was high at low flows at both reaches which corresponded to flows ~0.06-0.15x Q_{bkf}. While SWH area was maximized under low flow conditions, its availability diminished rapidly (~2 times) per-unit flow increased as Q approaches Q_{bkf} even for relatively small increases at the urban site (Figure 5). The natural reach on the other hand showed comparatively consistent patterns of SSWH availability from baseflow to increased flows. This is particularly important for different life stages of stream biota depending of such habitat [17]. The channel topographic variability at the natural reach resulted in more surfaces (e.g. higher-level lateral bars and benches) being inundated with shallow-low velocity waters as flow increased thus leading to larger areas of SWH. Also, it resulted in large SWH patches to be separated and distributed into many small units (Figure 6).

In contrast, the confined simplified channel form at the urban reach gives less variability in flow depth which results in steeper increase in depth and velocity with increasing flow. The SWH patches were relatively static which occurred at discrete locations even as flow increased (Figure 6). This is expected to have prolong impact on the biota for urban stream that experience frequent high flows therefore reducing rearing and breeding habitat as well as refuge [28]. This could be key contributing driver for local extinction and declined diversity and abundance and diversity of biota in urban streams. Lotic system with prolong availability usually support diverse biota populations [29].

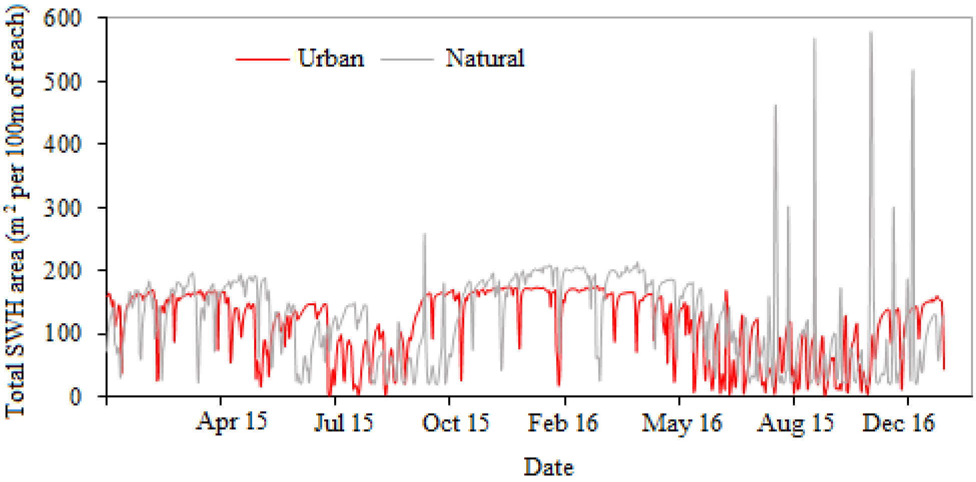

Figure 5. Daily total SWH area per 100m reach for the study period for the natural and urban site.

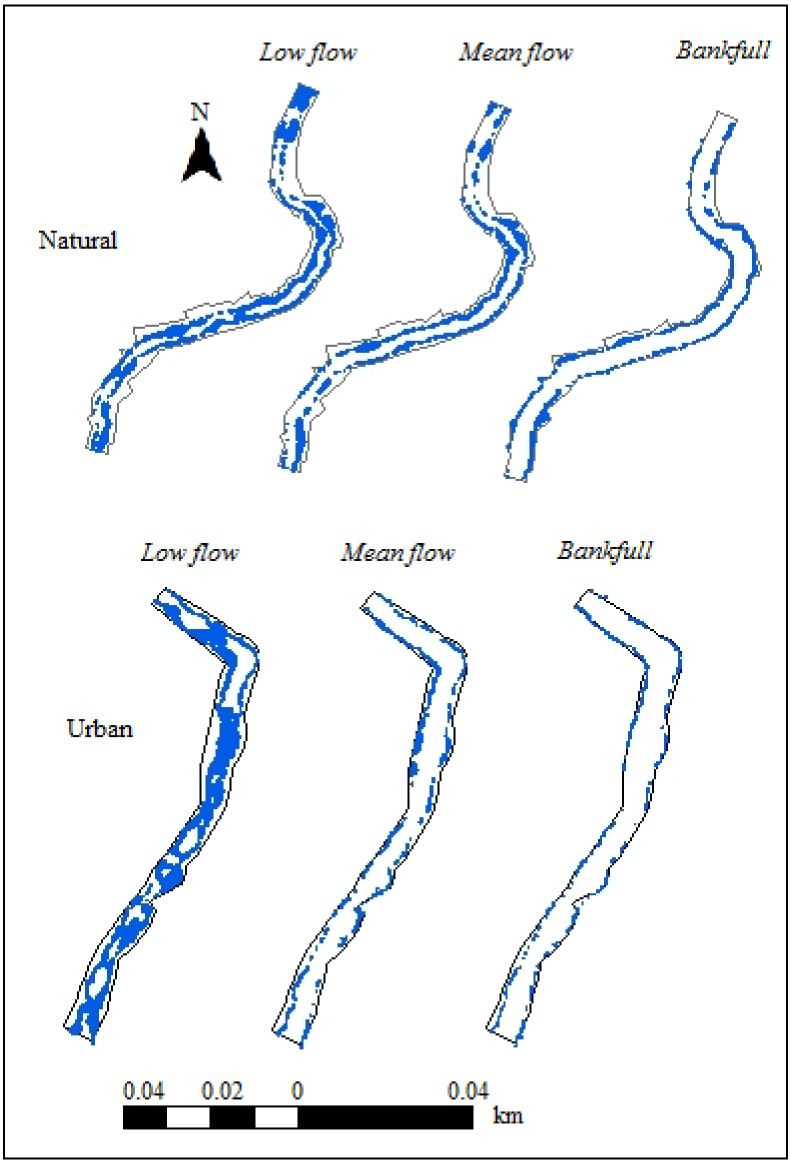

Figure 6. Planform maps of SWH area (shaded blue) pattern for low, mean and bankfull flow indicating spatial distribution of its availability as flow increases at each site.

4 IMPLICATIONS FOR URBAN STREAM MANAGEMENT

Current key management challenge with respect to protection or restoration of urban streams remains understanding of the link between catchment urbanization (particularly stormwater impacts) and the stream ecosystem process responses [1]. This study provides an important step towards that by underpinning a mechanistic understanding of urban-induced flow changes and stream's hydraulic habitat condition responses. The results suggest that the direct impact on the urban stream ecosystem structure and function is in fact likely to be largely driven by changes in the hydraulic habitat conditions. Thus, making it one of the key limiting factors influencing the natural ecosystem functions. The ecological consequence of altered hydraulic conditions is expected to be large given that hydraulic conditions form a key coordinating template for aquatic ecosystems processes and functions [30, 31].

The results highlight excess urban stormwater runoff as a driver of urban stream hydraulic habitat changes. This suggests that, it is likely hydraulic habitat condition of streams draining urban catchments, particularly those hydraulic characteristics of ecological importance can only be maintained if excess urban stormwater runoff can be prevented from reaching the stream through catchment-scale stormwater management approaches [32] such as retention and harvesting. It is therefore suggested that future management approach should include the goals of restoration and protection of natural hydraulic conditions, particularly those that support ecological and geomorphic functioning of streams. Better understanding of the role of the hydraulic regime is however required to inform management efforts. Further research to inform managers of hydraulic regime capable of supporting healthy stream habitats is particularly required to enhance new 'water sensitive' stormwater management approaches. While progress has been made towards restoring flow regime to natural levels, efficacy of these efforts will be limited if it does not lead to natural-like hydraulic regime pulses that support ecological functioning of streams.

5 CONCLUSION

This study presents a 2D hydraulic modeling approach that investigate and demonstrate the hydraulic habitat response to flow in an urban and natural stream. We found that catchment urbanization impacts drive substantial changes in the hydraulic regime of urban streams. This could be a key contributing factor for urban stream ecosystem health degradation. Management restoration strategies should therefore include objectives to restore a natural hydraulic environment for ecosystem benefits together with objectives for hydrological and water quality requirements. The results also highlight the important interplay between hydrology, geomorphology in dynamically evolving the discharge-hydraulic conditions in stream channels.

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