Received: 15 January 2025 | Revised: 8 April 2025 | Accepted: 9 May 2025

DOI: 10.1002/esp.70087

RESEARCH ARTICLE

ESPL WILEY

Can changes in geomorphic responses to urbanisation be predicted from stormwater outfalls?

Lukman A. Soboyejo | Kathryn L. Russell | Tim D. Fletcher

Waterway Ecosystem Research Group, School of Agriculture, Food & Ecosystem Sciences, Faculty of Science, University of Melbourne, Australia

Correspondence
Lukman A Soboyejo, Waterway Ecosystem Research Group, School of Agriculture, Food & Ecosystem Sciences, Faculty of Science, University of Melbourne, Australia.
Email: lsoboyejo@student.unimelb.edu.au

Funding information
This work was funded by The University of Melbourne through a Melbourne Research Scholarship and Melbourne Water through the Melbourne Waterway Research-Practice Partnership (http://mwrpp.org), respectively. Fletcher is supported by an Australian Research Council Industry Laureate Fellowship (IL230100020)

Abstract

Stormwater drainage is a primary pathway through which urbanisation degrades physical channel form and ecologically relevant in-stream attributes, such as the presence of large wood. However, there is a gap in the literature regarding methods or study designs that effectively isolate the specific effect of stormwater from those of catchment context, geology and other geomorphic controls. This study examines how stream geomorphology, characterised through variables such as bankfull cross-sectional area, pool-to-riffle spacing and large wood, relates to stormwater drainage inputs from urban areas. To achieve this, we employed historical data reviews, GIS techniques and field observations to assess morphological changes along a stream channel (Toomuc Creek, Melbourne, Australia), focusing on the differences between upstream and downstream of stormwater inputs. We hypothesised that: (i) stream bankfull cross-sectional area increases with catchment urbanisation and (ii) significant differences in geomorphic response variables exist between upstream and downstream of stormwater outfalls. However, contrary to our expectations, stream bankfull cross-sectional area did not follow a systematic downstream increase with catchment urbanisation, largely due to historical land-use practices (e.g. vegetation clearing) and channel stabilisation interventions (e.g. grade control structures, rock lining). Nonetheless, some outfall locations did show clear evidence of disturbance, confirming that widening, deepening and a combination of both occur locally and in a spatially discontinuous manner. These findings highlight two key directions for future research. Firstly, to properly isolate urban influences on stream geomorphic adjustments, controlled study designs should prioritise sites with minimal historical disturbance and no hardpoint interventions. Secondly, and perhaps more importantly, the influence of past channel corridor management and channel evolution on contemporary geomorphic responses needs to be specifically studied in urban settings. Understanding the complex interplay between urbanisation, channel geomorphology, historical land-use and in-stream features is vital for developing more accurate predictive models to mitigate urban stormwater impacts.

KEYWORDS
geomorphic variables, historical legacy, hydraulic geometry, stormwater outfall, urbanisation

1 | INTRODUCTION

Stream channels self-adjust their morphology when disturbed from their natural equilibrium state (Knighton, 1998; Morisawa & Laflure, 1979; Wolman, 1967). These alterations include pool and riffle adjustments (Hawley, MacMannis, & Wooten, 2013; Montgomery & Buffington, 1997), cross-sectional changes (Chin et al., 2017; Hammer, 1972; Leopold, Huppman, & Miller, 2005) and planform shifts (Bevan et al., 2018; Hawley et al., 2012). Urbanisation, characterised by widespread landscape sealing (e.g. roads, footpaths, carparks, roofs) and stormwater drainage connectivity, is a major land-use change which can trigger such morphological alterations in-stream channels (Booth, 1991; Chin, 2006; Gregory, 2006; Paul & Meyer, 2001) and associated in-stream features, such as pools, riffles, bars, benches and large wood (Blauch & Jefferson, 2019; Vietz et al., 2014; Walsh, Fletcher, & Vietz, 2016). The expansion of impervious surfaces and the development of hydraulically efficient drainage networks substantially increase surface runoff volumes and peak flows during rainfall events compared to natural catchments. In addition, underground stormwater drainage infrastructures, such as storm sewer networks and combined sewer overflows, can alter natural catchment boundaries and flows in complex ways. As a result, rainfall within the limits of urban catchment boundaries may be routed to nearby catchments, dramatically altering the streamflow response (Annable, Watson, & Thompson, 2012; Walsh, Fletcher, & Ladson, 2005) and limiting natural sediment delivery to streams after completion of surface sealings (Russell, Vietz, & Fletcher, 2017; Wolman, 1967).

Several authors worldwide have found a direct effect of stormwater inputs on stream channel morphology (Gregory, Davis, & Downs, 1992; Navratil et al., 2013; O'Driscoll, Soban, & Lecce, 2009; Sullivan et al., 2020). Specifically, these studies have identified the proximity of outfalls (mainly downstream) as hotspots of enlargement to catchment urbanisation. To date, no study has fully integrated the concept of proximate upstream and downstream changes into hydraulic geometry frameworks (a power function regression model), which typically examines the relationship between bankfull channel characteristics and bankfull discharge or a given return interval flow event (Leopold & Maddock, 1953). Common study designs used to investigate channel form changes due to urbanisation, such as comparing urban and rural reference sites, are constrained by limitations in the space-for-time substitution model, i.e. finding a rural reference sites with similar catchment characteristics to urban sites (Soboyejo, Russell, & Fletcher, 2025), and direct observation studies are rarely conducted over the timescales necessary to detect responses to urbanisation.

Moreover, urbanised streams may exhibit alterations to in-stream features, such as longer and deeper pools, shorter riffles (Hawley, MacMannis, & Wooten, 2013) and reduced large wood density, which affects habitat availability and stability of stream channels (Blauch & Jefferson, 2019). These in-stream features, recognised as ecologically relevant geomorphic attributes (Montgomery et al., 2003; Vietz, Rutherfurd, & Stewardson, 2004), have received limited attention in studies investigating channel forms and enlargement due to urbanisation. Similarly, there is also a lack of understanding regarding the direct impacts of stormwater outfalls on these features.

In southeastern Australia, effective impervious cover (EI) has been identified as an important explanatory metric for investigating the impact of stormwater drainage on channel morphology and features, in-stream biodiversity and stream water chemistry (Burns et al., 2015; Hatt et al., 2004; Vietz, Rutherfurd, & Stewardson, 2004; Walsh, 2004). These studies, as well as studies in other parts of the world, have ascertained that relatively low levels of urbanisation, with as little as 2% effective impervious cover, can significantly impair stream channel forms and functions (Booth & Jackson, 1997; King et al., 2011; Vietz, Rutherfurd, & Stewardson, 2004; Walsh, 2004).

This study aims to investigate how geomorphic response variables, such as cross-sectional area, width, depth, width-to-depth ratio, bars and benches, pool-to-riffle spacing and large wood, respond to stormwater inputs from urban areas. To achieve this, a novel downstream hydraulic geometry study design was implemented, focusing on observations directly upstream and downstream of stormwater outfalls. This approach isolates the influence of stormwater on channel dimensions and in-stream features as much as possible from the effects of catchment context, geology and other geomorphic controls. We set out to test the following research hypotheses:

1. Stream channel dimensions, such as bankfull cross-sectional area or capacity, increase with catchment urbanisation, and
2. Significant differences in geomorphic attributes, such as large wood, bars and benches and pool-to-riffle spacing, exist upstream and downstream of stormwater outfalls.

2 | MATERIALS AND METHODS

2.1 | Study area

The study was undertaken on Toomuc Creek, in the southeastern part of Greater Melbourne (Figure 1a), Australia, within the Eastern Upland and Eastern Plain landform units (Joyce, 1992). In Greater Melbourne, urbanisation began during the 19th century along the fringe of Port Phillip (Figure 1b). Urban development in the region is ongoing, including the expansion of Pakenham in the Toomuc Creek catchment. Toomuc Creek originates from hills near Cardinia Reservoir and ultimately drains to Western Port, a shallow bay to the south. The upstream (northern) rural zone is mainly characterised by farms and rural housing, whereas the urban section, which is the focus of this study (Figure 1c and d), is characterised by mostly single-family detached housing, with some townhouses and some areas of industrial and commercial development (Figure 1d). Downstream of the urban zone, the creek flows again through farmland, where it passes through enlarged and straightened constructed drainage channels within the former Koo Wee Rup swamp (Yugovic, 2011). The creek drains a catchment area of approximately 43 km^2 at the downstream extent of its urban zone. The drainage area of the upstream rural zone of the catchment is approximately 39 km^2. The urban area is served by networks of roads (e.g. Princes Highway and Princes Freeway) and a railway line that played pivotal roles in its growth and development (Figure 1).

The climate of the region is characterised as mild and temperate oceanic (Köppen climate classification: Cfb), with evenly distributed precipitation throughout the year (Peel, Finlayson, & McMahon, 2007). The study area is made up of highly dissected ridge and valley landscapes in the upland zone transitioning to a moderate-

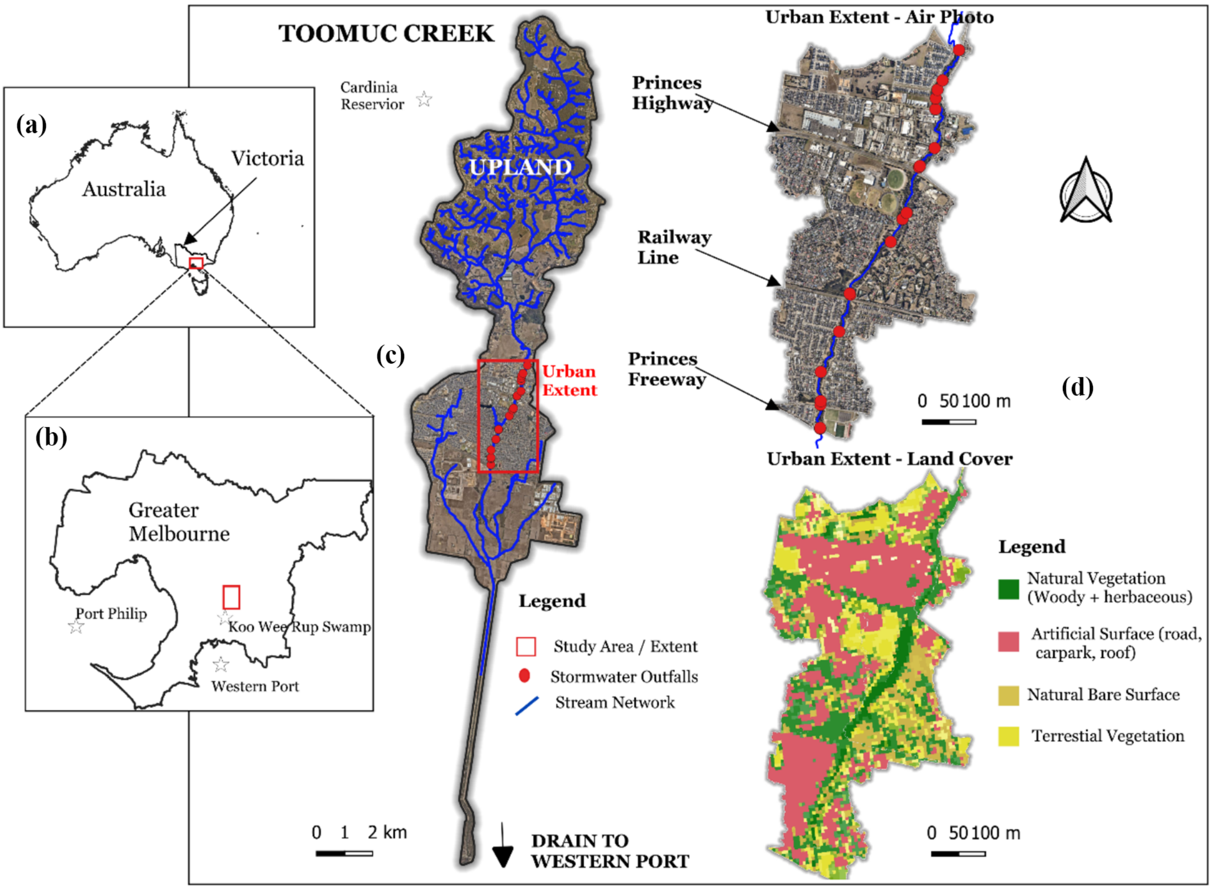

FIGURE 1 Location map of (a) the study area within southeastern Australia, (b) the Greater Melbourne extent, (c) Toomuc Creek catchment, within the Pakenham suburb, showing stream channels and (d) Toomuc urban extent and land cover (Tissott & Mueller, 2022).

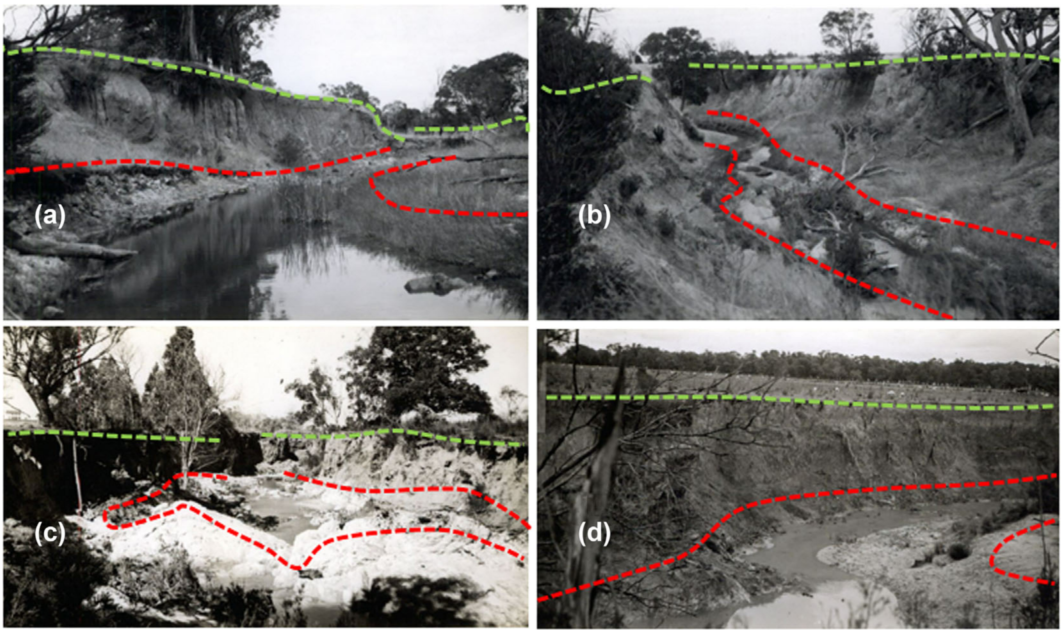

FIGURE 2 Lower urban zone channel morphology (incision) from princes highway to the south. Pictures were taken in 1959. (a) High cliff in danger of undercutting and mass failure, (b) entrenched channel in a stabilising state, (c) bed eroded to soft Silurian bedrock bar and (d) vertical banks in danger of undercutting and mass failure. Green lines indicate the former floodplain surface, and red lines indicate the incipient inset channel margins. Retrieved and modified from the Australian River basin management society (RBMS) archived historical waterways photos.

to-gentle plain to the south. The elevation of the upstream rural area ranges from 57 to 330 m, while the elevation of the urban area ranges from 25 to 58 m. The geology of the catchment is characterised by intrusive Lysterfield Granodiorite, Devonian Sedimentary formations (low-grade metamorphic sediments and breccias), with some Tertiary basalts and associated volcanic materials in the upstream (northern) rural area. In the lowland plain, including the urban zone, the underlying geology is made up of poorly consolidated Cenozoic alluvial, colluvial, aeolian, lacustrine and coastal deposits (Geoscience Australia, 2025).

2.1.1 | History of land use

The study area has undergone a prolonged history of land-use and drainage alteration since early European settlement, such as vegetation clearance, agriculture, channel straightening, wetland drainage and dredging (Bird, 1980). These land-use alterations have led to increased runoff, the formation of hydraulically efficient channel structures and base-level lowering, ultimately driving the evolution of incised channel forms, such as enlarged channels, inset active floodplains, abandoned historical floodplains and the development of knickpoints. (Figure 2).

The study area is within the land of the Bunurong people of the Kulin nation, who are the Traditional Owners and who continue to be custodians of the land with a deep connection to Country. In the 1830s, early colonial settlements in the region were comprised mostly of individual migrants engaged in the bark industry and seal-hunters (Butler, 1996; Natica et al., 2017). Permanent settlement in the area commenced in the late 1830s, with pastoralists and farmers attracted to locations such as the Great Koo Wee Rup Swamp, drawn by the abundant water resources provided by tributary creeks, such as the Cardinia, Toomuc and Ararat creeks, which facilitated agricultural pursuits (Natica et al., 2017; Victoria Heritage Branch, 1989).

Throughout the 1840s, the district continued to attract pastoralists and farmers, encouraged by government settlement initiatives such as the Closer Settlement and Soldier Settlement Schemes, which promoted agricultural activities and reshaped landscapes through small-scale farming (Natica et al., 2017). In the 1860s, parcels of land became available to the public (typically settlers) to purchase during the "Selection Era", a period during the mid to late 19th century when various land selection acts were introduced by Australian colonies to promote closer settlement and agricultural development (Butler, 1996; Natica et al., 2017).

In 1876, efforts were made to drain more land for agricultural purposes, particularly in the former Koo Wee Rup swamp. To maximise this opportunity, drainage networks were established to divert floodwaters from creeks to Western Port and dewater the swamp ("Through the Koo Wee Rup Swamp", 1883). This continued until 1962, causing major channel incision due to base-level lowering that migrated upstream along the creek (Yugovic, 2011). Hanslow, the past commissioner of the State Rivers and Water Supply Commission, in 1939 stated, 'If you go along the Princess Highway through Gippsland, you will see Toomuc Creek, which is now one great scour, in places 50 feet [15.24 meters] wide and 30 feet [9.14 meters] deep'. Also, in 1944, he wrote, 'When you pass Dandenong, have a look at the horrible scour in the Toomuc creek, and you will see that thousands of tons of earth have been carried to Westernport'. Prior to this event, channel beds and banks were frequently cleared of riparian vegetation and large wood from the 1880s to enhance swampland drainage to Western Port. These practices led to significant channel incision from the Princes Highway to the south (Hanslow, 1939; Richard, 1940).

Prior to urban development, towns and villages in the Pakenham area were far apart from other suburbs. This changed in the 1870s with the introduction of transportation infrastructure, including railways and enhancements to the east–west road, now known as the Princes Highway ("Country News", 1898; "Pakenham", 1914). The town of Pakenham was established on the railway line near Toomuc Creek in the 1880s, and it grew through the 20th century to become a regional centre. In the 1960s and 70s, Pakenham became part of a planned growth corridor of Melbourne, and suburban rail was extended to Pakenham in 1975, fostering the beginnings of urbanisation. Population growth has been strongest from the 1980s to the 2010s. In 2015, urbanisation began to spread rapidly to the western part of the catchment and is now progressing northwards, with the population rising from 11,283 in 2001 to 54,118 in 2021 (Australian Bureau of Statistics, 2024). Today, the urban area incorporates a formal stormwater drainage pipe network, some draining to stormwater ponds or wetlands, resulting in complex hydrologic alterations. Owing to this complex arrangement, different reaches of Toomuc Creek receive different magnitudes of stormwater flow. Recent management efforts, such as the construction of grade control structures and the re-establishment of riparian vegetation, aimed to address channel incision and/or widening from prior historical disturbances and current urbanisation on stream morphology.

2.2 | Data acquisition and elaboration

We employed a combination of field observations and spatial analysis to assess differences in geomorphic forms and related features upstream and downstream of stormwater outfalls along an urban channel gradient (Figure 3). Historical data were sourced from various published materials, such as government websites and archived newspapers, to aid interpretation and provide important historical context to the current day influence of urbanisation. Spatial elaboration was performed using QGIS to delineate and extract catchment features such as stormwater pipe networks. Field measurements involved surveys of the cross-sectional channel geometry at the pool and riffle and qualitative assessments of channel characteristics (e.g. bars and benches, large wood and pool-to-riffle spacing). The spatial information used in the GIS analyses and field measurements is described in more detail below.

2.2.1 | Outfalls identification and channel categorisation

The shapefiles of catchment area and stormwater pipe networks used in this study were extracted from the stream network developed by Walsh (2024). We imported shapefiles of stormwater pipe networks into QGIS (Version 3.40.2) to identify stormwater outfalls along the urban channel gradient. After this process, the catchment area of each

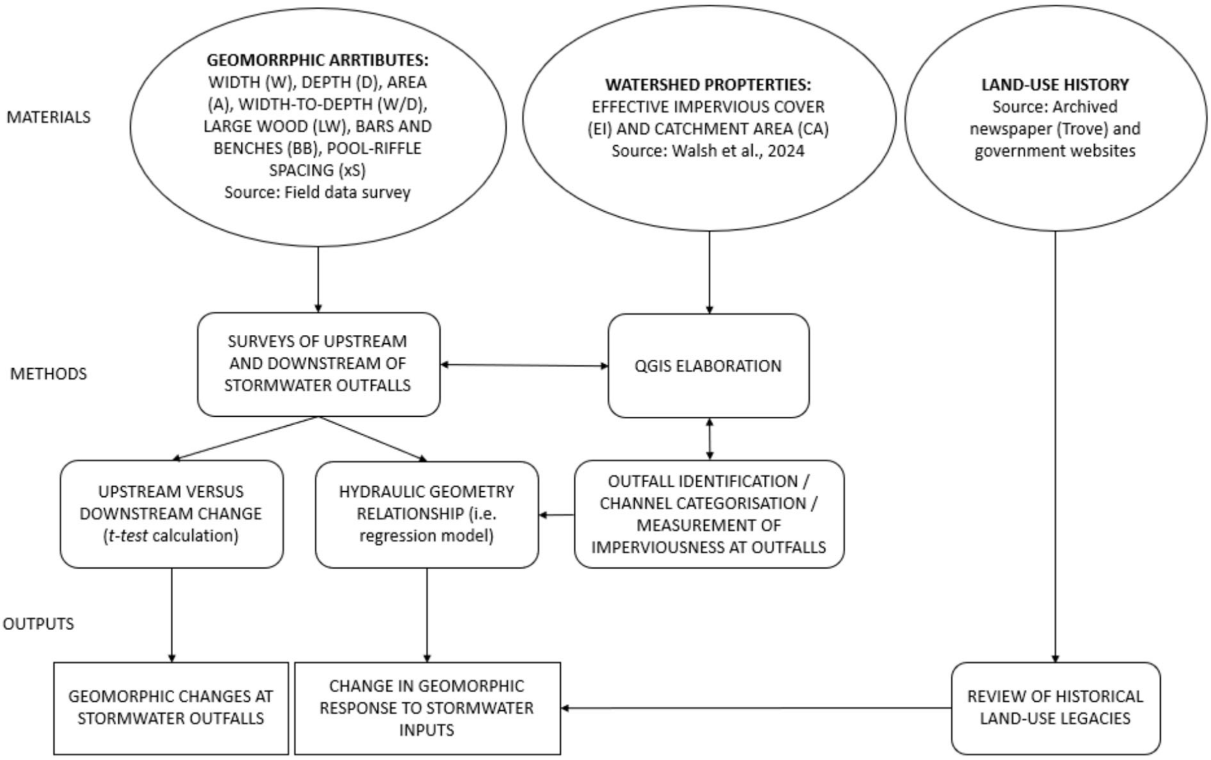

FIGURE 3 Flowchart of the methodology used to assess the potential threats caused by urbanisation on channel dimensions and related features in the study area.

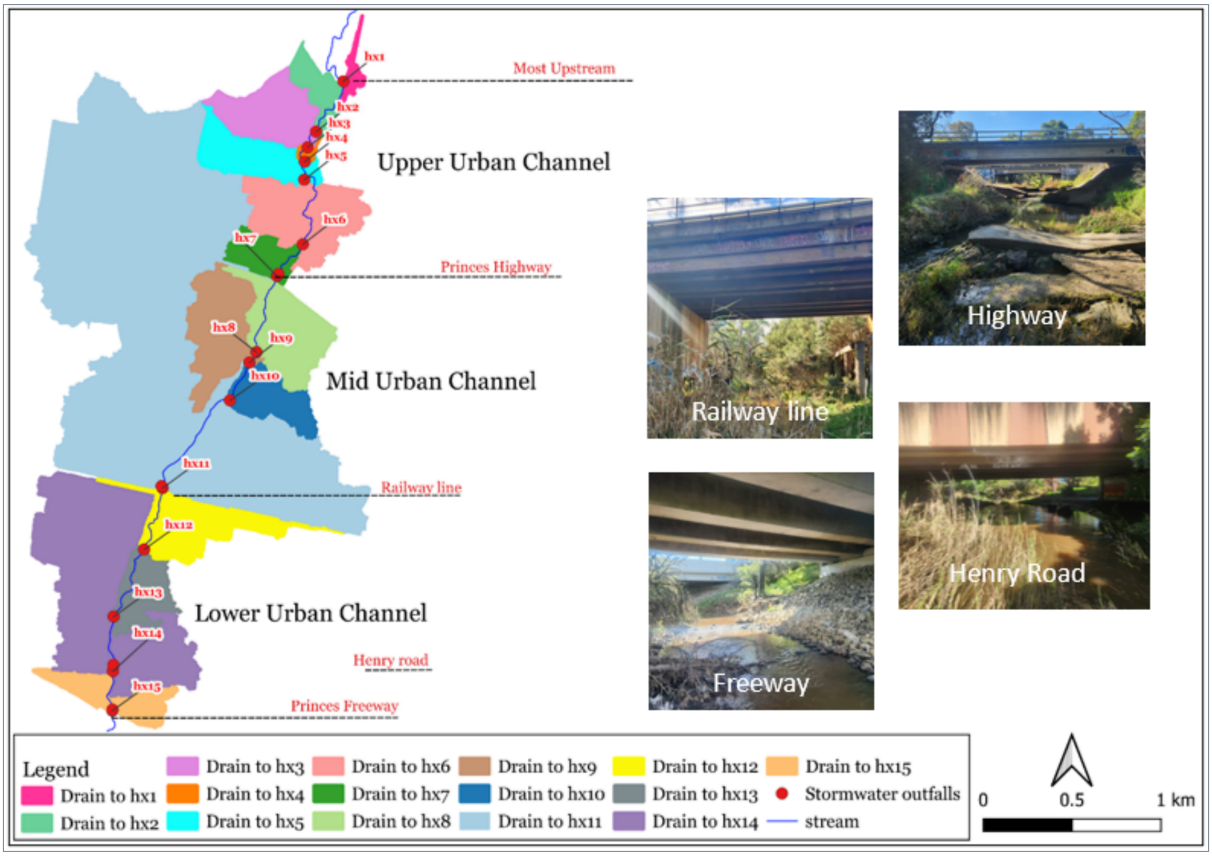

FIGURE 4 Urban channel segments of Toomuc Creek (with crossings) and stormwater outfalls (hx1 to hx15) draining urban areas of varying sizes along the urbanisation gradient. A flow-gauging concrete weir existed beneath Princes Highway.

TABLE 1 Summary of catchment and stormwater drainage characteristics along the creek.

Urban segments	Outfalls (hx)	Distance to next outfall, m	CA (km^2)	EI (%)	TI (%)	ΔCA	ΔEI	ΔTI
Upper urban channel	hx1†	320	38.89	0.15	1.63	0.02	0.02	0.02
	hx2	109	38.95	0.20	1.67	0.07	0.04	0.04
	hx3†	81	38.96	0.39	1.85	0.01	0.19	0.18
	hx4†	107	38.97	0.39	1.86	0.01	0.01	0.01
	hx5†	359	39.27	0.55	2.01	0.30	0.16	0.15
	hx6†	225	39.49	0.69	2.15	0.22	0.14	0.14
Mid-urban channel	hx7$^{\dagger CR}$	466	39.57	0.91	2.36	0.08	0.22	0.21
	hx8†	72	39.76	0.98	2.43	0.19	0.07	0.06
	hx9	234	39.97	1.07	2.51	0.21	0.09	0.09
	hx10	621	40.08	1.23	2.66	0.11	0.16	0.15
Lower urban channel	hx11$^{\dagger CR}$	362	42.38	3.34	4.69	2.30	2.11	2.03
	hx12	409	42.57	3.52	4.87	0.19	0.18	0.17
	hx13	304	42.67	3.61	4.95	0.10	0.09	0.08
	hx14$^{\dagger CR}$	253	43.31	4.32	5.65	0.64	0.72	0.70
	hx15$^{\dagger CR}$		43.43	4.41	5.73	0.12	0.09	0.08

CA = catchment area; EI = effective impervious area; TI = total impervious area; ΔCA = downstream CA mean value minus upstream CA mean value; ΔEI = downstream EI mean value minus upstream EI mean value; ΔTI = downstream TI mean value minus upstream TI mean value; † = presence of one or more hardpoints (grade controls and rock lining) at the downstream section of stormwater of an outfall (grade controls; often spaced out and not visible during high flow events). ^{CR} = presence of crossing (rail and road). Between hx8 and hx9, two closely spaced grade control structures (rock chutes) were in place.

stormwater outfall was delineated. In some instances, stormwater outfalls were combined and treated as a single outfall (e.g. hx14), due to their close proximity (<50 m) to each other (Figure 4). Subsequently, the urban channel was divided into segments based on major crossings in the area (Figure 4) to better illustrate alterations in urbanisation influences along a stream with distinct legacy influences. Notably, the mid-urban channel section from Princes Highway to the Railway line was the most disturbed segment in terms of historical land use and subsequent channel incision, as shown in Figure 2.

In the region, identifying urban streams that have been allowed to adjust naturally was challenging. However, the urban stream channel examined in this study has not been entirely hardened or reconstructed. Hardpoints, such as rock linings and vertical grade controls, were spaced out and strategically placed at pipe outlets, certain meandering bends, underneath crossings (e.g. Princes Highway and Princes Freeway) and downstream sections of outfalls (Table 1).

2.2.2 | Measurement of imperviousness at outfalls

Effective impervious cover (EI) is a critical metric for investigating the impact of urbanisation on stream channel geomorphology in the study area. Vietz et al. (2014), for instance, showed that as little as 2% effective impervious cover was sufficient to impair geomorphic form and features in the region. In this study, EI estimation for 2022 land use change was based on the method outlined by Walsh (2024). They estimated effective impervious cover by weighting the total impervious cover based on its drainage connectivity to streams (see Walsh et al., 2022 for a detailed explanation). We used R Version 4.4.2 (R Core, 2024) to extract EI values from the spatial database developed for the region (see Walsh, 2024). The EI value was extracted for Toomuc Creek upstream and downstream of each stormwater outfall, with a change in EI upstream to downstream per outfall ranging from 0.02 to 2.1% (Table 1). Note that there were no natural tributaries in the urban section, so that the EI value downstream of an outfall (e.g. hx1) was the same as the EI value upstream of the next outfall (e.g. hx2).

2.2.3 | Field measures of geomorphic attributes at outfalls

Surveys were conducted to measure cross-sectional channel width and depth at pools and riffles, as well as to assess the abundance of large wood, sediment bars and benches, along with pool-to-riffle sequence spacing. These assessments were carried out upstream and downstream of identified stormwater outfalls (hx1 to hx15). Where a compound channel form existed, with an active bankfull channel within a historical macro-channel (arising from historic channel incision), both active bankfull and historical (former floodplain) channel dimensions were recorded. The bankfull stage was determined in the field by noting bankfull indicators, such as the tops of the point bars, vegetation changes and slope breaks of the active channel banks. When bankfull indicators were identified on both banks, the lower elevation was selected as the bankfull level. The historic macro-channel measurement was only used to compare past morphology to current morphology and infer channel evolution history and trajectory.

A Global Navigation Satellite System (GNSS) rover (Emlid Reach RS2; https://emlid.com/docs/) was used to perform cross-section measurements. This device has centimetre accuracy and uses real-time kinematic (RTK) information to measure point coordinates (x, y and z) along a cross-section. Specifically, we measured eight channel cross-sections upstream and eight cross-sections downstream of each outfall, comprising four pool and four riffle cross-sections each. We followed the pool-riffle sequence, with each cross-section located at approximately the middle of the pool or riffle, to ensure that we captured the width and depth variation along the stream in a balanced way. Afterwards, we counted all large wood (>50 mm in diameter) within the active bankfull channel between each cross-section. To avoid biased sampling, we normalised the count by dividing the number of large wood (LW) by the stream distance over which they were recorded (count/m). Additionally, we recorded the number of bars and benches between cross-sections upstream and downstream of the outfalls. The field-measured pool and riffle cross-sections were analysed in QGIS to examine the pool-to-riffle sequence spacing (xS) across upstream and downstream outfall sections.

We used the survey cross-sections to estimate bankfull cross-sectional width (W), average bankfull cross-sectional depth (D), width-to-depth or incision ratio (W/D) and channel area (A). Average depth (D) for each cross-section was calculated by averaging the depth for all surveyed points within the bankfull channel. W/D was determined by dividing the width by the maximum depth. A larger W/D ratio indicates more widening than deepening (which could be caused by stabilisation after channel incision), whereas a smaller ratio indicates more deepening than widening (which could be caused by incision). Channel area (A) was determined using a trapezoidal approximation between all surveyed points along the cross-section.

Due to the close proximity of some outfall sections (e.g. hx2, hx3, hx4, hx5, hx8 and hx9; Figure 4), surveying eight separate upstream and downstream cross-sections between two adjacent outfalls was not feasible. To address this, adjustments were made such that the downstream cross-sections or geomorphic measurements of a given outfall (ds_hxi) were used as the upstream cross-section for the next downstream outfall (us_hxi + 1).

2.2.4 | Statistical analysis

To analyse our dataset, we incorporated the geomorphic attributes into a downstream hydraulic geometry model to make statistical inferences about changes occurring along the urban channel gradient. The downstream hydraulic geometry model relates channel morphology to discharge at the bankfull stage, often using catchment area or effective impervious cover as a surrogate for discharge (Soboyejo, Russell, & Fletcher, 2025). In urban environments, discharge is influenced by both the catchment area (CA; typically unaffected by urbanisation) and impervious cover (EI; strongly affected by urbanisation). In this study, we investigated the effect of urbanisation on channel dimensions and related attributes by separating the effects of non-urban and urban influences on discharge. This was achieved by using statistical measures, such as Akaike Information Criterion (AIC), coefficient of determination (r^2) and *p-values* (with alpha = 0.05) to investigate how well geomorphic variables (Y) measured upstream and downstream of outfalls respond to increasing EI and CA when used individually in a regression and together as predictor variables to meet the statistical test assumptions e.g. normality. The response (Y) and explanatory variables (CA and EI) were log-transformed to fit a power function model before being tested for statistical inferences. We specifically looked at the difference in AIC scores (ΔAIC), r^2 values and *p-value* to ascertain whether the addition of EI to CA significantly enhanced the plausibility of and variance explained by the model, as well as the significance of predictors at alpha = 0.05. The AIC analysis was performed separately for each geomorphic response variable (Y), with ΔAIC used to compare the relative plausibility of each model (i.e. with or without EI). For example, we tested three models for each response variable: Y ~ CA, Y ~ EI and Y ~ EI + CA. We then calculated the ΔAIC for each model, where the ΔAIC represents the difference between each model's AIC and that of the best-performing model (i.e., the model with the lowest AIC). In particular, models with the smallest ΔAIC values were considered similarly plausible to the best-performing model, while those with larger ΔAIC values were interpreted as having less plausibility (Burnham & Anderson, 2004). This approach was also extended by substituting total imperviousness (TI) as an alternative explanatory variable to EI, allowing for a comparative assessment of model performance.

Following a similar procedure, we also examined how well the differences in geomorphic variables (ΔY) upstream and downstream of outfalls respond to change in catchment area (ΔCA) and change in effective impervious cover (ΔEI) when used individually and together as predictor variables. Before the incorporation of the difference in explanatory variables and response variables at outfalls into the hydraulic geometry model, the response (ΔY) and explanatory variables (ΔCA and ΔEI) were log-transformed to fit a power function model. Subsequently, we estimated the changes in explanatory and response variables, such as ΔCA, ΔY and ΔEI, by subtracting downstream mean values from upstream mean values (Table 1). For some response variables, such as bars and benches and large wood contained zero values and therefore cannot be directly log-transformed. An offset was added to these responses (ΔY + 0.0001) prior to applying the log10 transformation.

Lastly, we performed a Student's t-test on the mean values of measured response variables at cross-sections upstream and downstream of each outfall. A *p-value* of ≤ 0.05 indicated statistically significant changes in geomorphic attributes downstream of an outfall compared to upstream, while a *p-value* of > 0.05 indicated no significant difference in response variables. All statistical analyses were performed using R Version 4.4.2 (R Core, 2024).

3 | RESULTS

3.1 | Impact of EI on geomorphic attributes

Some geomorphic attributes (average depth, width, width-to-depth ratio, area and large wood) had a significant relationship with each of the catchment area (CA) and effective impervious cover (EI) when assessed individually in a regression model (Table 2). CA was a better predictor than EI, producing more plausible models with lower AIC. For all models, goodness of fit was generally poor, with a maximum r^2 of 0.17, indicating that the model explained only a small proportion of the overall variance. Frequency of bars and benches and pool-to-riffle sequence spacing had no relationship with EI or CA. When both EI and CA were included as predictors, the effect of EI was not significant for any response variables, nor did it improve plausibility or goodness of fit (i.e. substantially reduce AIC or increase r^2). Analysis of the relationship between increasing CA and increasing EI along an urban channel gradient revealed strong multicollinearity between these explanatory variables ($r^2 = 0.9$) (Figure 5), which clearly explains why EI does not improve the model when fitted with CA (Table 2).

To address predictor variable collinearity, we used a model relating the difference in response and explanatory variables upstream and downstream of each stormwater outfall. The relationship between change in catchment area (ΔCA) and change in effective impervious cover (ΔEI) was found to be weaker ($r^2 = 0.54$), indicating less multicollinearity (Figure 5). The Variance Inflation Factor (VIF), a statistical output from regression models used to assess multicollinearity, should be less than 5 to be confident that multicollinearity is not a concern (Kutner et al., 2005; O'brien, 2007). In this study, the VIF of models utilising both ΔCA and ΔEI as explanatory variables were below this threshold (Table 2). Therefore, change in effective impervious cover (ΔEI) and change in catchment area (ΔCA) can be expected to effectively distinguish the individual effects of these explanatory variables on response variables along a gradient of urbanisation. Notably, AIC model outcomes for total impervious cover (TI) were marginally better than those using EI when used individually and in combination with CA to predict geomorphic responses (Supplementary Material: Table S1 and Figure S1). However, the VIF of models utilising both ΔCA and ΔTI (and CA and TI) as explanatory variables were far above the recommended VIF threshold (i.e. <5), confirming strong multicollinearity between these explanatory variables. As a result, models using ΔCA, ΔEI, or a combination of both were deemed more appropriate in this study for capturing the independent effects of CA and urbanisation along the urban stream.

TABLE 2 Comparison of Akaike information criterion (AIC), coefficient of determination (r^2) and *p-values* (with alpha = 0.05) for candidate models using increasing EI and CA or change in EI and CA as the explanatory variables with dependent variables of geomorphic attributes upstream and downstream of outfalls (Y or ΔY), including the combination of both explanatory variables (CA and EI).

Increasing CA and EI vs. response variables measured from upstream to downstream of outfalls							
Model Set / Response	Model A (Y ~ CA)		Model B (Y ~ EI)		Model C (Y ~ CA + EI)		
	AIC (ΔAIC)	r^2	AIC (ΔAIC)	r^2	AIC (ΔAIC)	r^2	VIF
D	**-67.94 (0.00)**	0.15*	-57.38 (10.57)	0.10*	-67.92 (0.02)	0.16†	6.99
W	**-262.78 (0.00)**	0.11*	-256.81 (5.97)	0.08*	-261.36 (1.42)	0.11†	6.99
A	**54.16 (0.00)**	0.17*	64.97 (10.81)	0.12*	54.74 (0.58)	0.17†	6.99
W/D	**-127.69 (0.00)**	0.06*	123.72 (3.97)	0.04*	126.64 (1.05)	0.06†	6.99
LW	**581.79 (0.00)**	0.06*	581.92 (0.13)	0.06*	583.39 (1.6)	0.06	7.02
BB	743.39 (0.10)	0.01	**743.29 (0.00)**	0.01	745.28 (1.99)	0.01	7.02
xS	87.24 (0.13)	0.00	**87.11 (0.00)**	0.00	89.05 (1.94)	0.00	7.02
At outfalls, change in CA and change in EI vs. change in response variables							
Model Set / Response	Model A (ΔY ~ ΔCA)		Model B (ΔY ~ ΔEI)		Model C (ΔY~ ΔCA + ΔEI)		
	AIC (ΔAIC)	r^2	AIC (ΔAIC)	r^2	AIC (ΔAIC)	r^2	VIF
ΔD	**-22.66 (0.00)**	0.10	-21.08 (1.58)	0.00	-21.83 (0.75)	0.17	2.16
ΔW	-34.05 (1.06)	0.01	**-35.12 (0.00)**	0.08	-33.51 (1.64)	0.10	2.16
ΔA	**-14.85 (0.00)**	0.09	-14.12 (0.73)	0.05	-12.85 (2.00)	0.09	2.16
ΔW/D	-28.14 (1.03)	0.05	-27.65 (1.41)	0.02	**-29.41 (0.00)**	0.24	2.16
ΔLW	**35.95 (0.00)**	0.01	36.06 (0.11)	0.00	37.66 (1.71)	0.03	2.16
ΔBB	**22.75 (0.00)**	0.12	24.16 (1.41)	0.03	24.56 (1.81)	0.13	2.16
ΔxS	**-10.03 (0.00)**	0.03	-9.62 (0.68)	0.01	-8.13 (2.17)	0.04	2.16

Best-performing models are highlighted in bold. Δ = change; * = significant at p < 0.05; CA: catchment area († only significant for CA); EI: effective impervious cover; D: average depth (m); W: width (m); A: channel area (m^2); W/D: width-to-depth ratio or incision ratio (m/m); WD: large wood (count/m); BB: bars and benches (count) and xS: pool-to-riffle sequence spacing (m). Variance Inflation Factor (VIF) = 1/ (1 – $r^2 i$): is the coefficient of determination when the i-th predictor is regressed on all the other predictors: VIF > 10; strong multicollinearity, which can significantly affect the regression model and its coefficients, VIF > 5; high correlation indicating possible multicollinearity concerns, 1 < VIF ≤ 5; multicollinearity is low and not a significant issue and VIF = 1; no multicollinearity.

Despite this, our analysis revealed that neither ΔCA nor ΔEI were statistically significant predictors of geomorphic response variables when used individually or together in a regression model (Table 2). As a result, the change in geomorphic attributes measured upstream and downstream of stormwater outfalls cannot be explained by changes in urbanisation along the creek.

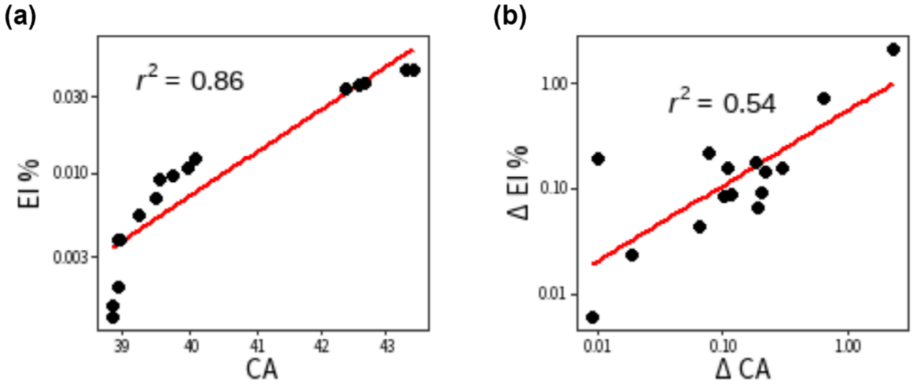

FIGURE 5 Relationship between catchment area and effective impervious area: (a) incremental change between catchment area (CA) and effective impervious cover (EI) and (b) step change between change in catchment area (ΔCA) and change in effective impervious cover (ΔEI) at stormwater outfalls.

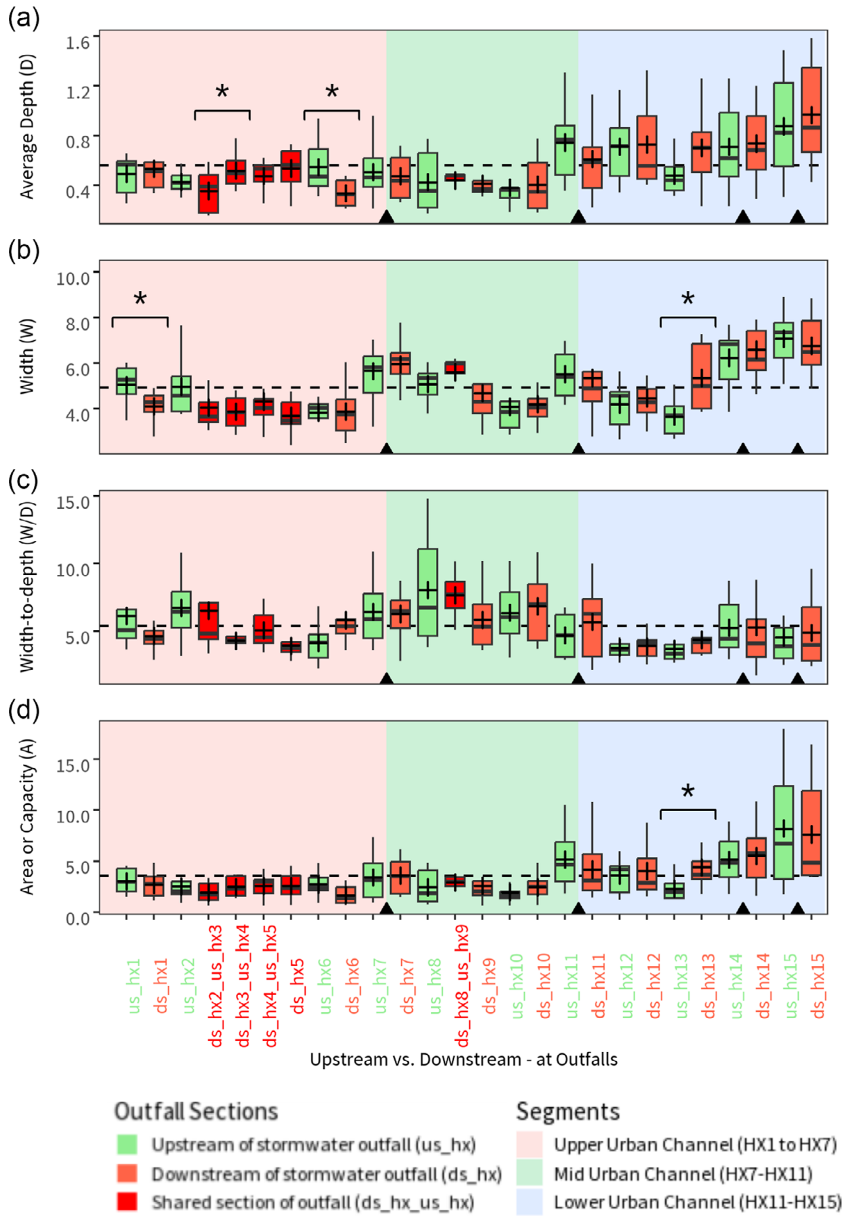

FIGURE 6 Changes in channel dimensions between upstream and downstream sections of outfalls. Asterisk (*) indicates significant change ($p \le 0.05$; see supplementary table S3 for each t-test value). For the shared or overlapping section of a given outfall (ds_hxi_us_hxi+1), acting as both upstream and downstream, the adjacent upstream section of a given outfall (hxi-1) was used for comparison. (a) Average depth (m), (b) width (m), (c) width-to-depth ratio or incision value (m/m) and (d) channel area or capacity (m^2). The plus in the middle of the boxplot indicates the mean values. Dashed lines indicate the overall average. Arrows indicate crossings (road and railway).

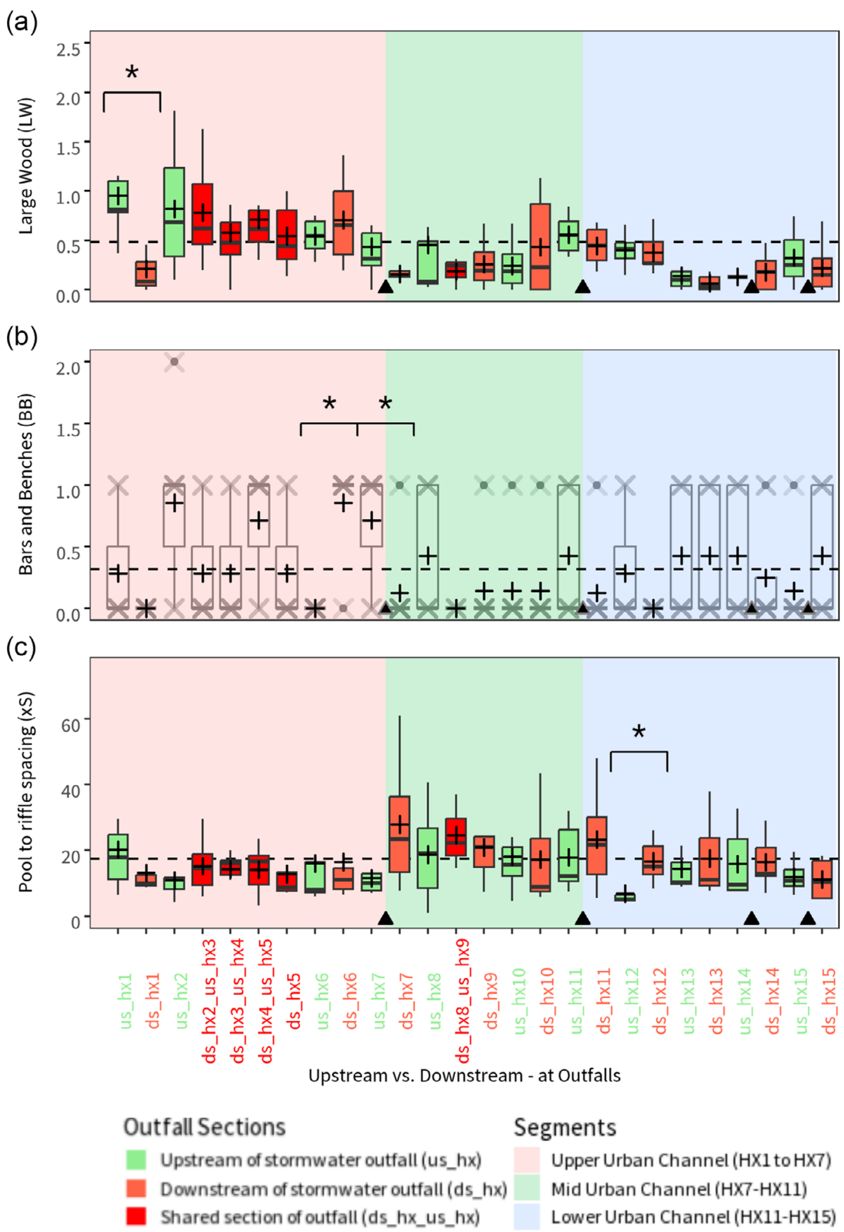

FIGURE 7 Changes in ecologically relevant channel features between upstream and downstream sections of outfalls. Asterisk (*) indicates significant change ($p \leq 0.05$; see supplementary table S3 for each t-test value). For the shared or overlapping section of a given outfall (ds_hxi_us_hxi+1), acting as both upstream and downstream, the adjacent upstream section of a given outfall (hxi-1) was used for comparison. (a) Number of large wood pieces per m of channel section length (count/m), (b) number of bars and benches (count) and (c) pool-to-riffle sequence spacing (m). The plus in the middle of the boxplot indicates the mean values. Dashed lines indicate the overall average. Arrows indicate crossings (road and railway).

3.2 | Geomorphic changes at stormwater outfalls

Figures 6 and 7 present box plots of various geomorphic attributes, such as average depth, width, area, width-to-depth ratio, large wood, pool-to-riffle spacing and the presence of bars and benches, measured both upstream and downstream of outfalls (hx1 to hx15). Table 3 shows the summary of the mean values for each geomorphic variable measured upstream and downstream of outfalls. While substantial or significant alterations between upstream and downstream cross-sections were observed at a few outfall locations, the large number of hypothesis tests conducted increases the likelihood that some of these significant changes may be due to chance, i.e., false positives (Table 4).

3.2.1 | Average cross-sectional depth (D)

At all but two outfalls, there was no significant difference in depth between upstream and downstream cross-sections (Figure 6a). The exceptions were hx3, which had a significant increase in depth, and hx6, which had a significant decrease ($p \leq 0.05$). Interestingly, the mean value of average depth both upstream and downstream of outfalls was clearly higher at the lower urban channel segment (hx11 to hx15; Railway to Princes Freeway crossings) (Figure 6b and Table 3). In this part of the urban channel, hx11 corresponds to the location where the cumulative EI begins to exceed 2%, reaching 4.4% downstream of hx15 (Table 1).

TABLE 3 Summary of the mean values for each geomorphic attribute.

Outfalls	Outfall sections	Segments along the creek	Mean D	Mean W	Mean A	Mean W/D	Mean LW	Mean BB	Mean xS
hx1	us_hx1	Upper segment	0.49	5.06	3.03	6.14	0.95	0.29	20.28
	ds_hx1		0.53	4.12	2.68	4.66	0.21	0.00	13.20
hx2	us_hx2		0.43	4.98	2.51	6.73	0.82	0.86	10.89
	ds_hx2_us_hx3		0.35	4.06	1.93	6.54	1.10	0.29	15.24
hx3									
	ds_hx3_us_hx4		0.52	3.87	2.47	4.31	0.58	0.29	14.31
hx4									
	ds_hx4_us_hx5		0.48	4.32	2.57	5.08	0.97	0.71	14.16
hx5	ds_hx5		0.54	3.70	2.56	3.93	0.54	0.29	12.84
hx6	us_hx6		0.55	3.84	2.72	4.14	0.54	0.00	16.04
	ds_hx6		0.34	3.89	1.65	5.83	0.99	0.86	16.50
hx7	us_hx7		0.51	5.67	3.41	6.45	0.91	0.75	19.08
	ds_hx7	Mid segment	0.47	5.96	3.60	6.29	0.15	0.00	28.90
hx8	us_hx8		0.43	5.09	2.44	8.05	0.48	0.43	21.81
	ds_hx8_us_hx9		0.44	5.61	2.91	7.68	0.12	0.00	17.90
hx9	ds_hx9		0.41	4.69	2.57	5.85	0.29	0.14	20.94
hx10	us_hx10		0.38	4.093	1.95	6.37	0.24	0.14	18.12
	ds_hx10		0.41	4.21	2.44	6.86	0.92	0.14	17.22
hx11	us_hx11		0.74	5.52	5.18	4.71	0.56	0.43	17.91
	ds_hx11	Lower segment	0.61	5.35	4.18	5.70	0.44	1.00	23.30
hx12	us_hx12		0.71	4.20	3.61	3.79	0.398	0.29	6.91
	ds_hx12		0.73	4.47	4.03	3.90	0.37	0.00	16.72
hx13	us_hx13		0.48	3.66	2.30	3.71	0.14	0.43	14.39
	ds_hx13		0.70	5.36	4.40	4.38	0.07	0.43	17.54
hx14	us_hx14		0.71	6.24	5.15	5.27	0.13	0.43	30.63
	ds_hx14		0.74	6.60	5.53	5.31	0.18	0.25	16.45
hx15	us_hx15		0.88	7.09	8.21	4.55	0.32	0.14	11.90
	ds_hx15		0.97	6.77	7.61	4.90	0.22	0.43	21.02

hxi: a given outfall; us_hxi: upstream section of a given outfall; ds_hxi: downstream of a given outfall; ds_hxi_us_hxi + 1: shared section of outfall, i.e. acting as both upstream and downstream; D: average depth (m); W: width (m); A: channel area (m^2); W/D: width-to-depth ratio or incision ratio (m); WD: large wood (count/m); BB: bars and benches (count) and xS: pool-to-riffle sequence spacing (m).

3.2.2 | Width (W)

Only hx1 and hx13 showed a significant increase ($p \leq 0.05$) in bankfull width between upstream and downstream cross-sections (Figure 6b). There were no other significant differences in width upstream and downstream of outfalls. More importantly, the mean value of channel width both upstream and downstream of outfalls near rail and road crossings was distinctly higher compared to those outfall sections without crossings, specifically at hx7 (Princes Highway), hx11 (Railway line), hx14 (Henry Road) and hx15 (Princes Freeway), as well as at hx8, which featured closely spaced vertical-grade controls (or rock chutes) (Figure 6b and Table 3).

3.2.3 | Width-to-depth ratio (W/D) or incision value

There were no significant differences ($p > 0.05$) in the width-to-depth ratio between upstream and downstream of outfalls (Figure 6c). However, more widening than deepening (higher W/D) was clearly observed both upstream and downstream of hx2 and all outfall sections located in the most disturbed segment (i.e. mid-urban segment) of the urban channel (hx7 to hx11; Railway to Princes Freeway crossings). Conversely, more deepening than widening (lower W/D) was clearly observed at hx5 and some sections located in the lower segment, specifically hx12 and hx13. In the lower segment of the urban channel, where EI crosses 2%, outfalls without crossings (i.e. hx12 and hx13) showed more deepening than widening (lower W/D), whereas outfalls with crossings (i.e. hx11, hx14 and hx15) showed more widening than deepening (higher W/D).

3.2.4 | Cross-sectional area or capacity (A)

Only outfall hx13 showed a significant increase in bankfull channel capacity ($p \leq 0.05$) between upstream and downstream sections (Figure 6d). Notably, the mean value of channel capacity both upstream and downstream of outfalls with crossings was slightly higher compared to those sections without crossings, except outfalls hx12 and hx13 located in the lower urban channel segment (Figure 6d and Table 3).

This pattern mirrored the pattern for channel widening, but the hx12 and hx13 sections were narrower. Additionally, the mean value of channel capacity, both upstream and downstream of outfalls, was clearly higher at the lower urban channel segment (hx11 to hx15; Railway to Princes Freeway crossings), where the cumulative EI was greater than 2%. At this threshold, the lower segment of the urban channel gradient (hx11 to hx15) exhibited greater variability in width (W), average depth (D) and channel area (A) compared to the upper and middle segments (Figure 6a, b and d). In contrast, the width-to-depth (W/D) ratio showed more variation in the middle segment (Figure 6c).

3.2.5 | Large wood (LW)

Only the most upstream outfall, hx1, showed a significant reduction ($p \leq 0.05$) in large wood frequency between upstream and downstream sections (Figure 7a). Notably, the mean frequency of large wood both upstream and downstream of outfalls was slightly higher in the upper urban channel segment (hx1 to upstream of hx7) compared to the mid and lower segment of the urban channel (downstream of hx7 to hx15).

3.2.6 | Bars and benches (BB)

At hx6, the frequency of bars and benches significantly increased, and at hx7, it significantly decreased ($p \leq 0.05$) between upstream and downstream sections (Figure 7b). These outfall sections were located immediately upstream of Princes Highway crossings and a flow-gauging concrete weir, which might explain why we also observed a significant decrease in average depth at hx6 (Figure 6a and Table 3). There were no significant differences upstream and downstream of other outfalls. However, the mean value of bars and benches was sometimes higher at some outfall sections at the upper urban channel (hx1 to upstream of hx7) compared to the mid and lower urban channel (downstream of hx7 to hx15). Both large wood and bars and benches were more frequent in the upper segment than in the lower segment (Figure 7a and b).

3.2.7 | Pool-to-riffle sequence spacing (xS)

Only hx12 exhibited a significant increase ($p \leq 0.05$) in pool-riffle spacing between upstream and downstream sections (Figure 7c). There were no other significant differences in pool-to-riffle sequence spacing between upstream and downstream of outfalls. However, the mean value of pool-to-riffle spacing tended to be slightly higher in the most disturbed segment (i.e. mid-urban segment) of the urban channel (downstream of hx7 to upstream of hx11) compared to the upper (hx1 to upstream of hx7) and lower (downstream of hx11 to hx15) segment (Figure 7c and Table 3).

4 | DISCUSSION

Results from this study show that geomorphic attributes observed upstream and downstream of stormwater drain outfalls along a suburban creek could not be well explained alone by changes in catchment impervious cover (ΔEI; typically considered the primary drivers of stormwater inputs). Instead, other factors, such as historical land uses and hardpoints, played a significant role in shaping these geomorphic attributes. In the region (southeastern Australia), published findings have shown that relatively low levels of urbanisation were sufficient to impair geomorphic forms and features (Vietz et al., 2014), in-stream biota (Burns et al., 2015; Walsh, 2004) and stream water quality (Hatt et al., 2004). As the levels of urbanisation in the study area exceed geomorphic and ecological degradation thresholds previously established in this region, we anticipated an increase in channel dimensions, such as bankfull cross-sectional area, with increase in stormwater inputs. However, this expected trend was not observed along Toomuc Creek. This irregular response to urbanisation accords with worldwide findings reported by Soboyejo, Russell, & Fletcher (2025), which indicate that hydraulic geometry relationships developed for urbanised catchments are often disrupted by non-alluvial influences (e.g. hardpoints). Such disruptions often result in highly variable responses, poor model fit and statistically insignificant relationships.

In the wider literature, hardpoints interventions, such as grade controls, have been reported to cause unintended erosion or sediment deposition issues (e.g. Beschta & Platts, 1986; Chin et al., 2017; Navratil et al., 2013; Taniguchi et al., 2018), as well as channel fragmentation, variable sediment deposition patterns and prevention of upstream knickpoint migration (Grable & Harden, 2006). Similarly, Chin et al. (2017) found that hardpoint interventions like road crossings resulted in channel deepening downstream and widening upstream. Taniguchi et al. (2018) also reported that channels closer to hardpoints were larger than those farther away. In this study, cross-sections close to crossings (roads and rail) and closely spaced grade controls (or rock chutes) appear wider compared to sections without such structures.

Historical land and stream management practices, such as channelisation, also play a major role in overshadowing or superimposing the influence of modern stormwater inputs. Wohl (2015, 2019) highlighted that past human activities (such as farming practices, deforestation, or past construction, river damming and channelisation) often leave behind geomorphic impacts (such as altered sediment dynamics and modified channel dimensions) on rivers, streams and creeks that can still be observed, even though those activities stopped long ago. Historical legacies sometimes complicate the ability of scientists or waterway managers to fully understand or predict river behaviour in response to modern-day influences (in our case, urbanisation). In this aspect, Channel Evolution Models (CEMs) are common conceptual and qualitative tools used in interpreting the evolutionary states and trajectories of a channel (e.g. Bevan et al., 2018; Booth & Fischenich, 2015; Hawley et al., 2012; Schumm, Harvey, & Watson, 1984; Simon, 1989; Simon & Hupp, 1987). The most widely recognised conceptual model, which has served as a basis for the development of more recent and complex models, is that of Schumm, Harvey, & Watson (1984). The Schumm Channel Evolution Model (CEM) describes five stages of channel evolution: Stage I (Initial Equilibrium), where the channel is stable and undisturbed; Stage II (Degradation), marked by channel incision due to increased runoff or base-level lowering; Stage III (Widening), where banks become unstable, leading to lateral erosion; Stage IV (Aggradation), characterised by

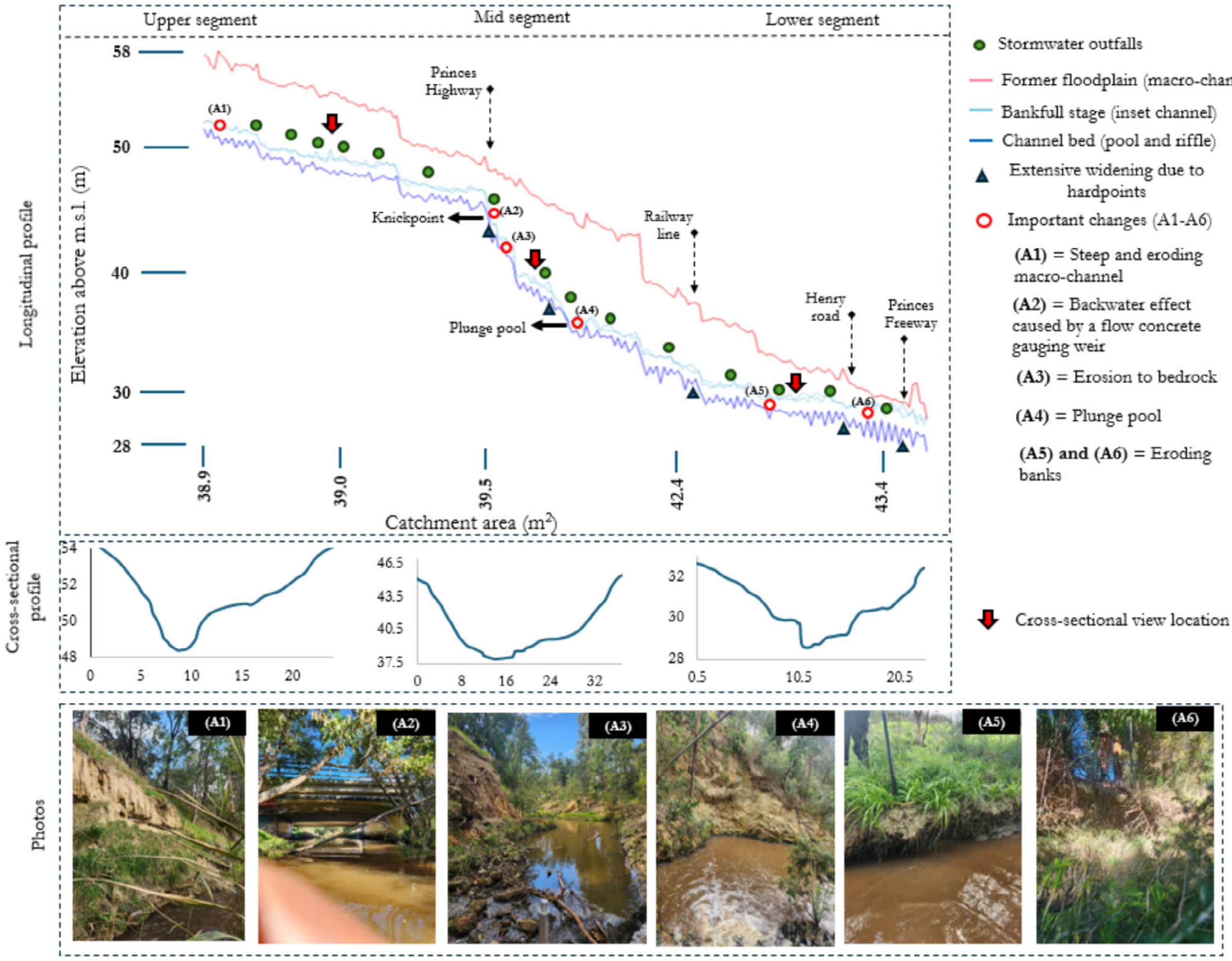

FIGURE 8 Longitudinal profile, cross-sectional profiles and representative images of geomorphic changes along the urban channel segments.

sediment deposition as the channel begins to stabilise and Stage V (Re-equilibration), where the channel reaches a new equilibrium with reduced erosion and deposition rates.

In this study, historical land-use practices have left lasting geomorphic signatures, such as erosion to bedrock, plunge pools and knickpoints along the urban stream channel (Figure 8). Consequently, the morphology of the creek is highly complex, with an active bankfull channel existing within a macro-channel (arising from historic channel incision and subsequent recovery). In the upper urban channel segment, the macro-channel has steep and relatively unstable banks in most places, revealing signs of bank failure (undercutting and slumping) and ongoing macro-channel widening. The channel also displays a complex and variable cross-sectional profile because of the meandering bend morphology and a wide and narrow inset floodplain existing in various places. The stream bed mostly contains sandy material, interspersed with in-channel vegetation. Bars and benches are common in this segment, as shown in our analysis, owing to recent lateral erosion of banks and sediment from upland areas. Many studies have reported that the primary sources of sediment delivery in urbanising streams originate from collapsing banks and construction sediment from upland areas (e.g. Chin, 2006; Nelson & Booth, 2002; Russell, Vietz, & Fletcher, 2017; Trimble, 1997; Wolman, 1967). Large wood is also abundant in the upper channel segment. These in-stream features are favoured by the gentle channel slope, as well as rock chutes placed downstream of many outfalls.

Current macro-channel surveys and field observations indicate that some channels in the upper segment are actively incising, while others have progressed beyond incision and are beginning to accrete and widen (Stages II and III; Schumm, Harvey, & Watson, 1984). Introducing stormwater into a system still adjusting to historical legacies may result in channel responses to modern influences (such as urbanisation) being superimposed on or overshadowed by ongoing historical adjustments. Alternatively, these historical adjustments may enhance the resilience of the channel to future increases in runoff (O'Driscoll, Soban, & Lecce, 2009). In this study, changes in channel dimensions between upstream and downstream of outfalls appeared to be influenced by ongoing historical adjustments (such as macro-channel bank failure) and hardpoints strategically placed at downstream sections of outfalls (such as rock chutes). These phenomena, coupled with a relatively gentle bed slope, have slowed down channel incision in most areas, but active widening continues to occur near these features.

At Princes Highway, a flow-gauging concrete weir constructed beneath the crossing altered the natural flow of the stream by creating a backwater effect, sediment aggradation upstream of the weir, widened bankfull channel morphology and high velocity stream flow coinciding with a steep bed profile downstream of the weir. This concrete weir, with other rock chutes placed strategically along the creek, has generally disrupted flow patterns and contributed to reducing channel incision.

In the mid-urban channel segment, historic incision resulting from past swampland drainage, channelisation and vegetation clearance during the late 1800s to mid-1900s has produced an over-steepened stream gradient and eroded thousands of tons of sediment (Hanslow, 1939; Richard, 1940). The stream bed at this segment has incised to non-erodible Silurian bedrock, such that incision has stopped occurring and widening has become dominant, with some accretion of sediment occurring further south (due to rock chutes), such as near hx8, hx9, hx10 and hx11. An article from 1944 reported that channel morphology downstream of the Princes Highway measured 15 m wide (Richard, 1940). Current macro-channel surveys indicate that the channel width from the Princes Highway to the railway crossings is no less than 22 m, further underscoring the trend of significant widening of the historic channel over time. Bankfull channel data also suggested that the mid-segment morphology has not responded to urbanisation because there was no significant difference in any geomorphic attributes at outfall sections.

The upstream migration of knickpoints due to historical base-level change, straightening and land use change, has largely ceased due to the presence of bedrock, rock chutes and a flow-gauging concrete weir beneath the Princes Highway. In Second Creek, in Knox County, Tennessee, USA, Grable & Harden (2006) also reported that the presence of road crossings and other infrastructure, such as vertical grade controls, influenced or decoupled the upstream migration of knickpoint along their urban channel. Currently, macro-channel surveys and field observations further indicated that the morphology of the mid segment is relatively stable with disconnected historical floodplains and vegetated inset floodplains in certain places, highlighting Stage III and IV of the channel evolution model (Schumm, Harvey, & Watson, 1984). Moreover, pool-to-riffle spacing appeared to be slightly higher at the mid segment than at the upper and lower urban channel segments. Wohl, Vincent, & Merritts (1993) reported that pools are spaced closer to riffles in steep sections but farther apart in flatter sections in the non-urban influenced stream. In this study, the reverse is the case.

At the railway crossing, historic records from 1877 indicated that the creek bed measured only 2.7 m deep and 3.4 m wide below the railway bridge deck. In comparison, by 1940, the creek bed had increased to 8.8 m deep and 4.6 m wide. The rail level is just above the historic floodplain level, suggesting that the railway bridge deck has likely remained at a similar level since pre-incision times. Current surveys reveal that the bed is now 5.7 m deep and 21 m wide, suggesting that widening has occurred more than deepening over the years. The reduction in depth is most likely due to vertical grade controls (rock chutes) and reduced channel slope, as well as increased sediment supply from erosion progressing upstream, which might explain why bankfull channel dimensions showed no significant difference between upstream and downstream of hx11, despite draining the largest urban sub-catchment.

In the lower urban channel segment, the cumulative EI begins to exceed 2% at hx11, which distinctly raises the channel capacity and deepening at upstream and downstream sections of outfalls, reaching 4.4% downstream of hx15. Currently, macro-channel surveys and on-site observations suggest that the lower urban channel has relatively stable banks with completely disconnected historic floodplains. Macro-channel floodplain to bankfull stage is quite low in most places and uniform with bankfull stage in some places at the farthest downstream channels (Stage IV and V; Schumm, Harvey, & Watson, 1984). The stream bed is very sandy, just as much as the upper urban channel, interspersed with emergent in-stream vegetation in many places. However, the amount of large wood within and along the lower urban channel was not as much as in the upper urban channel. Blauch & Jefferson (2019) noted that large wood density decreased as urban intensity increased and wood transport increased with urban intensity. Also, this segment has a substantial amount of aggrading sediment on the bed, which is favoured by a gentle channel slope. On the contrary, field observations suggested that the lower urban channel has started to show evidence of undercutting in many places, possibly signalling another cycle of channel evolution (Stage III; Schumm, Harvey, & Watson, 1984), typical of urban streams.

Many non-urban streams in southeastern Melbourne with catchment characteristics similar to Toomuc Creek (such as those located within sedimentary and alluvial reaches) have experienced extensive land use changes, including farming, vegetation clearance, livestock access and swampland drainage. These disturbances have led to highly incised, complex channel forms with limited floodplain connectivity and increased channel gradient as a result of drainage works in the downstream areas (Sammonds & Vietz, 2015). However, natural streams in other parts of Melbourne and surroundings have different characteristics (e.g. geology, topography, climate) and are therefore not appropriate to use as reference sites for Toomuc Creek. Investigations by Sammonds & Vietz (2015) into pre-disturbance conditions in the southeastern region where Toomuc Creek is located revealed that natural streams were originally characterised by: (i) shallow channels with a low channel gradient, (ii) high lateral connectivity through braided flow paths, (iii) active floodplain processes, such as the formation of natural levees, point bars and backswamps and (iv) wide riparian zones full of grassy woodlands. In nearby areas of southeastern Melbourne, Vietz et al. (2014) found that natural headwater streams are typically characterised by dynamic and variable channel morphology, as well as dynamic and limited bank erosion. Based on this early and contemporary understanding of natural streams in the area, the urban segment of Toomuc Creek showed a clear departure from its natural state.

Overall, these observations along an urban channel reflect that physical channel forms and in-stream feature adjustments are not driven by singular processes but by various ongoing series of changes evolving over time and space. The influence of past trajectories on present channel conditions and future evolution of Toomuc Creek is consistent with broader understandings of the importance of temporal context in shaping geomorphic form and function (e.g. Brierley & Fryirs, 2004; E. Wohl, 2018). This study highlights the relevance of this concept within urban environments, where it has received limited attention. Local context, such as hardpoints, sediment construction, riparian vegetation and geology, plays a significant role in shaping stream channel form and function. Isolating the influence of these site-specific factors is essential for accurately attributing changes in channel form and functions to urbanisation (Soboyejo, Russell, & Fletcher, 2025). Nevertheless, certain outfall locations along the urban channel gradient exhibited clear evidence of disturbance (or significant difference) in widening, deepening and the combination of both, indicating that proximity of outfalls may still act as hotspots of disturbance to urbanisation in locations with limited historical land-use and no hardpoints influence.

5 | CONCLUSION AND FUTURE DIRECTIONS

Urban channels worldwide face disturbances due to land-use changes and in-channel activities, posing significant threats to stream health and associated aquatic ecosystems. This study provides insights into the predictability of channel morphologic adjustments to urbanisation using a controlled field-based experiment (upstream and downstream of stormwater outfalls). This novel approach could serve as a guide for researchers and waterway managers seeking to explore the complex relationship between channel geomorphology and urbanisation. Contrary to our expectations, stream channel capacity or cross-sectional area did not follow a systematic downstream increase with catchment urbanisation due to arrays of factors, although some outfall locations did show clear evidence of disturbance, confirming that widening, deepening and a combination of both occur locally and in a spatially discontinuous manner. This suggests two future directions. Firstly, future research seeking purely to isolate urban influences on geomorphic adjustments in streams needs carefully controlled study designs involving sites with little historical disturbance and no hardpoint interventions. Secondly, and perhaps more importantly, the conditioning influence of past management and channel evolution on contemporary geomorphic responses needs to be specifically studied in urban settings. Understanding the complex interplay between urbanisation, channel morphology, historical land-use context and in-stream features is vital for developing more accurate predictive models that could inform effective and broad management strategies. However, the modelling approach in this study is subject to some limitations, such as the relatively small number of sites, the limited geographic scope (a single watershed) and a limited range of effective imperviousness.

AUTHOR CONTRIBUTIONS

Conceptualisation: [LAS, KLR, TDF]; Funding acquisition: [KLR, TDF]; Methodology [LAS, KLR, TDF]; Formal analysis and investigation: [LAS]; Supervision [KLR, TDF]; Roles/Writing - original draft: [LAS] and Writing - reviewing & editing: [LAS, KLR, TDF]. All authors have read and agreed to the published version of the manuscript.

ACKNOWLEDGEMENTS

We acknowledge First Nations peoples as the Traditional Owners and custodians of the land and water on which all Australians rely. This research was conducted on Bunurong Country, and we acknowledge their enduring connection to the land and waterways. We pay our respects to their elders, past and present, recognising their role as traditional river managers and caretakers of Country for thousands of years. Sincere gratitude to The University of Melbourne for the provision of a scholarship to Soboyejo Lukman Adeboye and Melbourne Water for project funding. We also thank Peter Poelesma, Claudia Nicklason, Kathryn Russell, Tim Fletcher, Peter Cottingham and Paulo V.R.M. Silva for their immense help with fieldwork. We thank Jasper Kunapo and Mathew Burns for their great help with dealing with the spatial database and delineation of catchment properties. We thank Rhys Coleman (Melbourne Water) for his review and suggestions for improvement in the draft manuscript. We also extend our gratitude to two anonymous reviewers for their valuable feedback and constructive suggestions, which have significantly improved the quality of this manuscript. Open access publishing facilitated by The University of Melbourne, as part of the Wiley - The University of Melbourne agreement via the Council of Australian University Librarians.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no competing interests.

DATA AVAILABILITY STATEMENT

Available upon request.

ORCID

Lukman A. Soboyejo https://orcid.org/0000-0002-2953-1150
Kathryn L. Russell https://orcid.org/0000-0002-9613-4665

REFERENCES

Annable, W.K., Watson, C.C. & Thompson, P.J. (2012) Quasi-equilibrium conditions of urban gravel-bed stream channels in southern Ontario, Canada. *River Research and Applications*, 28(3), 302–325. Available from: https://doi.org/10.1002/rra.1457

Australian Bureau of Statistics. (2024) 2021 pakenham, census all persons quickstats https://abs.gov.au/census/find-census-data/quickstats/2021/SAL22027

Beschta, R.L. & Platts, W.S. (1986) Morphological features of small streams: significance and function. *JAWRA Journal of the American Water Resources Association*, 22(3), 369–379. Available from: https://doi.org/10.1111/j.1752-1688.1986.tb01891.x

Bevan, V., MacVicar, B., Chapuis, M., Ghunowa, K., Papangelakis, E., Parish, J., et al. (2018) Enlargement and evolution of a semi-alluvial creek in response to urbanization. *Earth Surface Processes and Landforms*, 43(11), 2295–2312. Available from: https://doi.org/10.1002/esp.4391

Bird, J.F. (1980) Geomorphological implications of flood control measures, Lang Lang river, Victoria. *Australian Geographical Studies*, 18(2), 169–183. Available from: https://doi.org/10.1111/j.1467-8470.1980.tb00366.x

Blauch, G.A. & Jefferson, A.J. (2019) If a tree falls in an urban stream, does it stick around? Mobility, characteristics, and geomorphic influence of large wood in urban streams in northeastern Ohio, USA. *Geomorphology*, 337, 1–14. Available from: https://doi.org/10.1016/j.geomorph.2019.03.033

Booth, D. B. (1991) Urbanization and the natural drainage system—impacts, solutions, and prognoses https://digital.lib.washington.edu:443/researchworks/handle/1773/17032

Booth, D.B. & Fischenich, C.J. (2015) A channel evolution model to guide sustainable urban stream restoration. *Area*, 47(4), 408–421. Available from: https://doi.org/10.1111/area.12180

Booth, D.B. & Jackson, C.R. (1997) Urbanization of aquatic systems: degradation thresholds, stormwater detection, and the limits of mitigation. *JAWRA Journal of the American Water Resources Association*, 33(5), 1077–1090. Available from: https://doi.org/10.1111/j.1752-1688.1997.tb04126.x

Brierley, G.J. & Fryirs, K.A. (Eds). (2004) *Geomorphology and river management: applications of the river styles framework*, 1st edition. Malden, MA: Wiley. Available from: https://doi.org/10.1002/9780470751367

Burnham, K.P. & Anderson, D.R. (2004) In: Burnham, K.P. & Anderson, D.R. (Eds.) *Model selection and multimodel inference*. New York, NY: Springer. Available from: https://doi.org/10.1007/b97636

Burns, M.J., Walsh, C.J., Fletcher, T.D., Ladson, A.R. & Hatt, B.E. (2015) A landscape measure of urban stormwater runoff effects is a better predictor of stream condition than a suite of hydrologic factors. *Ecohydrology*, 8(1), 160–171. Available from: https://doi.org/10.1002/eco.1497

Butler, G. (1996) *Cardinia Shire heritage study*. Pakenham, Vic.: Graeme Butler & Associates.

Chin, A. (2006) Urban transformation of river landscapes in a global context. *Geomorphology*, 79(3), 460–487. Available from: https://doi.org/10.1016/j.geomorph.2006.06.033

Chin, A., Gidley, R., Tyner, L. & Gregory, K. (2017) Adjustment of dryland stream channels over four decades of urbanization. *Anthropocene*, 20, 24–36. Available from: https://doi.org/10.1016/j.ancene.2017.11.001

Country news. (1898, March 1) *Argus*. http://nla.gov.au/nla.news-article9792690

Geoscience Australia. (2025) AGSON geoscience portal https://portal.geoscience.gov.au/

Grable, J.L. & Harden, C.P. (2006) Geomorphic response of an Appalachian Valley and ridge stream to urbanization. *Earth Surface Processes and Landforms*, 31(13), 1707–1720. Available from: https://doi.org/10.1002/esp.1433

Gregory, K.J. (2006) The human role in changing river channels. *Geomorphology*, 79(3), 172–191. Available from: https://doi.org/10.1016/j.geomorph.2006.06.018

Gregory, K.J., Davis, R.J. & Downs, P.W. (1992) Identification of river channel change to due to urbanization. *Applied Geography*, 12(4), 299–318. Available from: https://doi.org/10.1016/0143-6228(92)90011-B

Hammer, T.R. (1972) Stream channel enlargement due to urbanization. *Water Resources Research*, 8(6), 1530–1540. Available from: https://doi.org/10.1029/WR008i006p01530

Hanslow, H. (1939, September 26) Erosion losses. Horsham Times. http://nla.gov.au/nla.news-article73141613

Hatt, B.E., Fletcher, T.D., Walsh, C.J. & Taylor, S.L. (2004) The influence of urban density and drainage infrastructure on the concentrations and loads of pollutants in small streams. *Environmental Management*, 34(1), 112–124. Available from: https://doi.org/10.1007/s00267-004-0221-8

Hawley, R.J., Bledsoe, B.P., Stein, E.D. & Haines, B.E. (2012) Channel evolution model of semi-arid stream response to urban-induced hydromodification. *JAWRA Journal of the American Water Resources Association*, 48(4), 722–744. Available from: https://doi.org/10.1111/j.1752-1688.2012.00645.x

Hawley, R.J., MacMannis, K.R. & Wooten, M.S. (2013) Bed coarsening, riffle shortening, and channel enlargement in urbanizing watersheds, northern Kentucky, USA. *Geomorphology*, 201, 111–126. Available from: https://doi.org/10.1016/j.geomorph.2013.06.013

Joyce, E.B. (1992) The west Victorian uplands of southeastern Australia: origin and history. *Earth Surface Processes and Landforms*, 17(4), 407–418. Available from: https://doi.org/10.1002/esp.3290170410

King, R.S., Baker, M.E., Kazyak, P.F. & Weller, D.E. (2011) How novel is too novel? Stream community thresholds at exceptionally low levels of catchment urbanization. *Ecological Applications*, 21(5), 1659–1678. Available from: https://doi.org/10.1890/10-1357.1

Knighton, D. (1998) *Fluvial forms and processes: a new perspective*, 2nd edition. London: Routledge. Available from: https://doi.org/10.4324/9780203784662

Kutner, M.H., Nachtsheim, C.J., Neter, J. & Li, W. (2005) *Applied linear statistical models*. New York, NY: McGraw-Hill. Available from: https://thuvienso.hoasen.edu.vn/handle/123456789/9564

Leopold, L.B., Huppman, R. & Miller, A. (2005) Geomorphic effects of urbanization in forty-one years of observation. *Proceedings of the American Philosophical Society*, 149(3), 349–371.

Leopold, L.B. & Maddock, T. (1953) *The hydraulic geometry of stream channels and some physiographic implications*. Washington, D.C.: U.S. Government Printing Office.

Montgomery, D.R., Bolton, S., Booth, D.B. & Wall, L. (2003) *Restoration of puget sound rivers*. Seattle: University of Washington Press.

Montgomery, D.R. & Buffington, J.M. (1997) Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin*, 109(5), 596–611. Available from: https://doi.org/10.1130/0016-7606(1997)109

Morisawa, M. & Laflure, E. (1979) Hydraulic Geometry, Stream Equilibrium and Urbanization. In: *Adjustments of the fluvial system*. London: Routledge.

Natica, S., Annabel, N., Louise, H. & Jessie, B. (2017) *Post-contact heritage assessment—PAKENHAM EAST PRECINCT prepared for Cardinia Shire Council* (Final report, 2017 2047) https://vpa-web.s3.amazonaws.com/wp-content/uploads/2018/01/Pakenham-East-C234-Post-Contact-Heritage-Report-Context-October-2017.pdf

Navratil, O., Breil, P., Schmitt, L., Grosprêtre, L. & Albert, M.B. (2013) Hydrogeomorphic adjustments of stream channels disturbed by urban runoff (Yzeron River basin, France). *Journal of Hydrology*, 485, 24–36. Available from: https://doi.org/10.1016/j.jhydrol.2012.01.036

Nelson, E.J. & Booth, D.B. (2002) Sediment sources in an urbanizing, mixed land-use watershed. *Journal of Hydrology*, 264(1), 51–68. Available from: https://doi.org/10.1016/S0022-1694(02)00059-8

O'brien, R.M. (2007) A caution regarding rules of thumb for variance inflation factors. *Quality & Quantity*, 41(5), 673–690. Available from: https://doi.org/10.1007/s11135-006-9018-6

O'Driscoll, M.A., Soban, J.R. & Lecce, S.A. (2009) Stream channel enlargement response to urban land cover in small coastal plain watersheds, North Carolina. *Physical Geography*, 30(6), 528–555. Available from: https://doi.org/10.2747/0272-3646.30.6.528

Pakenham. (1914) South Bourke and Mornington Journal (Richmond, Vic. : 1877 - 1920; 1926 - 1927), p. 3 (WEEKLY.). Retrieved May 17, 2025, from http://nla.gov.au/nla.news-article66186351

Paul, M.J. & Meyer, J.L. (2001) Streams in the urban landscape. *Annual Review of Ecology and Systematics*, 32(1), 333–365. Available from: https://doi.org/10.1146/annurev.ecolsys.32.081501.114040

Peel, M.C., Finlayson, B.L. & McMahon, T.A. (2007) Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences*, 11(5), 1633–1644. Available from: https://doi.org/10.5194/hess-11-1633-2007

R Core Team. (2024) *R: a language and environment for statistical computing, R Foundation for statistical [computer software]*. Vienna, Austria: R Foundation for Statistical Computing. Available from: https://www.R-project.org/

Richard, E. (1940) Soil erosion. Werribee Shire Banner (Vic. : 1911-1952). http://nla.gov.au/nla.news-article74058716

Russell, K.L., Vietz, G.J. & Fletcher, T.D. (2017) Global sediment yields from urban and urbanizing watersheds. *Earth-Science Reviews*, 168, 73–80. Available from: https://doi.org/10.1016/j.earscirev.2017.04.001

Sammonds, M. & Vietz, G. (2015) Setting stream naturalisation goals to achieve ecosystem improvement in urbanising greenfield catchments. *Area*, 47, 386–395. Available from: https://doi.org/10.1111/area.12181

Schumm, S.A., Harvey, M.D. & Watson, C.C. (1984) Incised channels; morphology, dynamics and control. In: *Incised channels*. Littleton, CO: Water Resour. Publ., p. 200. Available from: https://www.proquest.com/docview/2359010943/9BAAE35593034DCCPQ/1

Simon, A. (1989) A model of channel response in disturbed alluvial channels. *Earth Surface Processes and Landforms*, 14(1), 11–26. Available from: https://doi.org/10.1002/esp.3290140103

Simon, A. & Hupp, C. (1987) *Geomorphic and vegetative recovery processes along modified Tennessee streams: an interdisciplinary approach to disturbed fluvial systems*. International Association of Hydrologic Sciences, IAHS-AISH, p. 167.

Soboyejo, L.A., Russell, K.L. & Fletcher, T.D. (2025) Predicting urban channel morphology amidst multiple complexities. *Geomorphology*, 468, 109511. Available from: https://doi.org/10.1016/j.geomorph.2024.109511

Sullivan, J., Grubb, J., Willis, R., Boozer, D., Flickinger, B. & Dixon, C.E. (2020) Cohesive channel response to watershed urbanization: insights from the Sand River, Aiken SC. *Water*, 12(12), 3441. Available from: https://doi.org/10.3390/w12123441

Taniguchi, K.T., Biggs, T.W., Langendoen, E.J., Castillo, C., Gudino-Elizondo, N., Yuan, Y., et al. (2018) Stream channel erosion in a rapidly urbanizing region of the US–Mexico border: documenting the importance of channel hardpoints with structure-from-motion photogrammetry. *Earth Surface Processes and Landforms*, 43(7), 1465–1477. Available from: https://doi.org/10.1002/esp.4331

Through the Koo Wee Rup swamp. (1883, July 2) Argus. http://nla.gov.au/nla.news-article8534790

Tissott, B. & Mueller, N. (2022) *DEA Land Cover 25m (Version version 2.0, September 2018) [Dataset]*. Canberra, Australia: Commonwealth of Australia (Geoscience Australia). Available from: https://doi.org/10.26186/146090

Trimble, S.W. (1997) Contribution of Stream Channel erosion to sediment yield from an urbanizing watershed. *Science*, 278(5342), 1442–1444. Available from: https://doi.org/10.1126/science.278.5342.1442

Victoria Heritage Branch. 1989 Architectural survey of the Berwick-Pakenham corridor: A report/prepared by the Heritage Branch, Ministry for Planning and Environment Ministry for Planning and Environment

Vietz, G. J., Rutherfurd, I. D. & Stewardson, M. J. (2004) *Not all benches are created equal: Proposing and field testing an in-channel river bench classification*. Proceedings of the 4th Australian Stream Management Conference

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. Available from: https://doi.org/10.1016/j.geomorph.2013.09.019

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. Available from: https://doi.org/10.1071/MF03206

Walsh, C. J. . 2024. *Melbourne stream network: user's manual (version 1.3; Melbourne waterway research-practice partnership report)*. School of Agriculture, Food, and Ecosystem Sciences, The University of Melbourne, Melbourne. https://doi.org/10.26188/26866840

Walsh, C.J., Burns, M.J., Fletcher, T.D., Bos, D.G., Poelsma, P., Kunapo, J., et al. (2022) Linking stormwater control performance to stream ecosystem outcomes: incorporating a performance metric into effective imperviousness. *PLOS Water*, 1(2), e0000004. Available from: https://doi.org/10.1371/journal.pwat.0000004

Walsh, C.J., Fletcher, T.D. & Ladson, A.R. (2005) Stream restoration in urban catchments through redesigning stormwater systems: looking to the catchment to save the stream. *Journal of the North American Benthological Society*, 24(3), 690–705. Available from: https://doi.org/10.1899/04-020.1

Walsh, C.J., Fletcher, T.D. & Vietz, G.J. (2016) Variability in stream ecosystem response to urbanization: unraveling the influences of physiography and urban land and water management. *Progress in Physical Geography: Earth and Environment*, 40(5), 714–731. Available from: https://doi.org/10.1177/0309133316671626

Wohl, E. (2015) Legacy effects on sediments in river corridors. *Earth-Science Reviews*, 147, 30–53. Available from: https://doi.org/10.1016/j.earscirev.2015.05.001

Wohl, E. (2018) Geomorphic context in rivers. *Progress in Physical Geography: Earth and Environment*, 42(6), 841–857. Available from: https://doi.org/10.1177/0309133318776488

Wohl, E. (2019) Forgotten legacies: understanding and mitigating historical human alterations of river corridors. *Water Resources Research*, 55(7), 5181–5201. Available from: https://doi.org/10.1029/2018WR024433

Wohl, E.E., Vincent, K.R. & Merritts, D.J. (1993) Pool and riffle characteristics in relation to channel gradient. *Geomorphology*, 6(2), 99–110. Available from: https://doi.org/10.1016/0169-555X(93)90041-Y

Wolman, M.G. (1967) A cycle of sedimentation and erosion in Urban River channels. *Geografiska Annaler: Series a, Physical Geography*, 49(2–4), 385–395. Available from: https://doi.org/10.1080/04353676.1967.11879766

Yugovic, J.V. (2011) Ecology of the Kooweerup swamp and associated grasslands. *Proceedings of the Royal Society of Victoria*, 123(2), 172–188.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Soboyejo, L.A., Russell, K.L. & Fletcher, T.D. (2025) Can changes in geomorphic responses to urbanisation be predicted from stormwater outfalls? *Earth Surface Processes and Landforms*, 50(8), e70087. Available from: https://doi.org/10.1002/esp.70087