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Research Articles

Designed adaptation: A multidisciplinary framework for urbanized river-landform design and communication

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A B S T R A C T

Urbanized riverscapes are vulnerable to changing flow and sediment regimes with consequences including increased flooding and habitat degradation. The conventional engineering solution in this situation involves gray infrastructure, including concrete-lined trapezoidal channels and flood-prevention structures, retention and detention ponds, and closed subsurface piped systems. Gray infrastructure is failing to mitigate flooding under changing climate conditions, particularly in coastal regions impacted by rising sea levels, and it is well understood to eliminate essential, natural ecosystem functions and services. This study presents a multidisciplinary design framework to support adaptive riverscape planning with additional and complementary modeling applications. It integrates synthetic 3D rivers and real-world topographic data for design development, testing and selection, refinement, and presentation to yield project-specific alternatives to gray infrastructure while enhancing stakeholder engagement. The framework was applied to a semi-alluvial urban stream as a coastal case study. Three river-design scenarios were developed upstream from a flood-prone urban site to improve water retention and soil infiltration while reducing downstream flow rates for enhanced flood mitigation. Improved river-design outcomes are demonstrated by modeling flow velocity and water depth to test hydraulic responses to river-designs. Sediment transport models are presented to understand how river-designs may adapt to elevation change and the geomorphic-form-variation approach is applied as a measure of habitat heterogeneity. The framework's flexibility is showcased by revising a river-design and re-simulating hydraulic responses to new surface-form configurations. We also present a rendered perspective image to illustrate a tool available for communicating a nature-based solution action in urbanized contexts. The framework can be adapted to diverse urban riverscape projects that require hydraulic, geomorphic, ecological, and social trade-offs by supporting a collaborative planning approach for nature-based solutions.

1. Introduction

Urbanized riverscapes are vulnerable to climate change and long-term environmental degradation, requiring novel approaches to river management [1,2]. Imperviousness and rigid gray infrastructure contribute to increasing peak discharges and surface water volumes that strain closed drainage systems, resulting in changing flow and sediment regimes [3–5]. Urban channels were largely not designed for regime adaptation [6] and urbanized riverscape planning has historically relied on engineered flood-protection and drainage systems aimed at moving flow off-site quickly [7].

Streams have also been channelized, constraining natural morphology responses that result in channel incision and simplification [8]. Flood risks are compounded by hydrograph flashiness [9] and transport of an abundance of debris (wood and trash) that exacerbates flood damage (Poppema et al., [10]). Additionally, conventional gray infrastructure degrades ecosystems within urbanized contexts by homogenizing topographies, fragmenting habitat patches, making flood hydraulics more aggressive, and creating environments that limit opportunities for biodiversity development [11]. Replacing naturally filtrating porous surfaces with impervious material also degrades stream water quality, particularly when considering watershed scale impacts [12].

Here we present a collaborative river-design framework to address current challenges found in urbanized riverscapes and supports a new workflow for planning urban stream design. The framework builds on

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concepts in River Architect [13] by taking advantage of River Builder software and hydro-morphodynamic models. The new framework aims to innovate urban river-landform design by addressing the lack of design tools for changing flow and sediment regimes [14] and limited attention to processes in the practice of design [15]. It supports process-based design criteria and adaptation in the planning phase [16] rather than relying on post-construction case studies as an indicator of resilience, although project appraisals remain an important step in river restoration [17]. It also provides communication tools to enhance stakeholder engagement and community acceptance by increasing public understanding of design intentions [18] with 3D modeling and rendering for a digital twin perspective (Pal et al. [19]).

This study offers a novel four-step workflow for project-scale planning. The proposed design tools are intended for urbanized stream settings where risk tolerance is low. Assuming that a systematic planning process has already been completed and a project site has been selected, the framework emphasizes tools for creating design alternatives, assessing alternatives with mechanistic modeling, revising designs based on assessment outcomes, and presenting synthetic rivers to enhance stakeholder engagement. Innovative design procedures have been neglected by the scientific community [20], yet when used they have proven useful to envision and evaluate a range of geomorphic and ecological elements of restoration and environmental flow projects (e.g., [21,22]), including in urban streams [23].

Synthetic 3D channels are especially useful for designing rivers where a long history of land use, stream modification, and urban stream syndrome has made “reference reaches” unsuitable for capturing realistic, functional future stream opportunities [1]. The novelty of this study is the multidisciplinary approach for terraforming continuous urbanized riverscapes that are based on fundamentals in fluvial geomorphology, landscape architectural grading, and planting design for habitat restoration. The framework moves beyond conventional river-design methods of static cross-sectional surveys and simple geometries [24–26] and provides a workflow that is complementary to existing urban design tools and frameworks (see Supplementary Material, File 1). The presented workflow supports adaptive-river-design and multi-scale frameworks for hydraulic-physical habitat quality assessment [13] and communicating river restoration strategies [27].

The methodology applied here may be readily transferable and customizable to river management practice, supporting the multidisciplinary nature of building sustainable urban rivers. Different topographic and vegetative characteristics are represented as continuous digital surfaces, allowing the framework to generate hydraulic responses to designed features and illustrate geomorphic responses to surface changes. We showcase flexibility by revising and presenting a rendered perspective image of a selected river-design scenario. We discuss how engineers, planners, fluvial geomorphologists, ecologists, and the public can collaborate on strategic improvements to continuous 3D surfaces through multidisciplinary riverscape planning.

2. Conceptual framework and research design

2.1. Conceptualization

Building on the motivations of River Architect [13] and supporting the house-of-NbS workflow [27], our framework includes a four-step workflow for design development, testing and selection, refinement, and presentation of terraformed riverscapes to advance assessment strategies within urban contexts (Fig. 1). Flood mitigation and habitat heterogeneity are common design challenges for urbanized riverscapes due to spatial and infrastructure constraints. The framework was conceptualized to address these indicators with models applied to typical streams, but the workflow is flexible, allowing alternative and complementary design development objectives, testing metrics, and criteria for selecting a preferred river-design. The four-step framework is described below.

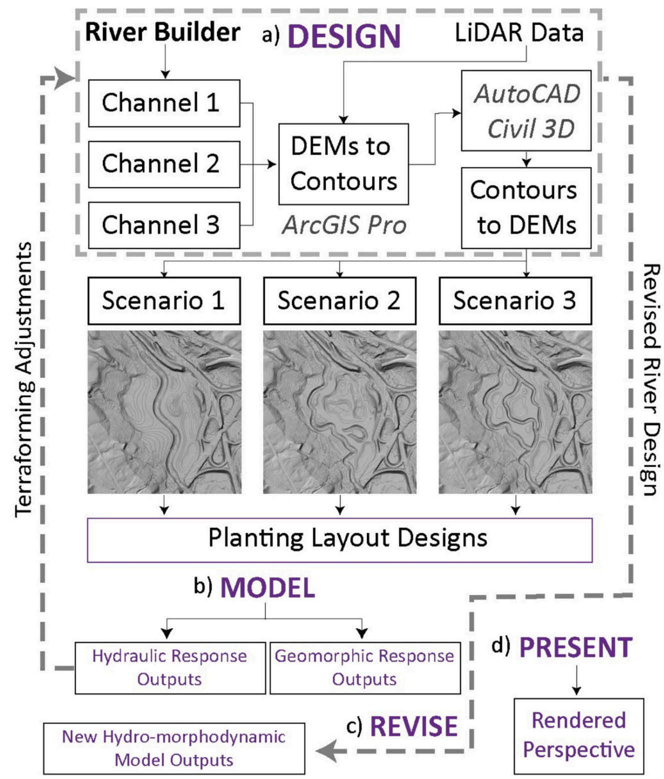

Fig. 1. Workflow diagram showing the process of a) designing synthetic 3D river surfaces and planting layouts, b) modeling hydraulic and geomorphic response outputs, c) revising and re-simulating designed rivers, and d) presenting rendered perspectives.

2.1.1. Step 1: Design development

Design development begins by defining objectives to guide terraforming solutions and achieve urban-river project goals. Goals may include relieving closed drainage-system stress, mitigating flood damage, adapting to changing climate conditions, or other common goals for urbanized riverscape design (Table 1). Such outcomes require a rigorous design-testing procedure and synthetic rivers provide assessment opportunities for river-design [24,25,28,29] that can point to design development strategies likely to balance multidisciplinary objectives and measure river responses to regime changes. To apply this type of river-design testing, Step 1 outputs include digital elevation models (DEMs) as continuous surface inputs and vegetative plantings to define roughness coefficients and rendering textures.

Step 1 includes the design creation of continuous river surfaces and planting layouts that use LiDAR-derived DEM data, River Builder, and AutoCAD Civil 3D. Real-world LiDAR data provides the topographic context, synthetic 3D channel surfaces are derived from River Builder, and AutoCAD Civil 3D is used for grading river landform alterations and floodplain features (Fig. 1a). Landforms then provide topographies for terraforming vegetative plantings and modeling hydraulic and geomorphic responses to different river-design scenarios (Step 2),

Table 1
List of common urban riverscape design goals.

Common Urbanized Riverscape Design Goals	
1. Channel stabilization and erosion control	7. Navigation
2. Flood mitigation	8. Municipal water supply
3. Recreation and leisure	9. Stormwater management
4. Aesthetics and historical value	10. Waterfront development
5. Ecosystem services 6. Groundwater management	11. Wildlife conservation
	12. Habitat enhancement

allowing post-testing refinement in Step 3.

2.1.2. Step 2: design testing and selection

Step 2 includes the assessment of different system responses to river-design scenarios. Modeling software helps test scenario performance by completing hydraulic and geomorphic modeling to identify best-performing river-designs and elements likely to mitigate downstream flooding (Fig. 1b). The selection of a preferred scenario(s) is guided by model outputs showing slower channel flow (velocity) and greater on-site surface water retention (water volume) to allow more time for soil infiltration. Geomorphic performance testing may include scenarios of greater habitat heterogeneity potential, both before-and-after morphodynamic modeling.

Our framework allows users to leverage a diversity of 2D modeling tools and approaches that are available for assessing components of geomorphic, hydraulic, and ecological processes and functions. A review of available modeling software and complementary assessment strategies is provided in Supplementary Material (File 1).

2.1.3. Step 3: design refinement

Step 3 includes the refinement of river designs in the planning phase. Synthetic 3D surfaces provide flexible, interactive models that allow derived design scenarios to be tested, assessed using expert judgment, and refined through targeted surface-feature adjustments. The revised river-design scenario then provides a new 3D surface for hydro-morphodynamic modeling to re-assess hydraulic (e.g., flow velocity) and geomorphic (e.g., GFV) responses for an adaptive and interactive approach to support urbanized riverscape planning (Fig. 1c). The ability to continually repeat the process of designing, testing, and refining provides a workflow of progressive improvement likely to increase the success of urban river engineering and restoration.

2.1.4. Step 4: design presentation

Finally, Step 4 includes the presentation of river design scenarios to enhance stakeholder engagement and community outreach. Rendering software can generate perspective images by using 3D topographic surfaces and referencing proposed planting layouts (Fig. 1d) to guide the automation of photo-realistic riverscape representations. Advancements in digital-twin technology can further improve the virtual experience of physical river processes from a human perspective [30], providing an important communication tool for public acceptance of river restoration projects.

2.2. Research design for scenario selection

Three river-design scenarios were created for performance testing. Scenarios included a conventional restoration method often found in Natural Channel Design (NCD, [31]) projects, an irregular planform stream, and a multi-thread channel (see details in Section 4.1.1). Indicators for selecting a preferred scenario included flow velocity, water depth, and geomorphology responses to modeled flood conditions and designed surface-forms. Specific test questions asked which scenario showed: 1) the lowest mean flow velocity, 2) greatest water volume, and 3) highest potential for habitat heterogeneity. Morphodynamic models can also suggest how designed geomorphic surface-forms respond to sediment transport dynamics by comparing elevation-change rasters [32].

Based on fundamental knowledge in fluvial geomorphology, we anticipate the irregular and multi-thread channel scenarios will hydraulically and ecologically outperform the conventional NCD approach, suggesting these design approaches as more aligned with a nature-based solution action [27]. The performance of each draft river design may identify features requiring iterative revision and re-testing to increase performance. Our framework allows flexibility for design adjustments in the refinement phase (Step 3), which is discussed further in Section 6.2.

3. Data and materials

3.1. Study area

A real-world site was selected as a case study that represents a typical flood-prone urban site with homogeneous topographic and vegetative characteristics in the Bedford community of Halifax Regional Municipality, Nova Scotia, Canada. The site is in a humid continental climate, characterized by warm summers and cold winters moderated by the Atlantic Ocean. The region's freshwater ecosystems are particularly susceptible to high-intensity storm events due to the geographic position along the Atlantic coast, where hurricane conditions are common [33]. The Lower Sackville River is a mix of boulder, gravel, and cobble in the upstream reaches while the lower tidal reaches include riverbed mixtures of silt and sand that drain into Bedford Bay [34]. Steeper upstream bed slopes transition into low gradients at the lowland coastal setting where the channel is confined and incised at the urbanized Bedford Place Mall (Fig. 2).

The Bedford Place Mall is located within a coastal lowland landscape that continues to experience flooding issues (CBCL [35]). These issues were highlighted by a major flood event that began on July 21, 2023 (Fig. 2a), causing significant economic damage in the area (DesignPoint [36]). The property is located west of the confined Sackville River channel, with largely impervious surfaces and three bridge crossings from the Bedford Highway to the east (Fig. 2b). The site was built on a floodplain. In fact, in April 2025, the regional council approved municipal planning changes to expand the Sackville River floodplain and new development restrictions have been introduced [37]). Existing flood protection infrastructure includes shallow overflow routes along the west side of the mall building with closed drainage storage systems on-site (see Fig. 3.4 in CBCL [35]).

Site constraints make it difficult to propose a reconfiguration of the channel. However, opportunity may exist upstream, where a well-planned river design could reduce peak discharge downstream to mitigate flooding while increasing on-site soil infiltration. An upstream National Rifle Range was selected as our case study site (Fig. 2c), providing an existing reach with river width ranges from 16 to 20 m useful for a scenario-based approach to showcase our four-step framework. The design site included a spatial extent of ~35 ha with data boundaries extracted along steep slopes bordering a forested area to the north-west and highway to the east. The inflow boundary was defined by a transitional area between a dense riparian forest and turfgrass maintained by the municipality. The outflow boundary was defined immediately upstream from a confined highway bridge, and the total site extent provided an adequate surface area and boundary slopes for containing hydraulic model outputs for performance testing.

3.2. Data collection

As in a growing number of global urbanizing areas, LiDAR data was available from the Province of Nova Scotia's open-access GeoNova website (URL:https://geonova.novascotia.ca/). The Province of Nova Scotia completed LiDAR surveys with a fixed-wing aircraft between June and August in 2019, with a density of 12.31 points per square metre. While the data was not bathymetric (sub-water level topography), the LiDAR provided floodplain topographic data for terraforming river-design scenarios. LAZ point files were collected as 1 km × 1 km tiles and LAS datasets were processed in ArcGIS Pro (version 3.6). A continuous digital elevation model (DEM) was derived by filtering Ground Points and converting the LAS Dataset to Raster with a Nearest Neighbor cell assignment. A pixel resolution of 1 m provided a suitable grid for investigating river morphologies, given a typical channel width above 15 m [38]. The existing reach DEM was extracted at the site extent, including a length of 0.68 km and mean width of 0.31 km (0.21 km^2) or 22 x bankfull widths. Further details on LiDAR data are provided in Supplementary Material (File 1).

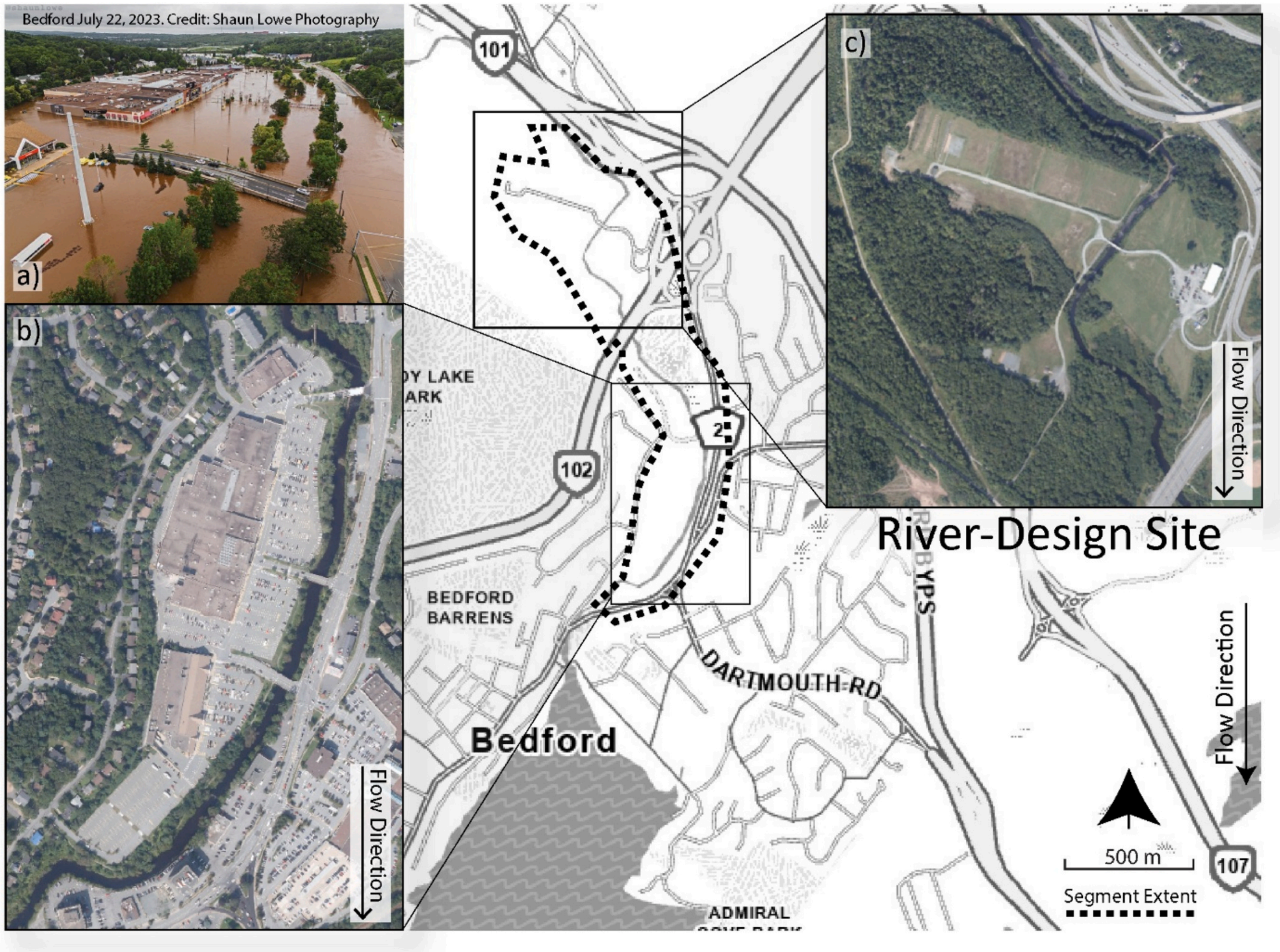

Fig. 2. Aerial images showing a) impacts of the July 21 flood event, b) extent and imperviousness of the downstream Bedford Place Mall property, and c) National Rifle Range proposed as the conceptual river-design site.

Unsteady flow data was sourced from Environment Canada's real-time flow hydrometric data at the gauge station 01EJ001 [39]. Data were collected for the flood event on July 21, 2023 [40], showing a real-time recorded peak discharge of 125 m^3/s followed by a gradual rate decline as flow dissipated. Sediment data included a uniform mixture of 0.05 m bed material grain size diameter, representing coarse gravel reported in CBCL Limited [35] and Cameron [34].

4. Methodology

4.1. Designing synthetic river-design scenarios

Building on River Architect [13], River Builder was used to generate a series of synthetic 3D channels by applying different input parameters and user-defined geometric equations [41,42]. Dawson [43] also applied River Builder for designing synthetic drainage channels as blue-green infrastructure within the Bedford Place Mall site, finding the approach suitable for similar elements of nature-based solutions.

River Builder's "Domain" parameters were sourced from the LiDAR-derived DEM and River Builder input files included user-defined functions for the meander centerline, inner-bank cross-sectional shape, and thalweg bed elevation undulation. These functions allow non-geomorphologists to experiment with designing different planform patterns, channel widths, and in-channel morphological features automated by geomorphic covariance structures in the software [44–46]. A description of River Builder functions and specific user-defined input scripts are included in Supplementary Material (File 1).

The existing topographic data were then adjusted for each scenario by proposing different grading plans in AutoCAD Civil 3D. Best management practices for floodplain features were applied, including ponds for surface water storage and mounds to provide variation in geomorphic form and balance cut-and-fill demands [27]. Conceptual planting layouts were also created to support grading plans and a list of plant species selected is provided in Supplementary Material (File 2). Planting design is an important step for riverscape planning to enhance habitat opportunities and surface roughness for controlling runoff, while optimizing elements of nature-based solutions (Uppala et al., [47]).

4.1.1. Design objectives for each river scenario

Each river-design scenario focused on reducing flow velocity, increasing water retention, and enhancing habitat heterogeneity by implementing features included in Table 2. Our framework allows a range of additional objectives and models for future performance testing in the planning phase of river design. Additional and complementary features may include gravel replenishment [48], in-stream large wood installation [49], and similar bioengineering approaches [50]. The following section describes the features used in each scenario to support urban riverscape design objectives with a design goal of mitigating downstream flooding.

River scenario 1 (S1) was designed with a conventional NCD method

Table 2
Design software and tools for terraforming features to support urbanized riverscape objectives.

River-Design Features and Objectives Scenarios: 1, 2, 3, and X (additional features)							
Design Tools	Flow Regime Accommodation	Water Storage	Habitat Quality	Slope Stability	Surface Roughness	Form Variation	Aesthetics
River Builder: Channel Features							
Re-meandering	1, 2, 3		1, 2, 3			1, 2, 3	1, 2, 3
Widening	1			1			
Width Variability	2, 3		2, 3			2, 3	2, 3
Multi-Threads	3		3			3	3
Geomorphic Units (e.g., pool-riffle)	1, 2, 3		1, 2, 3		1, 2, 3	1, 2, 3	
Civil 3D: Floodplain Features							
Storage Ponds	1, 2, 3	1, 2, 3	1, 2, 3			1, 2, 3	1, 2, 3
Wetland	2	2	2			2	2
Other Concave Forms (e.g., oxbow lake)	2	2	2			2	2
Mounds & Convex Forms			1, 2			1, 2	1, 2
Forest Plantings	1, 2, 3		1, 2, 3	1, 2, 3	1, 2, 3		1, 2, 3
Shrub Plantings	1, 2, 3		1, 2, 3	1, 2, 3	1, 2, 3		1, 2, 3
Herbaceous Plantings	1, 2, 3		1, 2, 3	1, 2, 3	1, 2, 3		1, 2, 3
Other Software: Complementary Features							
Bioengineering	X		X	X	X		X
Large Wood	X		X	X	X	X	
Gravel Replenishment	X		X	X	X		

that is common practice in North America [31]. A single-thread channel was widened to ~38 m with broad meander bends to accommodate an increased flow regime [51]. The floodplain surface included ponds to increase water retention. Mounds were designed to increase geomorphic variability and divert flow away from the existing highway. Mixed forest plantings were proposed largely around the boundary to increase surface roughness and stabilize slopes. Shrub species were proposed along the channel boundaries to increase surface roughness and stability, while herbaceous plantings were proposed as pond covers (Fig. S1a) to store runoff and filter contaminants [52].

River scenario 2 (S2) was designed with an irregular single-thread channel pattern of variable widths and greater sinuosity compared to S1, designed to reduce flow velocity and accommodate regime changes. The floodplain-grading design included mounds along inner bends and flat surfaces along outer bends to increase geomorphic variability, accounting for future migration from annual flow velocities [32]. Floodplain features also included an oxbow lake, positioned where the conceptual channel may have previously migrated, and a proposed pond described as a 'wetland' to increase water retention.

The concept was to terraform a dynamic floodplain that allows future channel migration with geomorphic processes responding to these forms (e.g., outer bank erosion) and to demonstrate a more process-based approach to riverscape restoration [16]. Mixed forest and shrub plantings were designed to increase surface roughness and slope stability, while the proposed wetland cover was largely herbaceous (Fig. S1b) to reflect common wetland restoration objectives in Canada [53].

River scenario 3 (S3) was the final surface generated for performance testing. The design included a multi-thread channel, where three separate River Builder channels were stitched to the topographic data, including the main channel and two side channels of shallower depths. The multi-thread planform pattern was designed to laterally spread flow and reduce mean velocities under flood conditions. The floodplain included pond features graded along the boundary of the site to increase water retention, while interior forms were flatter or gently sloped mounds (Fig. S1c). S3 was terraformed as an active floodplain, allowing future channel migration with more herbaceous plantings to increase surface roughness and is proposed as a dynamic reach with a process-based approach that is largely precluded within urbanized contexts [54].

4.2. Testing river-design scenario responses

We used open-source BASEMENT software for hydrodynamic and morphodynamic simulations. Model outputs included flow velocity, water depth, and elevation-change responses to synthetic river-design scenarios. A 36-h event was modeled with flow data beginning at 3.5 m^3/s, peaking at 125 m^3/s, and ending at 56.2 m^3/s, with a simulation time step of 2000 s. Missing values were interpolated with HEC-RAS software and exported as an unsteady flow input file.

Additional parameter inputs for modeling hydro-morphodynamics were defined by theoretical foundations or sourced from the BASEMENT (version 4.1.0) Manual [55]. Hydraulic layers (flow velocity and water depth) were imported to QGIS, and rasters were exported at a pixel resolution of 1 m for comparative testing. A file processing description is provided in Supplementary Material (File 3).

Morphodynamic modeling included an additional morphology block input to simulate sediment transport characteristics within the BASEMENT interface. Elevation-change layers were output layers showing erosional and depositional surface-forms which were exported as rasters. Elevation-change rasters were overlayed on river-design DEMs, and cross-sections were compared to illustrate geomorphic responses. While 2D morphodynamic models have advanced beyond 1D cross-sectional survey inputs [56], cross-section representations remain a valuable communication tool for illustrating elevation-change and can be extracted from priority areas within continuous river-design surfaces. The framework allows professionals to define specific simulation parameters depending on research and design objectives, and inputs proposed here showcase an analytical approach that may be suitable for real-world applications.

4.2.1. Analyses using hydraulic model outputs

Hydraulic responses to river-design scenarios were assessed with flow velocity and water depth rasters. Flow velocity patterns were spatially compared, and mean flow velocities were plotted to identify temporal peak values. Water depth rasters were also spatially compared, suggesting where channel flow began to overtop banks and when floodplain features became saturated. Sequential water volumes (m^3) were then plotted to suggest potential water retention differences between river-design scenarios, useful for estimating storage capacities and delaying peak flow downstream.

Flow velocity and water depth simulations are often combined for testing flood responses. Hydrodynamic models can also support habitat suitability assessments by estimating flow velocities [57] and combining additional eco-hydraulic parameters for river restoration planning (Padoan et al. [58]). Simulating water depth responses to storm events and mapping urban flood hazards is a common technique for climate-adaptive assessments (Bagheri and Liu, [59]), and the framework allows additional analyses beyond those applied here.

4.2.2. Analyses using elevation-change model outputs

Morphological responses to river-design scenarios were first spatially assessed with output rasters and cross-sections. These models provided a visual comparison useful for comparing locations of developed erosional and depositional surface-forms. The geomorphic form variation (GFV) approach was applied to quantify topographic variability across river-design scenarios and compare morphodynamic outputs for each scenario.

GFV was developed by Dawson et al. [60] for evaluating river morphology changes and applies the Focal Statistic type 'Variety' to input metric rasters including aspect, planform curvature, and flow direction. These inputs provide a topographic representation of potential habitat heterogeneity that is scalable across spatial extents and pixel resolutions [60] and GFV represents the mean value of metric inputs. GFV has been applied to synthetic rivers [25] and found real-world river designs aimed at stabilization were simplifying geomorphic variability compared to restoration projects guided by habitat enhancement [26].

Focal 'Variety' generates dimensionless values through neighbourhood processing in ArcGIS Pro (Esri, [61]). Variety classes are defined by the number of unique input values existing within a given neighbourhood window, where a variety class of 1 represents no variety or homogeneity. Parameters are customizable, allowing different neighbourhood window shapes and sizes (Fig. S2). Adjusting these parameters will generate different absolute variety values but proportional value comparisons can be made between input metrics of equivalent spatial extents and pixel resolutions. More information on GFV processing and component metric inputs are provided in Supplementary Material (File 1).

GFV was applied to both river-design surfaces and morphodynamic output rasters to compare proportional value responses to morphology changes. A river-design scenario showing a higher GFV value suggests more opportunity for habitat heterogeneity, relative to other scenarios.

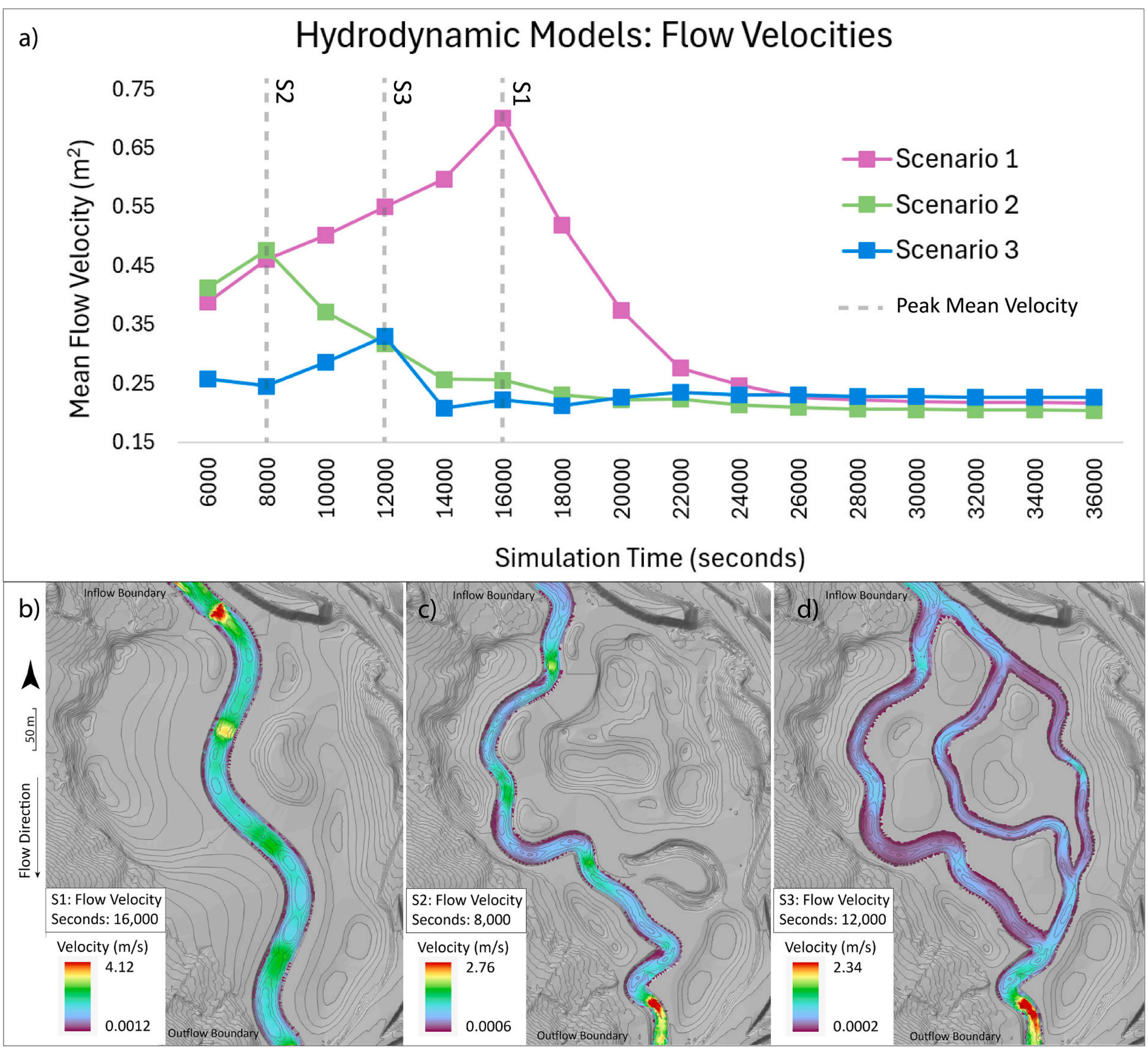

Fig. 3. Graph showing a) mean flow velocities and peak velocity time steps for scenario 1, a conventional NCD method, scenario 2, an irregular channel and wetland, and scenario 3, a multi-thread channel design. Peak velocity rasters show velocity responses to designed rivers including b) scenario 1, c) scenario 2, and d) scenario 3.

GFV and component input metric variety values (aspect, planform curvature, and flow direction) were compared to suggest how sediment transport dynamics may degrade or enhance habitat heterogeneity potential.

5. Results

5.1. Assessing flow velocity responses

Flow velocity simulations showed S3 produced the lowest mean velocity value for the 36-h flood model, followed by S2, while S1 produced the highest values. Mean flow velocity first peaked in S2 at a simulated time of 8000 s, followed by S3 at 12,000 s, and S1 was the last to peak at 16,000 s. S1 showed the greatest mean flow velocity of 0.70 m/s, while S2 and S3 showed mean flow velocity peaks of 0.48 m/s and 0.33 m/s, respectively (Fig. 3a). River-design scenarios began to stabilize at ~26,000 s, ranging in mean flow velocities between 0.23 m/s and 0.21 m/s for the remaining simulation time steps.

Velocity rasters generally showed flow values peaked before overtopping channel banks (Fig. 3b-d). Greater flow velocity clusters formed at the inflow boundary of S1 and along straighter and narrower channel sections (Fig. 3b). S2 showed the greatest velocity cluster near the outflow boundary and higher values along narrower meander bends (Fig. 3c). S3 also showed the greatest velocity cluster near the outflow boundary while velocity remained relatively low throughout the multi-thread channels (Fig. 3d), compared to S1 and S2.

5.2. Assessing water depth responses

All scenarios showed an inverse relationship between flow velocity and water depth, where mean velocities decreased as water volumes increased. This matches the expectation from hydraulic-geometry theory that depth and width usually change faster than velocity as discharge increases. S2 showed the greatest water retention with a volume of 344,947 m^3 at 30,000 s, followed by a peak water volume of 279,757 m^3 for S3 (also at 30,000 s), and S1 underperformed with the lowest peak water volume of 177,101 m^3 at 32,000 s. S2 showed the greatest proportional volume increase of 43% at the simulated time step 18,000 s, while S1 and S3 both showed the greatest proportional volume change at 22,000 s, including an increase of 28% and 33%, respectively (Fig. 4a).

Rasters showed the southern storage pond became saturated first in S1, with another small upstream pond saturated at 22,000 s. Low water depths began to flow towards the large retention pond to the west, but

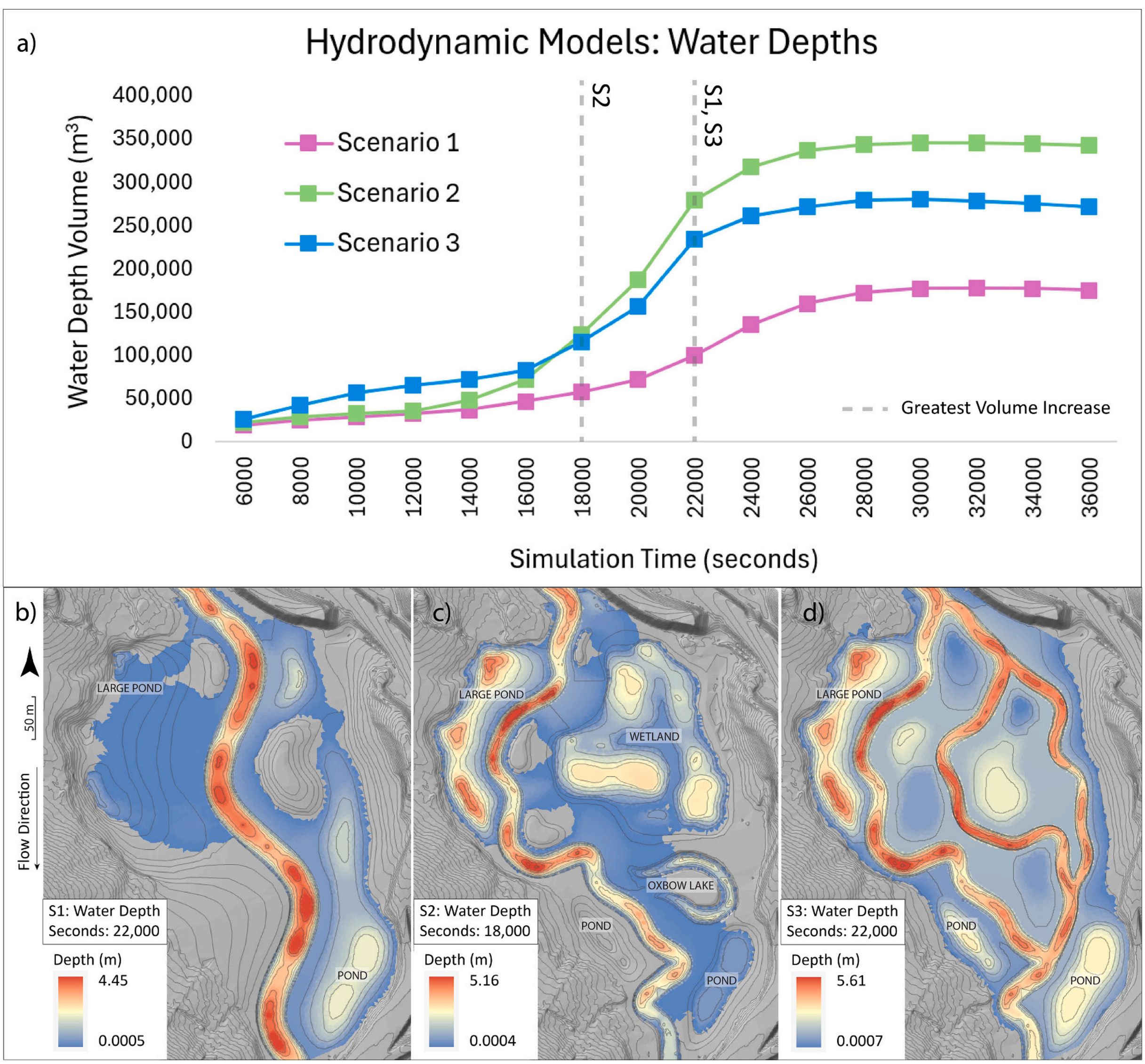

Fig. 4. Graph showing a) calculated water volumes and time steps of greatest proportional increase, while rasters show corresponding time step water depths for a) scenario 1, b) scenario 2, and c) scenario 3.

values were low relative to other floodplain features (Fig. 4b). S2 showed saturation of the large retention pond first, with a water depth of ~4 m. The proposed wetland feature and oxbow lake also became saturated at 18,000 s, while the pond to the south showed the lowest water depths (Fig. 4c). S3 was largely saturated at the 22,000 s time step, with low depths on gently sloped mounds near confluences. The deepest clusters formed within the channels, particularly on the main channel riverbed (~5.5 m), and water depths were relatively deep in the large retention pond to the west (Fig. 4d).

5.3. Assessing elevation-change responses

Each river-design scenario showed morphology responses to sediment transport dynamics. Erosional surface-forms were generally linked upstream to depositional surface-forms, particularly adjacent to broader meander bends. All elevation changes occurred within the channel boundaries in S1, while S2 showed depositional surface-forms also developed within the boundaries of each floodplain feature. S3 showed little depositional surface-forms within the floodplain and no significant elevation changes were found within the side channel to the east (Fig. 5a).

Cross-section 1 showed minor bank erosion along the upstream section of an outer meander bend, while minor deposition occurred along the inner bend. S2 showed relatively significant erosion near the outflow boundary, decreasing in elevation by ~0.8 m, while S3 showed a depositional surface-form on the inner bend and erosion along the outer bend of the same cross-sectional location (Fig. 5b). Cross-section 2 showed more significant erosion along the riverbed of S1, while depositional surface-forms were found on the riverbed of the S2 channel and sharp meander bend of S3, followed by an adjacent erosional surface-

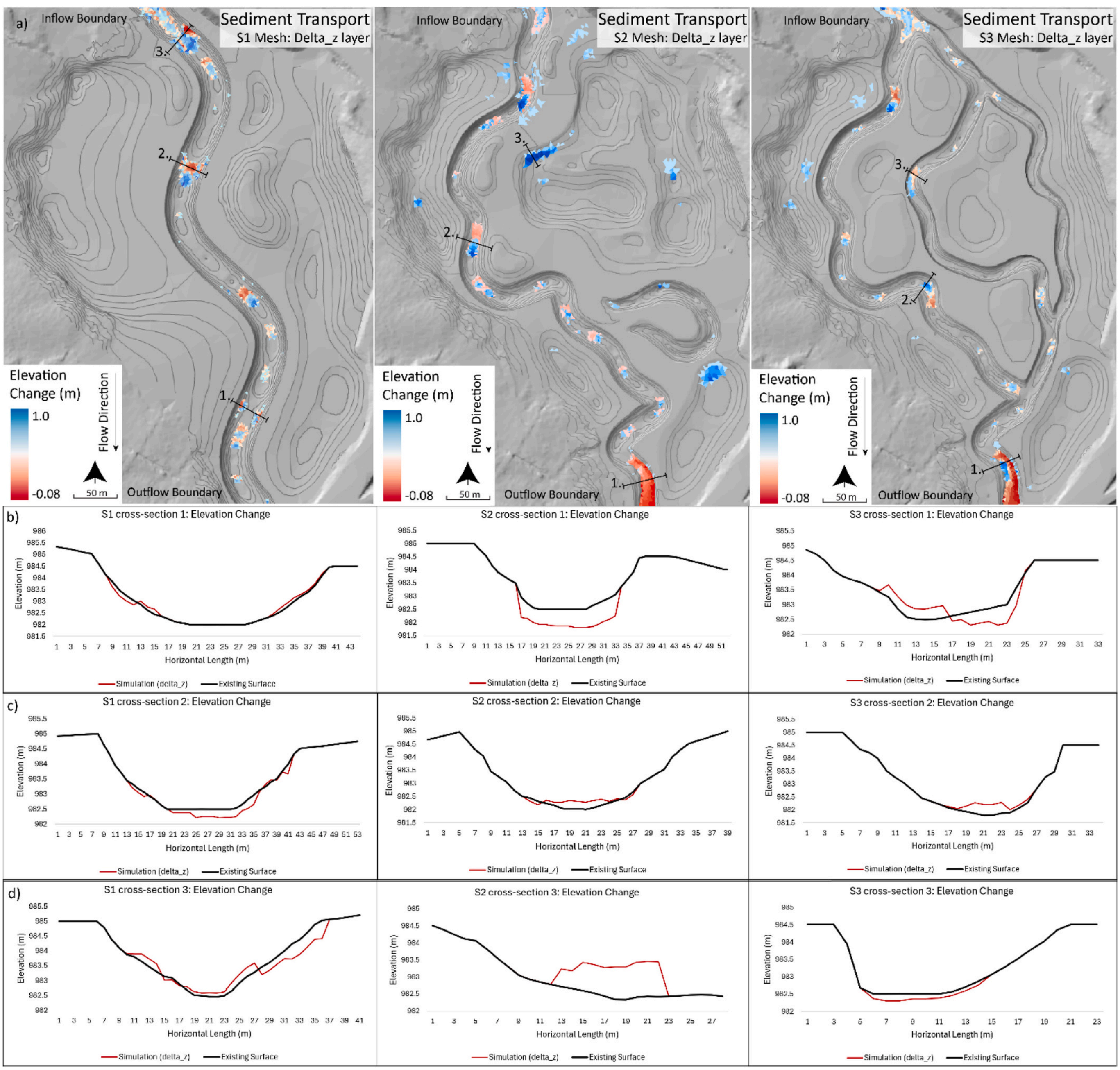

Fig. 5. DEMs and simulated elevation change rasters showing depositional and erosional surface-forms resulting from morphodynamic modeling in BASEMENT, while profile graphs show elevation changes at b) cross-section 1, c) cross-section 2, and d) cross-section 3 for each design scenario.

form immediately downstream (Fig. 5c). Finally, cross-section 3 showed elevation changes at a narrower riverbed section of S1, deposition in the wetland feature of S2, and erosion in the side channel of S3.

S1 showed relatively greater bank erosion, while deposition occurred on the riverbed and opposite bank. S2 showed the most substantial deposition along the wetland slope to the north, where the surface-form elevation was ~1 m. S3 showed relatively minor erosion along the side channel riverbed, followed by a depositional surface-form immediately downstream (Fig. 5d).

5.4. Assessing geomorphic form variation responses

River-design scenarios showed different GFV values and responses to morphodynamic modeling. S2 showed the highest GFV value of 8.2, followed by a value of 7.9 for S3, and 6.4 for S1 (Fig. 6a). Aspect contributed the highest variety value (12.5), but flow direction showed the greatest proportional difference of 27%, followed by planform curvature (26%). Aspect variety showed the greatest proportional difference between S2 and S3 (9%), followed by flow direction (4%), while planform curvature was slightly greater in S3 (3%). The general surface-form variety was similar between S2 and S3, while S1 consistently showed a simpler topographic surface value and underperformed alternative designs.

Elevation-change raster comparisons showed GFV values increased for each river-design scenario. S3 showed the greatest GFV value increase of 8.2%, followed by S2 at 6.6%, and S1 at 6.1%. Like initial GFV comparisons, aspect was the largest contributing surface-form variety value while planform curvature and flow direction variety values showed different proportional relationships. S3 showed the greatest planform curvature variety value change of 25.0%, followed by S1 (24.7%), and S2 showed the lowest surface-form change of 18.8%. Interestingly, flow direction showed an inverse relationship, where variety values decreased after morphodynamic modeling while GFV value changes remained positive (Fig. 6b).

6. Discussion

6.1. Selecting a preferred river-design scenario

All three river-design scenarios may reduce peak discharge downstream, compared to existing conditions, but S1 consistently underperformed relative to the experimental design objectives included for

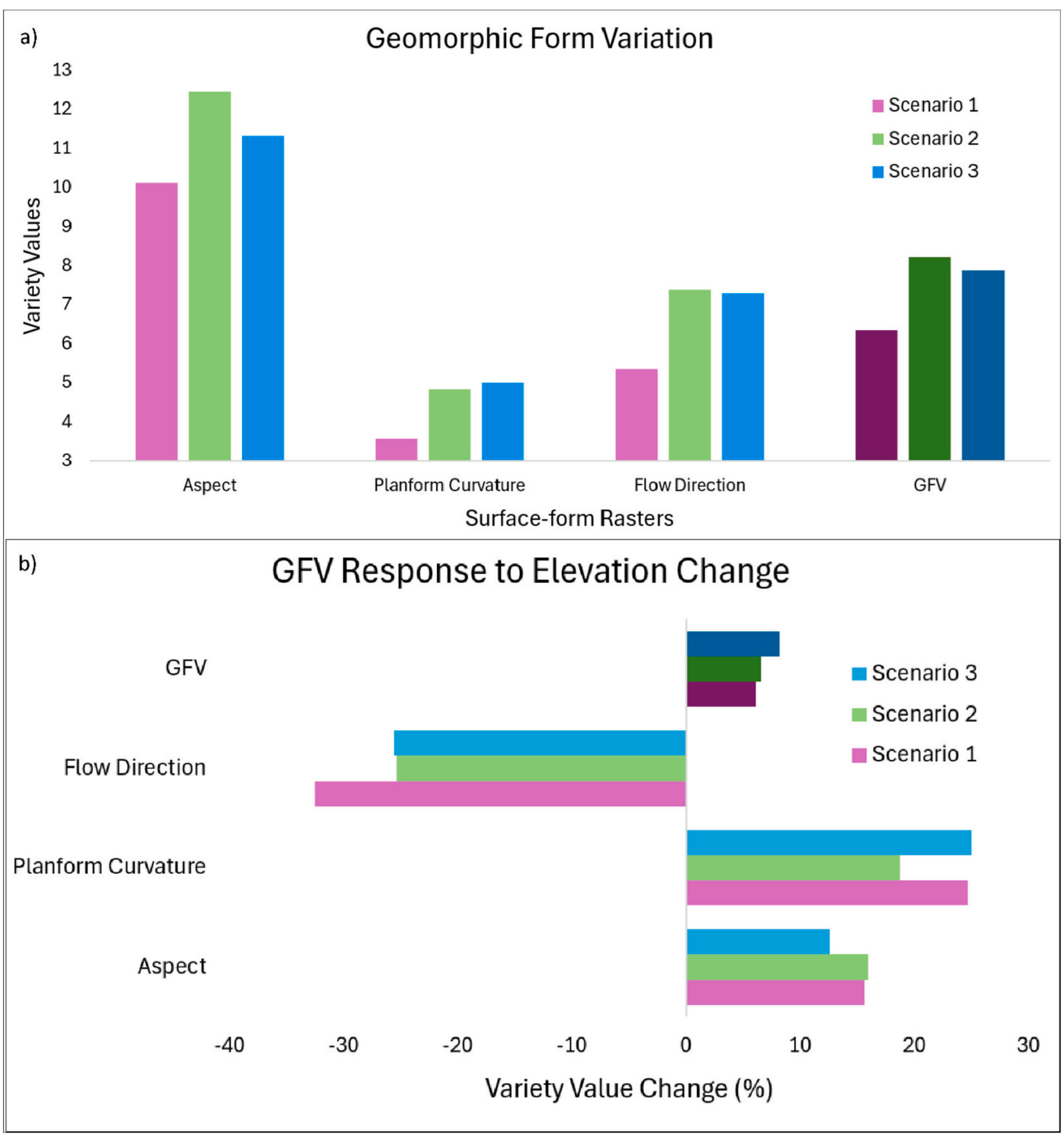

Fig. 6. Bar graphs showing a) DEM surface-form variety values for each river design scenario, and b) proportional variety value changes from morphodynamic models.

this study. S2 was the preferred river-design for mitigating downstream flood potential and enhancing habitat heterogeneity. S2 outperformed others at retaining the greatest volume of surface water (Fig. 4) and showed the highest GFV value (Fig. 6a), likely resulting from the upstream wetland feature, oxbow lake, and irregular channel pattern [26].

The geomorphic variability of S2 may promote dynamic process responses to climate-driven regime changes, enhancing riverscape resilience by mitigating downstream flooding at the urbanized site while enhancing ecosystem services by allowing biodiversity development [11]. S3 was a close second, outperforming others at reducing mean flow velocities (Fig. 3), likely resulting from the relatively flat floodplain topography and multi-thread channel that supported greater lateral flow dispersion [54]. The multi-thread channel design may improve soil infiltration and delay conveyance, contributing to the absorbing capacity of the designed reach [62].

S3 also showed the greatest proportional GFV value response to morphodynamic modeling (Fig. 6b), suggesting the designed adaptation could improve habitat heterogeneity conditions from changing flow and sediment regimes through time. S2 and S3 both demonstrate a suitable approach to design development (Step 1), where the testing and selection (Step 2) criteria may be transferable to nature-based solutions applications, although implementation may remain constrained by site-specific urban conditions.

Here, we designed riverscapes to mitigate downstream flooding while attempting to enhance habitat heterogeneity. However, urbanized streams are often targeted for stabilization due to infrastructure risks and safety concerns [14,26,63]. S1 limited riverbed scouring along the outflow boundary, which was relatively substantial in both S2 and S3 (Fig. 5). From a geomorphic perspective, S1 may outperform others when riverbed stabilization is the project aim (Table 2) because elevation-change models showed fewer morphologic responses. The potential for unpredictability or maintenance costs of more-dynamic scenarios (e.g., S2 and S3) may be acceptable, or unacceptable, for site-specific designs within urban contexts. Our framework allows an interactive decision-making process where trade-offs can be weighted in the planning phase of riverscape design.

Nature-based solutions should therefore not be interpreted as a one-size-fits-all approach to river design because preferred scenarios depend on how project-specific objectives are defined, weighted, and negotiated among disciplines. For example, riverscape projects may focus success criteria on species-specific habitat creation [58], water-quality improvement [12], aesthetic value [18], recreational use or community acceptance [64]. These criteria may introduce trade-offs between hydraulic performance, geomorphic dynamics, ecological function, maintenance requirements, and public perception. The multidisciplinary framework presented here can help address these challenges by allowing alternative objectives, model couplings, and evaluation metrics to be incorporated during design development, testing, refinement, and presentation, supporting a transparent process for selecting river-design scenarios that are appropriate to site-specific constraints and stakeholder priorities.

6.2. *Revising designed river surfaces in the planning phase*

One of the central advantages of the proposed framework is its flexibility to refine river-designs through interactive design development and modeling tools. Designed 3D surfaces can easily be adjusted after analysis, where new River Builder channels may be created, and floodplain features can be revised in AutoCAD Civil 3D. Revised designs may be tested to compare how surface changes affect hydraulic and geomorphic responses. This dynamic capability supports multidisciplinary riverscape planning. Stakeholders including fluvial geomorphologists, hydraulic engineers, landscape architects, ecologists, and urban planners can collaboratively evaluate and communicate proposed changes using real-time spatial and simulation outputs.

The re-simulation of hydraulic responses to revised surface-forms also serves as a diagnostic tool. For example, S2 velocity rasters showed flow first spread to the proposed wetland feature after overtopping banks (Fig. 7a). This flow pattern spatially correlated with a relatively significant depositional surface-form found after morphodynamic modeling (Fig. 5d). Considering excessive deposition as a potential issue for stream-wetland ecosystems [65], S2 was refined by designing a side channel in River Builder and merging the new channel into the existing surface. In AutoCAD Civil 3D, the wetland feature was also adjusted, and the existing mound was extended to divert flow towards the main channel. The hydraulic response to these revised features can be modeled and differences in flow velocity values and spatial patterns may be assessed (Fig. 7b).

By integrating hydro-morphodynamic modeling tools like BASEMENT into a flexible framework, designers can predict hydraulic and sediment patterns, guiding both restorative and adaptive strategies for advancing nature-based solutions [27]. This interactive design framework provides a process-based approach to support riverscape planning, where natural geomorphic responses are not only anticipated through strategic design but intentionally investigated to support adaptive-river-design and flood mitigation. An important step for advancing resilient riverscape planning and similar elements of nature-based solutions is community involvement in the design process [64]. The following section discusses how synthetic 3D surfaces and rendering software provide an inclusive approach to visual communication to enhance public acceptance of urbanized riverscape designs.

6.3. *Presenting perspective renders for stakeholder engagement*

Stakeholder engagement requires tools that communicate the impacts and benefits of proposed river-designs in accessible and interactive formats. Community design charrettes, led by landscape architects, exemplify a method for reaching diverse audiences through verbal and visual communication [66]. Advancements in digital twin technology are also supporting inclusive water management and sustainable planning solutions [67].

This framework incorporates synthetic 3D surfaces not only as analytical models but also as communication tools. Simulated flood conditions can be animated in ParaView or similar tools like RAS Mapper, where broad audiences can readily understand fluvial responses to river-design decisions through space and time [68]. Photo-realistic rendering software offers valuable human-scale representations, illustrating how rivers may change existing characteristics and how they are aesthetically perceived. Visual attractiveness is a qualitative consideration that needs balancing for the public acceptance of urbanized riverscape projects, and communities need to ‘sense’ the designed environment from a human perspective.

Rendered images help bridge the technical understanding gap by translating expert-based river-design components into spatial narratives that stakeholders can readily understand [18]. Visually communicating planning intentions with rendered 3D models can broaden community understanding that may not be fully captured through technical analyses or the design of naturally functional river forms alone. Once 3D river surfaces have been designed in AutoCAD Civil 3D, contours can be imported to software like SketchUp (Fig. 8a) to provide a 3D digital surface representation illustrating the geometric relationship of riverscape features. In SketchUp, V-Ray textures and vegetation types are chosen, lighting characteristics are defined, and the desired resolution outputs are finalized to render a photo-realistic perspective image (Fig. 8b). Common visual communication software such as Adobe Photoshop can further modify the appearance of rendered images, where specific native plantings may be proposed, and Artificial Intelligence (AI)-assisted patch tools can refine a final product for efficient presentation to receive constructive feedback.

Text-to-image generative AI tools are also advancing quickly, where Stable Diffusion models can automate photorealistic river images with corresponding morphological features [69]. AI tools have been designed

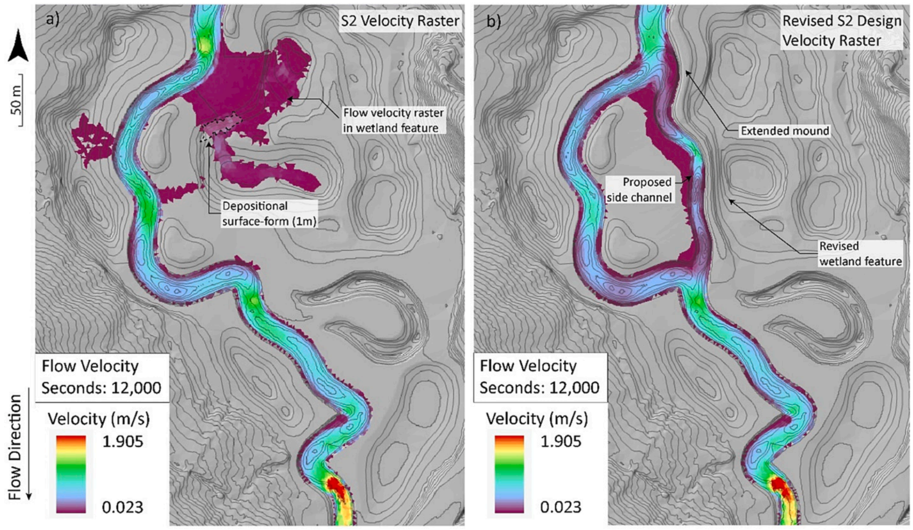

Fig. 7. DEMs and flow velocity rasters showing a) flow patterns of scenario 2 (S2) first overtopping banks and b) a revised river-design including an additional side channel, adjusted wetland feature, and extended mound surface-form.

Fig. 8. Visual communication drawings showing a) 3D SketchUp model of scenario 1 and b) rendered image using V-Ray software and AI-assisted patch tools in Adobe Photoshop.

to specifically identify reference reaches for river-design applications [70], which offers an additional tool that fits within the framework presented here. The result is a highly engaging analytical and visual product that can promote community acceptance, facilitate public consultation, and encourage collaborative input. This visual accessibility supports an inclusive action in nature-based solutions and positions the proposed framework as valuable for advancing adaptive-riverscape planning in urbanized contexts.

7. Future applications

Further research and real-world applications may include project-specific metrics and variables important to urban-design objectives. Examples may include investigation into soil infiltration characteristics [71] and rainfall interception from proposed canopy covers [72] to align with blue-green infrastructure approaches. Quantifying closed drainage system capacities [73] can also develop hybrid approaches to sustainable urban drainage systems [9]. Best practices for in-stream structural stability design may support fish passage [74] and additional climate-predictive models [75] may be applied for advancing similar elements in nature-based river management [27].

Infiltration volume and rate were not explicitly computed for the three scenarios, as the presented study focused on hydromorphodynamic responses derived from 2D river surface models. The scenario comparison therefore used greater on-site water volume and slower flow velocities as indicators of increased retention time and potential opportunity for soil infiltration, rather than as a direct infiltration estimate. While this is consistent with hydraulic safety assessments and ecohydraulic modeling approaches ([76–78]), future research may couple water-balance or subsurface-exchange modeling with software capable to simulating infiltration, transmission losses, or hyporheic exchanges [79–81].

Investigating continuous 3D river surfaces improves conventional analysis techniques of cross-sectional surveys. Our framework allows for comparative assessments of in-channel geomorphic diversity [82] and synthetic morphological feature responses to hydraulic conditions [83] in the planning phase of river-design. Together, these applications demonstrate the flexibility of the framework presented here, which enhances multidisciplinary design development, testing and selection, refinement, and presentation of synthetic 3D surfaces. Future research can incorporate a diversity of design objectives for defining best-performing criteria useful for advancing adaptive approaches for urbanized riverscape planning.

8. Conclusions

This study introduced a multidisciplinary and flexible design framework to support adaptive riverscape planning. It integrates real-world topographic data, synthetic 3D channel design, hydromorphodynamic modeling, and rendered visual communication techniques as part of a nature-based solutions approach for urban flood mitigation and habitat heterogeneity enhancement. Using a coastal site in Nova Scotia, Canada, we demonstrated how continuous 3D surfaces can be designed, tested, refined, and visually presented to enhance stakeholder engagement.

This framework allows multidisciplinary teams to interactively refine design scenarios in the planning phase and high-quality renderings can present visual narratives that improve community understanding, acceptance, and involvement in adaptive-river-design processes. By bridging scientific analysis, river-design practices, and stakeholder communication, this framework advances practical methods for addressing climate-driven challenges in urbanized riverscapes and lays the groundwork for more resilient, inclusive, and nature-based flood mitigation strategies. Future applications may leverage additional and complementary metrics, models, and assessments to define project-specific success and balance trade-offs through collaborative planning strategies.

CRediT authorship contribution statement

Corey Dawson: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Gregory B. Pasternack:** Writing – review & editing, Writing – original draft, Validation, Software, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Designed adaptation

A multidisciplinary framework for urbanized river-landform design and communication.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cacint.2026.100456.

Data availability

Data will be made available on request.

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