2024 LACF Annual Grant Final Report

Project 1: *Advancing green infrastructure design with synthetic 3D drainage channels: A scenario-based flood model for Bedford, Nova Scotia, Canada*

Project 2: *A flexible approach to riverscape design and restoration planning*

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SUMMARY

I would like to thank the LACF and Sustainable Buildings Canada for providing funding to complete two research projects for publication in peer-reviewed journals. Funding supported a summer research student, Ian Logan, from the Bachelor of Landscape Architecture (BLA) program at Dalhousie University. Our first project titled "*Advancing green infrastructure design with synthetic 3D drainage channels: A scenario-based flood model for Bedford, Nova Scotia, Canada*" is currently under review in the journal Nature-based Solutions, Special Issue: Sustainable Drainage Systems Networks (SuDSnet): Enhancing multiple benefits of SuDS as Nature-Based Solutions (NbS). The second completed project titled "*A flexible approach to riverscape design and restoration planning*" is in the final stages of manuscript development and aimed at publication in the journal Water Research in collaboration with Dr. Gregory Pasternack from UC Davis, the developer of River Builder software used for our projects.

Both projects applied real-world LiDAR data and River Builder software for deriving synthetic 3D digital surfaces for comparative analysis. Project 1 developed drainage channel scenarios as an approach to sustainable and adaptable bioswale design in urbanized landscapes while Project 2 considered an upstream riverscape for generating restoration design scenarios to reduce peak discharges at the downstream urbanized site (Project 1). The general aim of both projects was to present a flexible method for designing, simulating, analyzing, and presenting 3D surface designs to evaluate how fluvial processes respond to geomorphic and topographic differences for landscape design decision-making.

The following will summarize the research with an introduction while methodologies and results are presented for each project. The completed papers will published with Open Access and shared through the LACF website.

INTRODUCTION: Project 1 and 2

Climate change is driving flow regime changes in urbanized riverscapes. Storms are causing higher frequency and magnitude peak flows, while rising sea levels can also contribute to straining subgrade drainage systems in response to urbanized imperviousness and engineered gray infrastructure, particularly in coastal regions. Efforts to manage urbanized riverscapes have historically relied on stabilization techniques like channelization and hardening, prioritizing flood mitigation and infrastructure protection. Conventional flood protection structures, designed largely with planar geometries to confine flow, are failing under evolving regime conditions and compound flood risks from hydrograph flashiness, beyond initial design storm variables used for engineering. Gray infrastructure also fails to support ecological improvements and contributes to declining ecosystem quality. Perceived naturalness of urbanized riverscapes, whether designed or pristine, is largely preferred over conventional hardscape surfaces and provides ecosystem services to users that can enhance physical and mental well-being.

In response to these challenges, nature-based solutions are gaining traction, where system resiliency is enhanced by methods that emphasize naturally dynamic process-form responses designed for adaptation to regime changes. Process-based approaches to river restoration apply these principles to channel design and encourage morphology adjustments to riverscape changes. However, their implementation in urbanized riverscapes is limited because channels are largely constrained and stream migration, for example, is restricted by historic human intervention and river policies.

While process-based river restoration is difficult for confined urban landscapes, opportunity exists for applying these principals through:

Project 1: sustainable urban drainage systems (SUDS) where channels are designed as green infrastructure and;
Project 2: restoring upstream channel sections with process-based approaches.

These approaches may relieve strains put on closed drainage systems through new approaches to stormwater management that enhance ecosystem services and social acceptance.

Designing river and drainage channels with more irregular surface geometries and vegetative covers that reflect natural stream morphology may offer resilient alternatives to gray infrastructure by enhancing ecological function and aesthetic quality while addressing flood mitigation needs. Advancements in LiDAR derived high-resolution topographic data offer innovative approaches for green infrastructure design and software capable of generating synthetic 3D surfaces provide opportunity for designing, assessing, and communicating sustainable urban drainage systems (SUDS) in the planning phase. River restoration and green infrastructure projects are multidisciplinary, but collaboration may be impacted by gaps in technical understanding and interactive working structures for urbanized sites. Analytical process-based software available to non-geomorphologists are becoming increasingly valuable for collaborative design and innovative tools are essential for advancing nature-based solutions to stormwater management.

River Builder software provides an approach for re-imagining stormwater management planning by designing river and drainage channels with more natural stream-like morphology. When considering topographic data as a continuous surface, finer scales are involved in a hierarchical assemblage and require a statistical correlation to hydraulic data, particularly for flood risk assessment. Synthetic river surfaces derived form River Builder exemplifies a process-based method for designing 3D representations of continuous digital elevation models (DEMs) automated from fundamental process-form linkages defined as geomorphic covariance structures (GCSs). River Builder derived channels allow collaboration for landscape architects, engineers, planners, fluvial geomorphologists, and ecologists because geomorphic variables can be systematically adjusted to test, analyze, and propose morphology changes in a controlled digital environment. Research into synthetic 3D river surface applications is advancing. However, limited studies have considered synthetic 3D channels for controlling surface water through green infrastructure design to mitigate flooding by SUDS. Quantifying geomorphic process-form linkages by using 3D channels provides a repeatable representation of morphology change and can point to river restoration and green infrastructure objectives most likely to succeed and adapt to climate change impacts.

Here two proof-of-concept experiments are presented for a new green infrastructure design approach that integrates geomorphic variables into automated and process-based design frameworks. Four synthetic River Builder derived channel design scenarios were compared to demonstrate the potential for innovating aspects of green infrastructure relating to morphodynamics and assessment and proposing the methodology as a decision-making tool for SUDS (Project 1). Project 2 proposed three riverscape design scenarios upstream from the urbanized site of Project 1. Topographic data were collected for the urbanized and upstream sites in Bedford, Nova Scotia. Fluvial simulations and digital elevation models (DEMs) were used to investigate how geomorphic and hydraulic conditions responded to changes in channel geometries and vegetative surface covers.

Tools able to systematically test and present design scenarios may enhance climate adaptation strategies for flood mitigation that are derived from statistical and geometric correspondence to process-form linkages. The aim is to leverage advancements in 3D surface modelling to enhance flood mitigation through synthetic channel design and support multidisciplinary planning strategies for advancing nature-based solution to stormwater management.

Results were not intended to prove a statistical correlation between real-world hydrological data and site-specific flood mitigation components for hydraulic engineering purposes. Rather, new methodologies are presented for flood modelling applications by using real-world data as scenario-based experiments where fluvial simulations may point to 3D channel geometries useful for collaborative flood management planning. With further catchment-scale research, drainage channels can be designed to accommodate changing riverscape hydrology by combining both catchment and in-channel solutions to improve green infrastructure design that promotes self-sustaining drainage systems. This work ultimately aspires to showcase a strategy for bridging science, design, and practice, advancing climate adaptation strategies for urbanized riverscapes.

Project 1: Advancing green infrastructure design with synthetic 3D drainage channels: A scenario-based flood model for Bedford, Nova Scotia, Canada

1. METHODOLOGY

1.1 Existing topographic site data

To demonstrate our approach to green infrastructure design, a real-world urbanized riverscape was selected for investigation. The site is a coastal landscape in the Bedford community of Halifax Regional Municipality in southern Nova Scotia, Canada and has recently experience major flooding issues that may worsen from climate change impacts. The urbanized site includes the Bedford Place Mall (Figure 1), and topographic surface data were extracted at a spatial extent of 0.24 km^2. The land cover is a mix of medium to high intensity development with sandy clay loam soils and the mall is located north-east of the Bedford Basin, immediately west of a confined channel section of the lower Sackville River. The surface is mostly impervious, including large parking lots and three major bridge crossings from Bedford Highway to the east. Existing flood protection infrastructure includes shallow overflow routes and flow storage units to the west of Bedford Place Mall, designed to intercept flood water from the Sackville River.

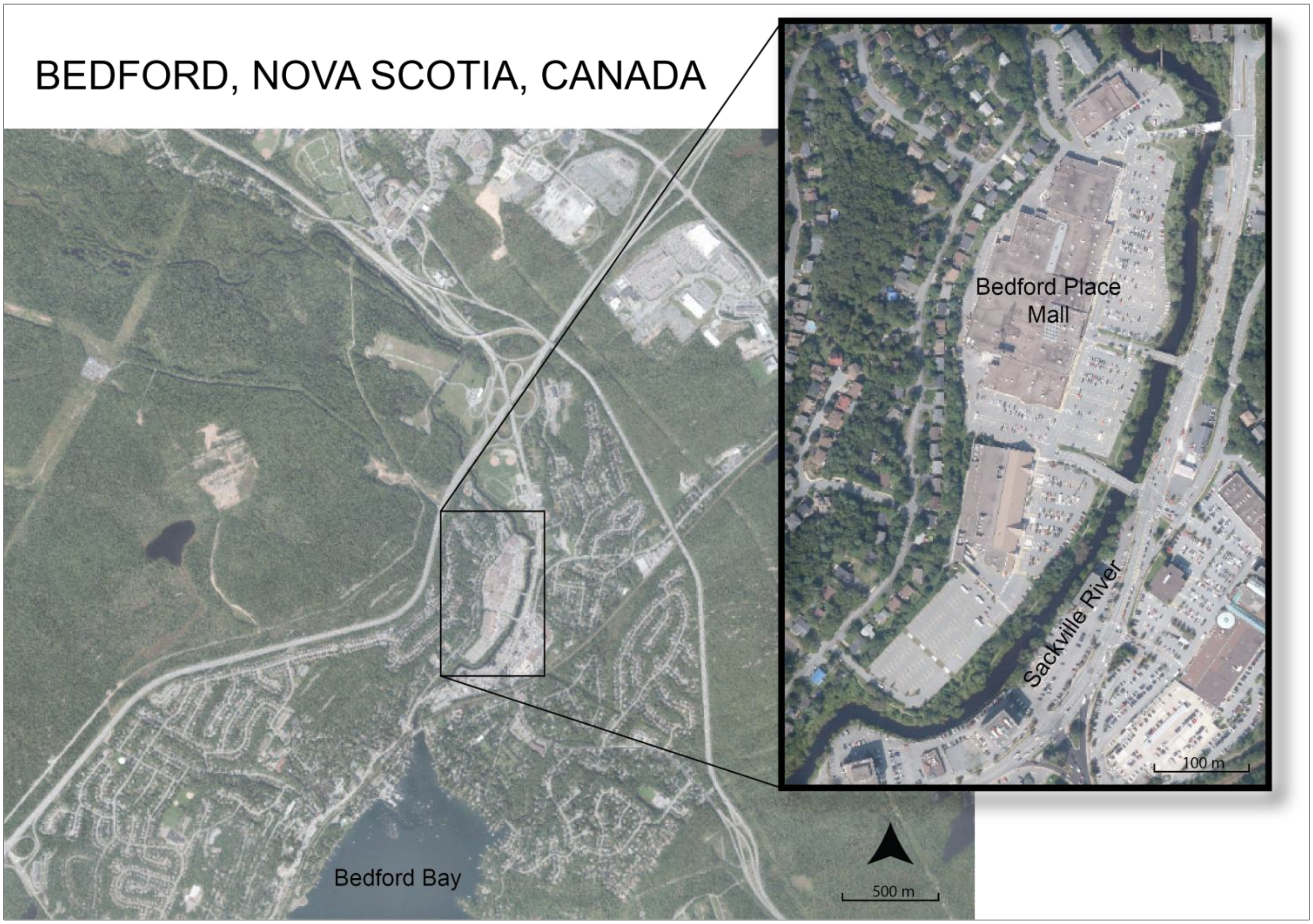

Figure 1. Aerial image of the Bedford Place Mall in the Bedford Community of Halifax Regional Municipality (Google Earth, 2024).

Topographic data were collected from the Province of Nova Scotia's Elevation Explorer. LiDAR data files (LAZ) included the newest available year (2019) with a pulse spacing and pulse density of 0.4 and 6.0, respectively. Data were converted to LAS files in ArcGIS Pro to generate a digital elevation model (DEM) at a 0.2 m pixel resolution. The site boundary was extracted, and a contour shapefile was exported to

AutoCAD Civil 3D where four drainage channel design scenarios were generated for analysis. Here after the original DEM is referred to as the 'existing reach' while the designed surfaces will be referred to as scenarios 1, 2, 3 and 4, where synthetic 3D channel surfaces were stitched with the real-world existing reach topographic data.

1.2 Designing synthetic drainage channel scenarios for comparative analysis

The novelty of this approach is the application of synthetic 3D digital channel surfaces as a tool designing sustainable urban drainage systems (SUDS). River Builder software provides a flexible strategy towards nature-based solutions because it offers computation for designing, evaluating, communicating, and revising green infrastructure in the planning phase. Synthetic digital channel surfaces derived form River Builder exemplifies a process-based method for generating 3D representations of continuous DEMs automated from fundamental process-form relationships in fluvial geomorphology. Synthetic 3D channels allow collaboration for multidisciplinary design decision-making, where geometric variables can be systematically adjusted to analyze and propose morphology changes in a controlled digital environment. River Builder has not yet been applied to urban drainage channels and prosed for green infrastructure design. The aim is to demonstrate this approach as a proof-of-concept experiment by comparing drainage design scenarios with a focus on evaluating fluvial simulation responses to 3D geometric channel adjustments.

Four synthetic drainage channel scenarios were generated for comparative analysis. Each scenario included a 3D channel surface created in River Builder that were stitched to existing reach surface data in AutoCAD Civil 3D and exported as DEMs for analysis in HEC-RAS and ArcGIS Pro. The channels were designed to intercept flood water from the Sackville River and divert flow along the west perimeter of the existing mall building to connect with an existing drainage route to the south. The idea here is to propose conceptual drainage structures that can relieve the strain put on subsurface drainage systems and offer an analytical approach for investigating how flood inundation patterns and flow velocities respond to different channel design scenarios.

Scenario 1 was designed with conventional drainage channel characteristics. The planform shape was straightened to quickly move flow off-site, and the cross-section was a standard symmetrical trapezoidal (EN) shape with a width of 1.5 m and depth of 0.5 m (Fig. 2a). Scenarios 2, 3 and 4 were designed to mimic a more 'natural' planform pattern and each included a meandered channel surface (Fig. 2b). The planform pattern was designed to conceptually accommodate an increased flow regime with the aim of reducing mean flow velocities during flood modelling and increasing geomorphic complexity for potential habitat enhancement. The resulting planform was generated from geomorphic covariance structures (GCSs) during River Builder computation and may aligned with morphologies that promote green infrastructure strategies for bioswale design, for example.

Scenario 2 was designed with a similar symmetrical cross-section (EN) as scenario 1, but of irregular planform shape (Fig. 2c). Scenario 3 was designed with an asymmetrical cross-section (AU) and variation in channel width (Fig. 2d), while scenario 4 included additional in-channel forms (pools) to further demonstrate the natural geomorphic process-form linkages of river morphology (Fig. 2e). These geometric adjustments provided continuous synthetic 3D surfaces to complete fluvial simulations, where the conventional drainage channel (scenario 1) was compared with more natural morphologies and offers an interactive approach to green infrastructure design decision-making.

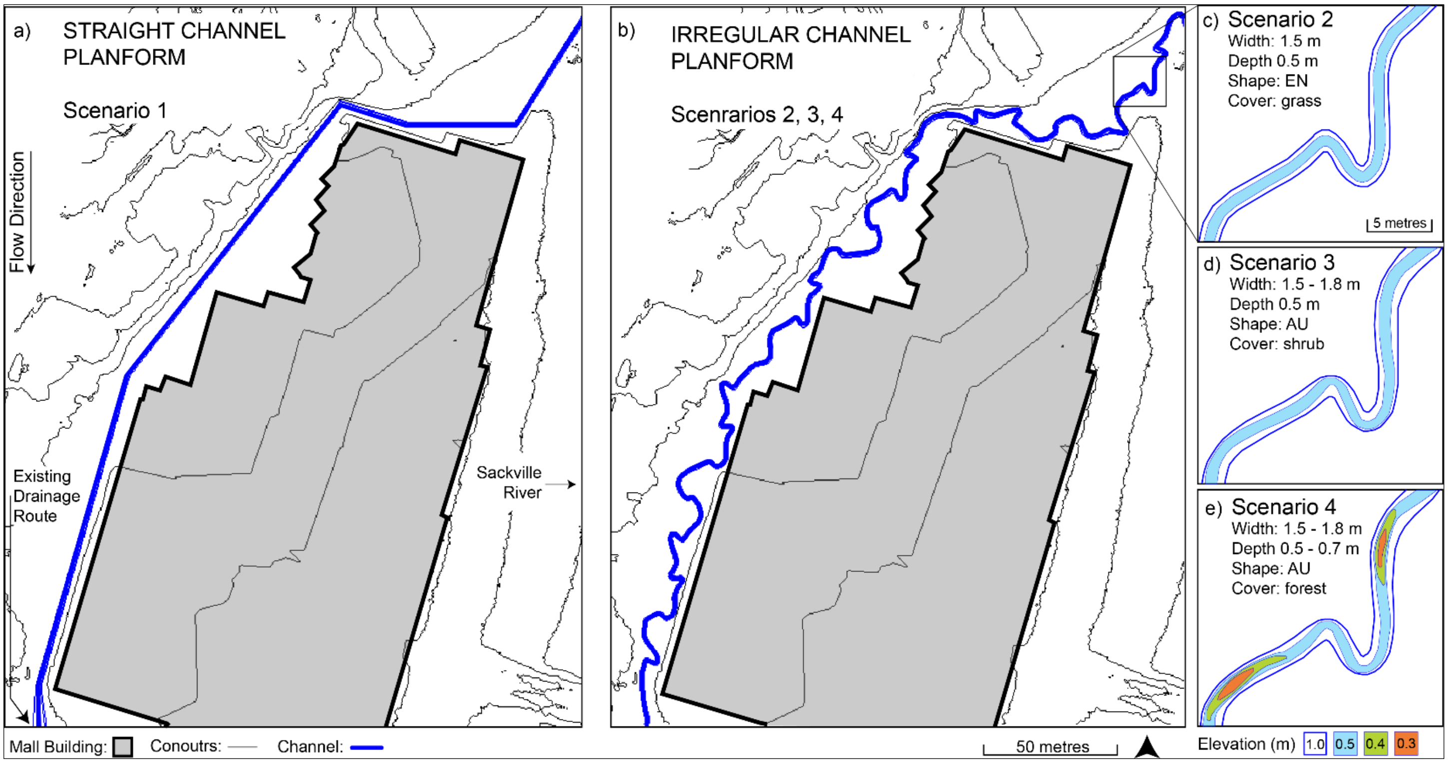

Figure 2. Contour drawings showing a) the straight channel planform of scenario 1, b) irregular channel planform of scenarios 2, 3, and 4, c) scenario 2 channel design variable, d) scenario 3 channel design variables, and e) scenario 4 channel design variables.

Drainage channel design scenarios were first derived with River Builder software, where real-world site domain parameters and GCSs were used to generate synthetic surfaces for comparative analysis. GCSs allow for non-geomorphologists to model 3D channels by adjusting input design scripts for a given site, including urbanized riverscapes, and provides a highly controlled digital environment for green infrastructure design and investigation. Different input values result in different channel geometries. For example, an asymmetrical (AU) cross-sectional shape will develop pool forms on outer meander bends, where flow velocity is fundamentally higher, and channel width variability will result from inner-bank functions applied to River Builder input scripts.

Several user-defined functions can be added in the design process. This offers substantial opportunities for further research into synthetic channels and practical applications for SUDS. Adjustments to geometric equation values can create unique 3D channel surfaces and the combination of user inputs are exponential. Function equations consist of amplitude and frequency value inputs, both for planform and vertical geometries. Amplitude defines the horizontal distance of meander bends along a channel length (meander centerline) while thalweg amplitude values adjust the height of in-channel forms (pools). Frequency then defines the quantity of those planform and vertical geometries with a single or series of amplitudes, while the inner-channel bank function can also fluctuate channel widths for continuous surface lengths.

Amplitude and frequency are controlled with sine and cosine function equations:

$$f(a) = amplitude * \sin\left(frequency * a + shift\right)$$

where;

$$a = 2\pi * \frac{x_i}{x_{max}}$$

River Builder input equations that were used to generate four synthetic drainage channels included the meander centerline, high curvature, inner-channel bank, and thalweg functions. The planform channel pattern was derived with the meander centreline function that is controlled with a sine and cosine input. Cartesian coordinates defined the channel alignment, where *y* is a function of distance along the coordinate with the equation:

$$y = fun_1(x) + fun_2(x) + fun_3(x) + \cdots$$

where $fun_{1,2,3}$ are sine and cosine inputs.

The meander centerline function generated a straight channel for scenario 1 with a single input value while scenarios 2, 3 and 4 included a series of sine and cosine equations to generate and irregular channel shape. The high curvature function was also applied to generate irregular channel patterns that reflect natural morphology curvatures. This function allows for multiple *y* values for each *x* position with the equation:

$$\omega = 2.2 * \sqrt{\frac{p-1}{p}}$$

$$\theta = \omega * cos(s_i)$$
$$x_{i+1} = x_i + cos(\theta)$$
$$y_{i+1} = y_i + sin(\theta)$$

where *p* is sinuosity and s_i are points along meandering line.

The inner-bank function was used for scenarios 3 and 4 to provide variation in channel width and response to asymmetrical (AU) cross-sectional shapes. The function defines the minimum distance between banks along the *x*, *y* 2D plane. The coordinate system allows for an offset distance to be determined from the meandering centerline length with the equation:

$$offset_{yi} = y_i + fun(x_i) + min_{offset} - \min\left(fun(x)\right)$$

The thalweg elevation was an additional function applied to scenario 4. The function develops in-channel forms (e.g., pools) and allows opportunity to evaluate fluvial responses to automated morphological features. A defined thalweg line controls the undulation of in-channel forms, where amplitude and frequency values determine variation in bed elevation points. Thalweg function values were added scenario 4 so that the in-channel forms ranged in elevation by 0.2 m. Fundamental GCS responses to planform pattern, width, and in-channel form characteristics demonstrate relationships expected from natural meandering channels. GCSs allow for an automated method that moves beyond conventional open channel stormwater drainage systems and points to solutions for green infrastructure design useful for advancing SUDS.

1.3 Applying fluvial simulations to derived drainage channel geometries

Synthetic drainage channels were designed from four unique River Builder input scripts and point files were imported to ArcGIS Pro. Point files were converted to DEMs with a 0.2 m pixel resolution and contours were created at an equivalent interval (0.2 m) and exported as shapefiles. Contour files were then imported to AutoCAD Civil 3D and used to stitch the synthetic channels into the existing reach topography. Channel contours were trimmed, rotated, and connected to existing surface contours to generate a continuous surface for each channel design scenario. Surfaces were exported as DEMs and provided terrain files for flood modelling and flow velocity comparisons. Design scenarios do not represent highly technical construction drawings developed for a real-world site, but rather, used real-world data (LiDAR) to demonstrate a 3D surface design strategy and assessment methodology which may be useful for practical applications to green infrastructure design.

Fluvial simulation comparisons can point to hydraulic responses to different channel design strategies and demonstrate how surface water variables may be quantified in the decision-making process. To understand how flood inundation patterns respond to vegetated drainage channels, a general plant cover type was proposed for each channel scenario. A grass surface was selected for scenarios 1 and 2, representing a common vegetative cover used for swale grading design in urban landscapes, while shrub cover was selected for scenario 3, and forest was selected for scenario 4. The idea here is to provide a series of drainage channel designs that sequentially enhance the quality of green infrastructure design components and evaluate fluvial responses to different geometric channel adjustments and vegetative cover roughness coefficients.

HEC-RAS software was used for 2D fluvial simulations, comparing the existing reach and four channel design scenarios in RAS Mapper. The spatial reference system (SRS) was set to a consistent projection (NAD_1983_UTM_Zone_20N), and the RAS terrain layer was derived from DEMs created in AutoCAD Civil 3D. A new geometry file was created for each case, including a perimeter mesh polygon covering the reach extent at a cell size of 10 m and a refinement region was included over the designed channel extent at a cell size of 1 m. The refinement region allowed for a higher accuracy and finer scale of observation for different channel design scenarios while keeping the computation time efficient. Boundary condition lines were also included upstream and downstream of the Sackville River.

A land cover classification layer was added with polygons for the existing reach extent. Land covers were then revised for each drainage channel scenario, including grass (scenarios 1 and 2), shrub (scenarios 3), and forest (scenario 4). Manning's (n) roughness coefficients are common variables for hydrological models and flood estimates, but values range from site conditions, assessment objectives, and sources. Methods for identifying appropriate coefficients for riverscape conditions are improving and site-specific investigation may refine the quantification of this type. The purpose of this study was to demonstrate an innovative approach for advancing green infrastructure design planning by using real-world site data as a case study. The focus is not to quantify hydrology conditions but rather applying this type of general assessment to showcase a methodology for advancing nature-based solutions to stormwater management. Therefore, land cover types, roughness coefficients, and imperviousness values were simply sourced from value ranges described in the HEC-RAS Mapper User's Manual (URL: https://www.hec.usace.army.mil/software/hec-ras/) to communicate the design and assessment process rather than a highly technical statistical investigation. The land cover classification parameters applied for investigation are included in Table 1 and were also applied for Project 2 simulations.

Land Cover	Roughness Coefficient (*n*)	Imperviousness (%)
Developed, High Intensity	0.15	90
Developed, Medium Intensity	0.1	80
Open Water	0.035	100
Grass/Herbaceous	0.04	0
Shrub	0.08	0
Mixed Forest	0.12	0

Table 1. Table listing the land cover types, Manning roughness coefficients (n), and imperviousness values used for fluvial simulation in HEC-RAS software.

Unsteady flow data was formulated for the upstream and downstream boundary conditions. The upstream boundary data were sourced from Environment Canada's historical hydrometric data (gauge station 01EJ001) at an interval of 1-hour for July 21 – July 22, 2023. These data were selected because a high magnitude flood event occurred on this date and provided peak discharge data for fluvial simulations. Flow hydrograph inputs began at 2.3 m^3/s (00h:00m) and ended at a peak discharge value of 120 m^3/s (36h:00), while the remaining values were generated by interpolating missing values. The unsteady flow analysis file was generated by computation at an interval of 15 sec, mapping output interval of 10 min, and hydrograph output interval of 5 min. These inputs provided five total flood models for the existing reach and four drainage channel design scenarios, allowing assessment of resulting water depths and flow velocities (Figure 3).

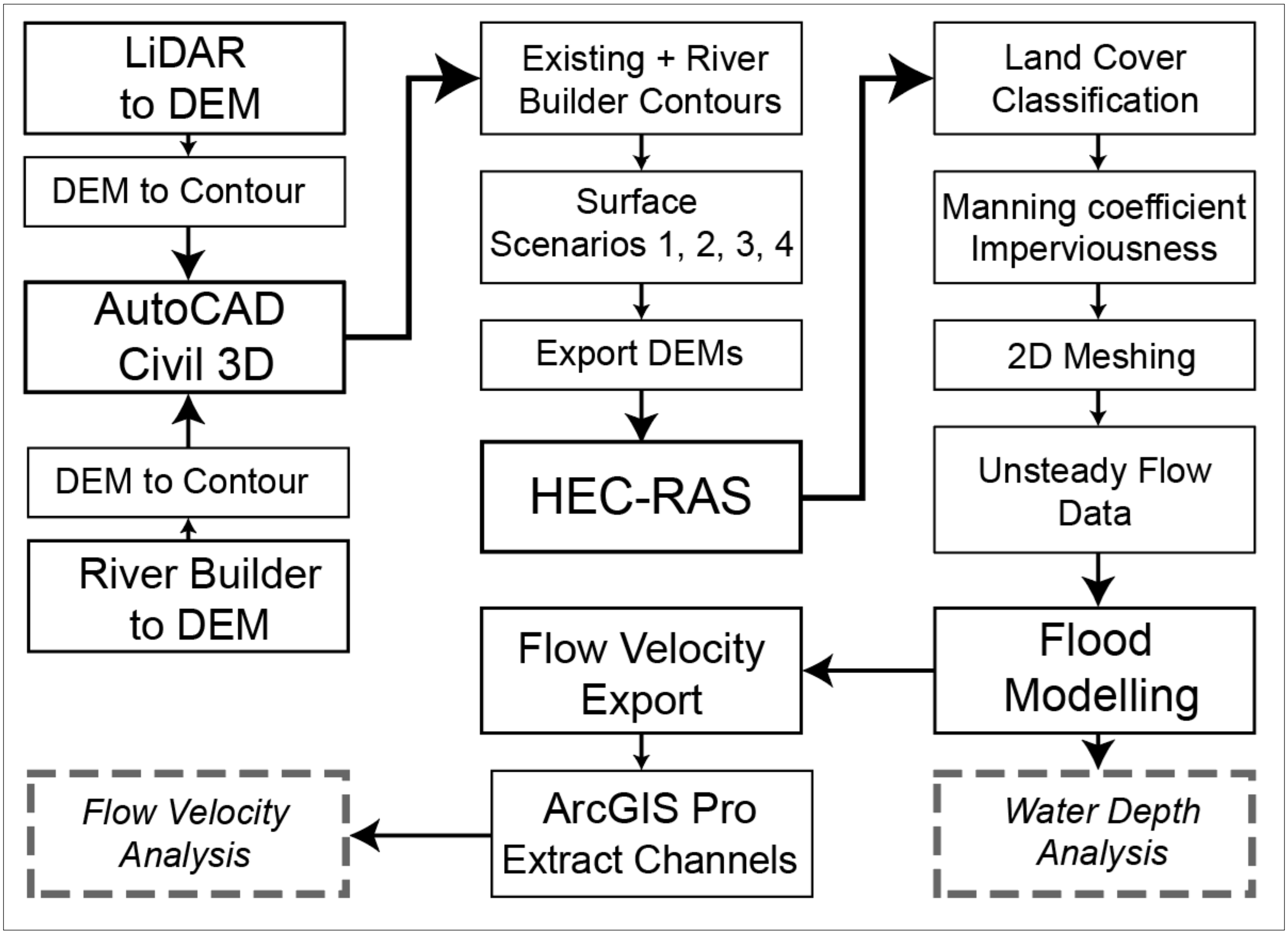

Figure 3. Workflow diagram illustrating the methodology for generating synthetic 3D drainage channel design scenarios, completing fluvial simulations, and analyzing resulting water depth and flow velocity data.

1.4 Evaluating drainage channel design scenarios

Flood models were evaluated to understand how fluvial simulations responded to channel design scenarios and how River Builder derived channels may be assessed with future applications. Water depth and flow velocity responses were assessed for differences in planform pattern (straight and meandered), vegetation cover (grass, shrub, and forest), and channel shape (symmetrical, asymmetrical, width variation, and in-channel features). Flood inundation patterns were evaluated by spatial water depth values first breaching the mall building. ‘Breach’ was defined as the inundation extent reaching a depth of 0.15 m at the first saturated 10 m computation point within the 2D mesh cell at the mall building location, allowing for cell statistics to be extracted. Assuming a conventional 0.15 m curb height for building entrances, floods were modelled until a breach occurred and water depths and simulation times (hh:mm) were plotted for the corresponding 2D cell. This allowed for flood comparisons to investigate how channel design scenarios influenced the lag time for water depths reaching the breach level relative to existing reach conditions.

Next, fluvial simulations were compared to understand how vegetative covers influenced flood inundation patterns for different channel designs. Three floods were modelled for each scenario, totally eight additional fluvial simulations, by adjusting the roughness coefficient value from 0.04, 0.08, and 0.12 to illustrate flood responses to grass, shrub, and forest covers, respectively (Table 1). Water depth (m) and discharge (m^3/s) were plotted for each scenario to understand how fluvial simulations responded roughness and different channel geometries.

Finally, floods were modelled for drainage channel surfaces at a consistent roughness coefficient of 0.04 (grass) to more specifically evaluate how fluvial simulations responded to adjusted channel geometries, without the influence of different vegetative covers. Flow velocities were mapped in HEC-RAS to show bankfull stages for each design scenario. Velocity rasters were exported to ArcGIS Pro and raster cells were extracted by Mask to include the channel surface extent. Mean flow velocity values were plotted, and velocity raster cells were assessed to understand how synthetic channel conditions were influencing the statistical and spatial relationship of velocity values.

2. RESULTS

2.1 Flood inundation responses to drainage channel scenarios

River Builder provided opportunity to design, investigate, and adjust synthetic drainage channels of different green infrastructure enhancement qualities. Synthetic 3D digital channels may not yet provide construction-ready working drawing for sustainable urban drainage systems (SUDS), but River Builder is a tool for advancing novel approaches to green infrastructure design and enhancing opportunity for nature-based solutions through geomorphic covariance structure (GCS) responses in the design process. Results of the existing reach and four drainage channel scenarios showed a sequential time lag in water depths reaching the breach level at the mall building, showing that designed channels were mitigating flood inundation. The greatest time difference was between the existing reach and scenario 4, demonstrating a relationship between additional green infrastructure components and flood mitigation.

To understand how each channel design scenario delayed flood inundation, water depth (m) and simulation time (hours) were plotted to evaluate scenario differences relative to the existing reach conditions (Figure 4). Scenarios 1 showed a simulated lag time of 5.75 hours, scenario 2 showed lag time of 7.25 hours, while scenarios 3 and 4 showed a relatively similar lag time of 10 hours. Flood models responded to River Builder control functions applied to designed drainage channels, particularly adjusting channel planform patterns from straight (scenario 1) to irregular channel shapes (scenario 2 – 4). As functions were added to irregular channels, the inundation lag time increased, with width variability showing a greater proportional difference than planform irregularity alone (scenarios 3 – 4 in Fig. 4). However, the flood inundation response to additional in-channel forms was lower, showing a slight difference between scenario 3 of variable widths with shrub cover, compared to scenario 4 of variable widths, in-channel forms, and forest cover.

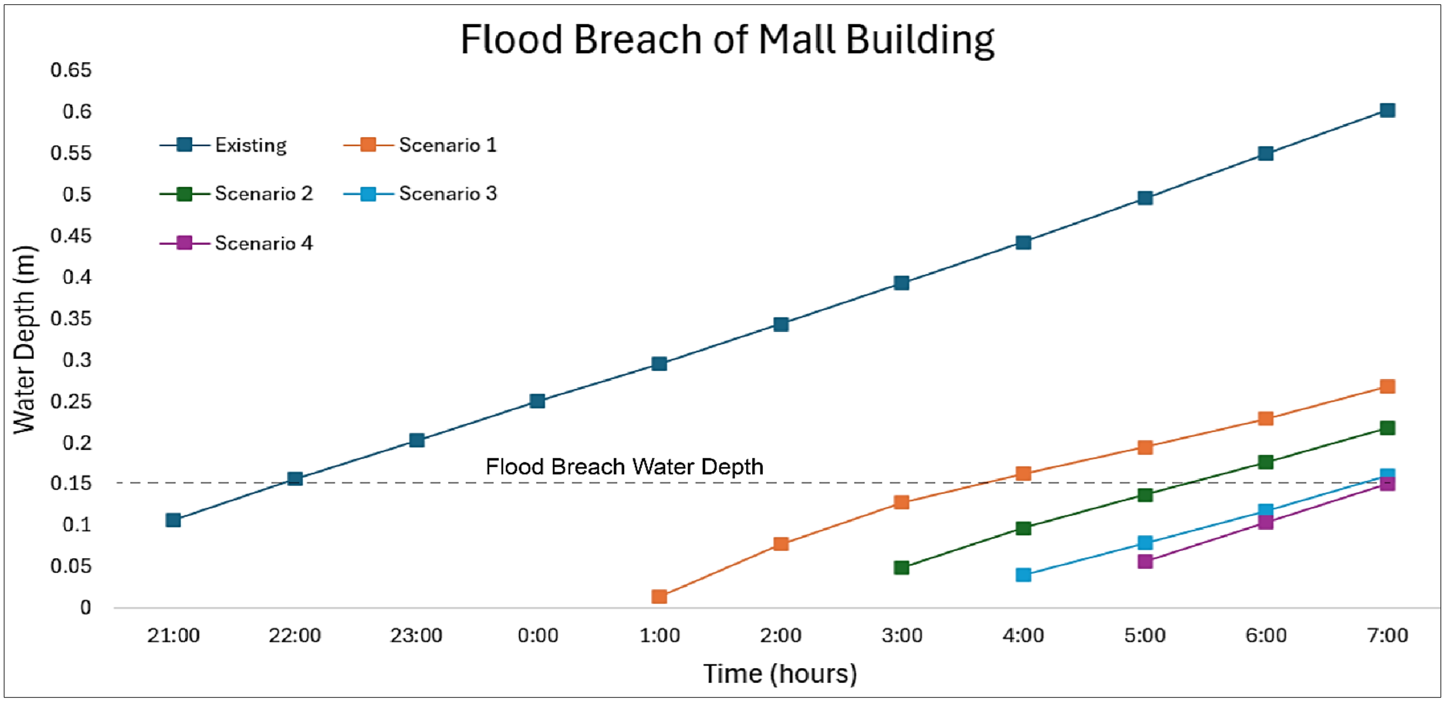

Figure 4. A graph illustrating water depth vs fluvial simulation time at the first saturated 2D computation point for the existing reach and channel design scenarios 1 – 4, showing when water depths reached the breach level of 0.15 m within the mall building.

The following will consider flood inundation responses to vegetative covers. Channel design scenarios included different roughness coefficients relative to land covers applied for flood modelling, including grass, shrub, and forest. Each flood scenario was simulated to more specifically understand how cover types influenced lag time responses and if channel geometry differences changed the relative effect of roughness coefficients.

2.2 Flood inundation responses to roughness coefficients of vegetative covers

Vegetative cover roughness showed a positive relationship between increased coefficient values and flood inundation lag time. Coefficient values of n = 0.04 (grass), n = 0.08 (shrub), and n = 0.12 (forest) were applied to each channel surface to simulate three floods for each scenario, totalling 12 flood models. Water depth (m) and simulation discharge (m^3/s) were plotted with trendlines to illustrate differences in relative cover roughness and where flow reached the breach water level of 0.15 m (Figure 5). Results show similar relationships between each scenario, where discharge reaching the breach level increased with coefficient values. The proportional discharge value between shrub (0.08) and forest (0.12) cover types remained relatively low for each scenario, showing limited relational change resulting from planform channel pattern differences or additional River Builder functions applied.

The proportional discharge difference between grass (0.04) and shrub (0.08) was consistently greater than the shrub (0.08) and forest (0.12) cover types for each channel scenario. The relative difference between vegetative covers progressively reduced as water depths increased, with shrub and forest trendlines intersecting after a discharge of 110 m^3/s. However, the proportional different between grass and other covers remained greater at this same discharge. Although roughness coefficient values were incrementally increased by 0.04 units for flood modelling, the relative influence of vegetation cover was not evenly distributed between scenarios and showed a vegetive cover change from grass to shrub had more influence on reducing flood inundation compared to changing from shrub to forest cover types.

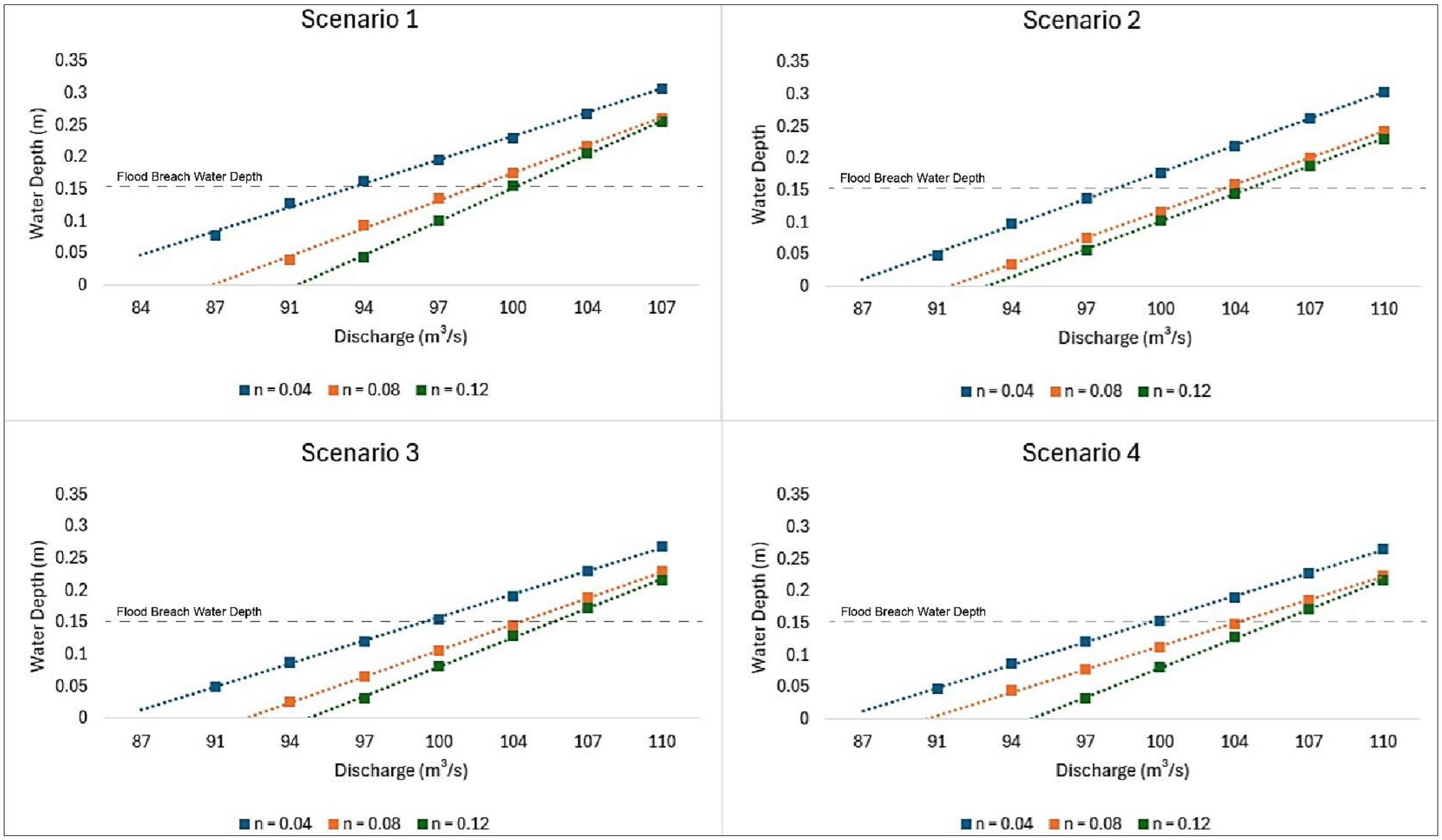

Figure 5. Trend lines showing fluvial simulation responses to different Manning roughness coefficients (*n*) for grass (0.04), shrub (0.08), and forest (0.12) covers for each channel design scenario. Plotted water depth vs discharge values illustrate when flow reached the breach water level (0.15 m) for each flood model.

2.3 Flow velocity responses to drainage channel geometry changes

Results have shown that synthetic River Builder derived drainage channels and applied roughness coefficient values provide a means for evaluating flood inundation patterns. Another assessment useful for green infrastructure design is channel flow velocity because it may provide a statistical and spatial link between geomorphic form and fluvial process. Channel geometries were assessed at the channel extent for each design scenario. Equivalent roughness coefficients (n = 0.04) were used to understand how flow velocities responded to planform pattern, width variation, and in-channel forms, without the influence of different vegetation cover types. Velocity rasters were extracted at bankfull water depth where mean velocity values were compared.

Mean velocity values progressively decreased as channel geometry became more complex resulting from additional River Builder input functions applied (Figure 6a). A proportional mean velocity difference of 69%, or range of 0.16 m/s, was found between the straight channel pattern with symmetrical cross-sectional shape (scenario 1) and the asymmetrical channel designed with geomorphic forms more reflective of natural stream morphologies (scenario 4). The greatest sequential difference in mean velocity was found between scenario 2 and 3, showing a proportional value difference of 49% resulting from width variability and asymmetrical cross-section functions applied in River Builder. The second greatest proportional mean velocity difference was found between scenario 3 and 4 resulting from additional in-channel forms (scenario 4) while a proportional the lowest difference was found between scenario 1 and 2 resulting from straight (scenario 1) and irregular (scenario 2) channel planform patterns. Compared to flood inundation findings described above, mean velocities responded more to additional geometric functions (cross-section, width variability, and in-channel forms) than irregular planforms.

Velocity values were mapped to further investigate the spatial relationship between geometric channel differences and understand how velocity responded to GCSs (Fig. 6b). Scenario 1 showed a relatively consistent distribution of velocity values ranging from 0.119 to 0.165 m/s through the centre length of the channel while lower velocities (0.104 – 0.118 m/s) formed along the channel banks. As a meandered planform pattern was introduced in scenario 2, higher velocity value cells (0.139 – 0.165 m/s) began to cluster near bends and values decreased along the outer channel banks. Scenario 3 showed a similar relationship, where higher velocity values clustered near meander bends, but clusters began to shift towards outer bends resulting from the asymmetrical cross-section and width variability of the channel. Straighter channel sections showed lower velocity values forming along the banks while scenarios 1 to 3 showed higher velocity values that progressively dissipated along the center of the channel.

Scenario 4 showed the greatest spatial velocity difference throughout the length of the channel and resulted from additional in-channel forms. Higher velocity values clustered where River Builder GCSs developed pool-like forms along channel bends (Fig. 6b). Compared to former scenarios, velocity values decreased substantially (0.025 – 0.087 m/s) along straight channel sections where riffle forms developed. Geometric surface differences at the channel extent were impacting the distribution of flow velocity values as design functions were added, illustrating a fluvial response to designed geomorphic forms.

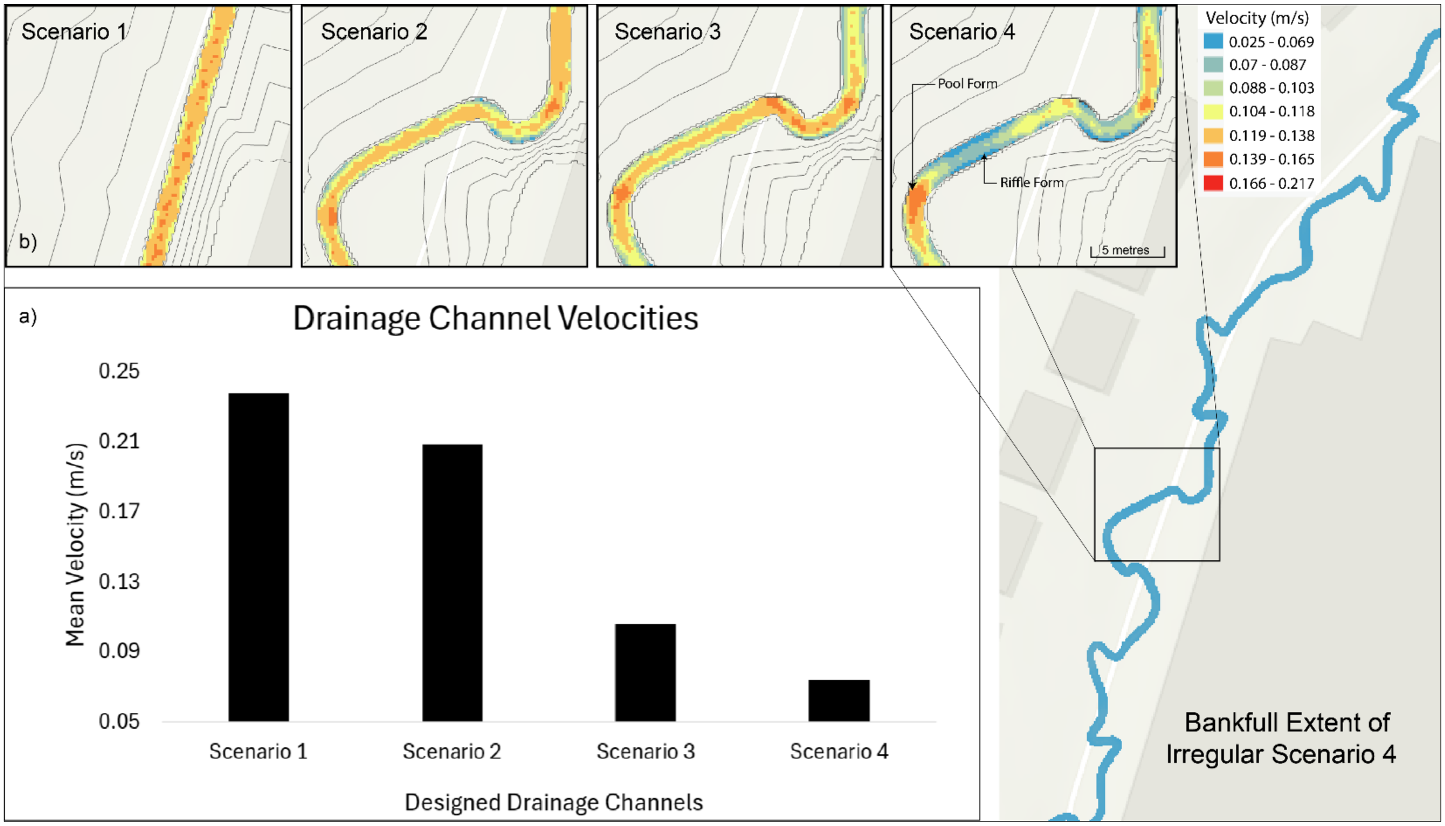

Figure 6. Bar graph showing a) mean flow velocities for each extracted channel scenario showing decreased values from scenario 1 to 4, and b) mean velocity rasters showing the spatial relationship between higher and lower value cells for each channel scenario.

Project 2: A flexible approach to riverscape design and restoration planning

3.0 METHODOLOGY

3.1 Topographic data for riverscape design

To generate a series of 3D riverscape design scenarios for comparative analysis, we first selected a real-world site as a case study for deriving synthetic channels with River Builder software. The LiDAR data from Project 1 (see Section 1.1 above) was applied to consider the upstream Bedford Rifle Range for riverscape restoration planning (Figure 7). In response to high flood risks, we identified the Bedford Place Mall as a rehabilitation site and targeted an upstream Bedford Rifle Range for intervention through riverscape restoration design. The idea here is to propose riverscape design scenarios that decrease flow velocity and increase water storage upstream (Bedford Rifle Range) to reduce peak discharge and flood risk downstream (Bedford Place Mall). The total spatial extent of both sites is 1.2 km^2, while the riverscape restoration site includes a spatial extent of 0.82 km^2.

LAZ files were converted to LAS Datasets in ArcGIS Pro and a continuous digital elevation model (DEM) was derived at a resolution of 1 m. The spatial reference projection was set (NAD_1983_UTM_Zone_20N) and the restoration site (Bedford Rifle Range) was extracted by mask and contour shapefiles were created at an interval of 0.5 m. Contours were exported to AutoCAD Civil 3D to provide elevation data for generating riverscape design scenarios by adjusting existing floodplain surfaces (e.g., proposed storage ponds) and importing 3D River Builder channels. The following section will describe our general workflow while subsequent sections will detail software procedures used for our methodology.

Figure 7. Aerial image of the Bedford Rifle Range in the Bedford Community of Halifax Regional Municipality (Google Earth, 2024).

3.2 A workflow for flexible riverscape planning

This study applied a methodology for riverscape planning and restoration decision-making in urbanized landscapes. We present a four-staged approach for designing, simulation, analyzing, and presenting synthetic 3D riverscape design scenarios to demonstrate a flexible approach suitable for several software applications. Figure 8 shows the general workflow, and the following sections will detail the stages of methodology applied here.

Stage 1 is the design phase (Fig. 8a). We generated three surface design scenarios by collecting real-world LiDAR data from a site in Nova Scotia and used River Builder software to derive a series of synthetic 3D river channels based on different design parameters. Continuous riverscape 3D surfaces were generated from contour lines in AutoCAD Civil 3D and exported as DEMs at a resolution of 0.5m. Conceptual planting designs were created for each riverscape scenario, where a mix of forest, shrub, and herbaceous planting were selected (see Section 3.3). A full list of suitable plant species was developed and provided in Supplement Material. Riverscape planting designs are a key for riverscape restoration and general planting layouts were used in our study to define variation in surface roughness by applying correlating Manning's roughness (n) coefficients for fluvial simulation inputs (see Table 1) and provided spatial planting forms for final design renderings.

Stage 2 is the fluvial simulation phase (Fig. 8b). Derived DEMs were applied as elevation data, and we used software packages BASEMENT and HEC-RAS to complete 2D fluvial simulations to generate flow velocity, water depth, water surface elevation, and flood inundation maps for scenario comparisons. QGIS was used to generate triangulated 2D meshes for BASEMENT setup command files while gridded 2D mesh were generated in RAS Mapper for flood inundation mapping in HEC-RAS software.

Stage 3 is the analysis phase (Fig 8c). A common objective for river design is to lower peak discharge for reducing the risk of more severe flooding events. Our riverscape design scenarios included strategic geometric differences in surface conditions to understand how designs may reduce mean flow velocity, increase surface water storage (volume), enhance geomorphic and hydraulic variation, and delay flood inundation time. We used QGIS for post-processing assessments of hydraulic conditions, including mean flow velocity and water storage differences determined by volume calculations for water surface rasters and velocity rasters. ArcGIS Pro was used to compare geomorphic variety values of input metric rasters including aspect, flow direction, and planform curvature, while hydraulic variety was computed form water depth rasters generated in BASEMENT. Finally, the 2D gridded mesh derived for HEC-RAS fluvial simulations was used to spatially compare point source flood inundation statistics at the downstream Bedford Place Mall.

This is a key stage for the decision-making process because it allows for strategic adjustments to the synthetic 3D riverscape surfaces (stage 1) and re-simulate derived channels with new surface conditions. Surface adjustments may include contour data manipulation in AutoCAD Civil 3D or adjustments to input parameters in River Builder scripts. Simulation parameters can also be adjusted in stage 2, allowing a flexible approach for processing and re-processing synthetic riverscape design scenarios through the decision-making process.

Finally, stage 4 is the presentation phase (Fig. 8d). Community acceptance of river restoration projects is particularly important for urban landscapes. Potential problems may arise when attempting to communicate riverscape designs with conventional drawings (e.g., plan, section, etc.) because the public are not often familiar with 2D drawing representations. Section drawings, for example, are largely limited to a single cross-section line determined by the designer, planning, or other professional, while a 3D representation or interactive animation may be more easily understood. Communicating statistical data may also be a challenge for communication because a statistical understanding of geomorphic or hydraulic conditions should not be assumed for the public. Providing multiple options for 3D surface and data presentation can enhance public acceptance, beyond a series of 2D drawings.

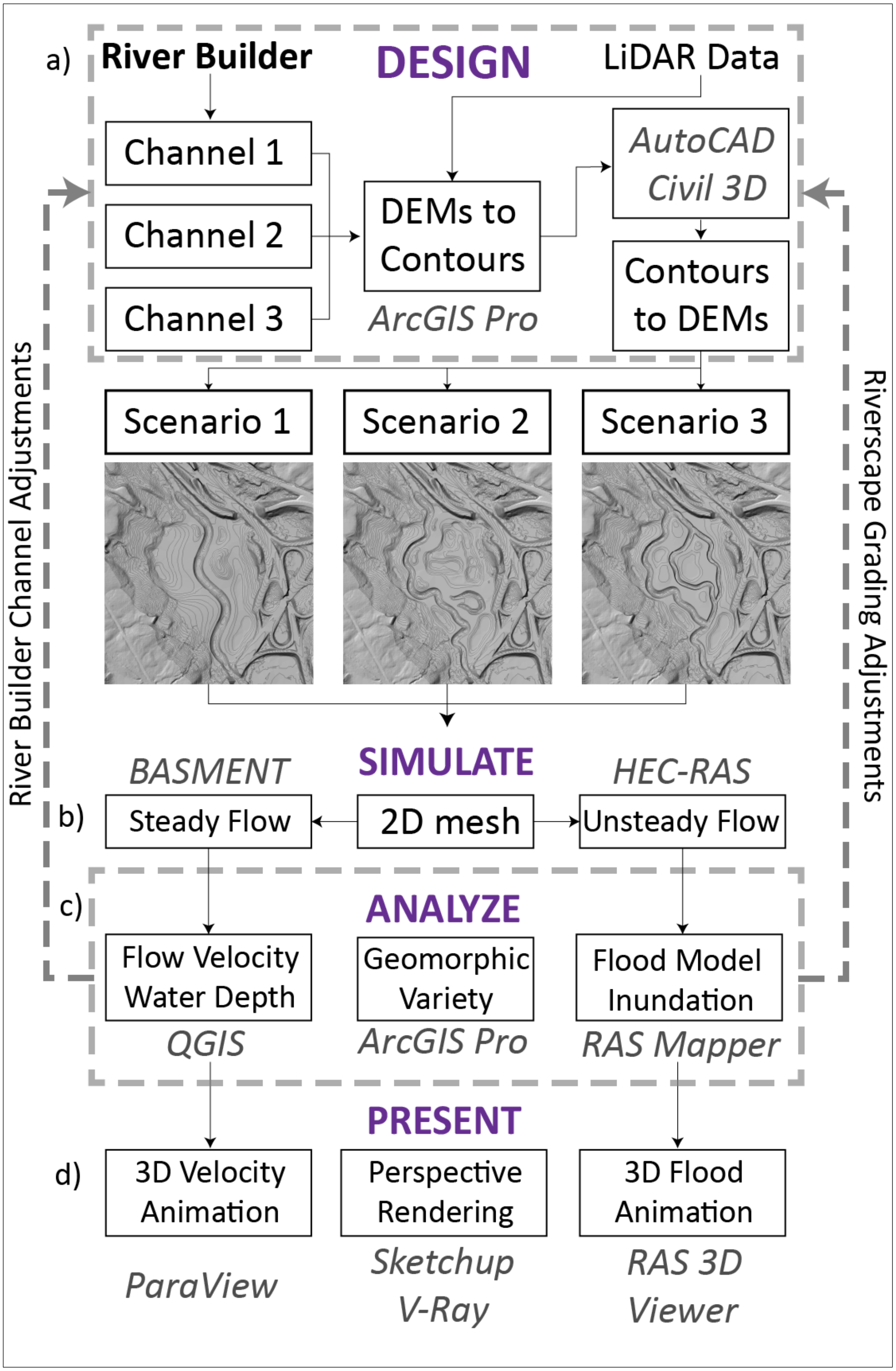

Figure 8. A workflow diagram showing the methodology for a) designing, b) simulating, c) analyzing, and d) presenting synthetic 3D riverscape design scenarios.

Our methodology allows for proposed designs and analytical animations to be presented in a 3D render or temporal animation for a broader understanding of key features, geometries, and hydraulic conditions. We present a series of examples for visually communicating different design data and analysis components that open opportunity for broader understanding of the decision-making process. ParaView was used to present a 3D render of flow velocity to illustrate velocity conditions, V-Ray and Generative AI (Photoshop) was used to present a rendered perspective from the human scale, while RAS 3D View was used to present a temporal animation of flood stages. This is all a move to advance beyond the conventional approach to landscape design in general and suggest the benefits of working on common 3D surface files throughout the process of initial to design to public communication.

3.3 Designing synthetic riverscapes with River Builder and AutoCAD Civil 3D

Three continuous riverscape design scenarios were created with contour elevation data in AutoCAD Civil 3D and exported as digital elevation models (DEMs) at a 0.5 m pixel resolution. Like Project 1, River Builder software was used to derive a series of synthetic 3D channels by applying different input parameters and user defined geometric equations. Once River Builder channels were created, point files were imported to ArcGIS Pro and converted to DEMs. Contour shapefiles were generated at an equivalent interval (0.5 m) and exported as CAD shapefiles files (.dwg). AutoCAD Civil 3D was used to stitch the synthetic channels into the existing reach topography, deriving a continuous 3D riverscape surface plane for each design scenario. The existing floodplain data was then adjusted for each scenario by proposing grading concept designs. Best management practices for floodplain features were designed in 3D surfaces, including ponds to increase water storage capacities and mounds to provide variation in topographic form and reduce net cut-and-fill volumes. Grading design scenarios were proposed as a conceptual approach to river restoration design and planning, where 3D digital surfaces may be compared, tested, and adjusted in the decision-making process. Three alternative riverscape design scenarios were generated to demonstrate different approaches to river restoration and general planting layouts (Figure 9). Hydraulic and geomorphic comparisons can then point to how these measures respond to different restoration approaches and quantify variables for design decision-making.

Riverscape scenario 1 (S1) was designed with a conventional Natural Channel Design (NCD) method, where a single-thread channel was widened, and planform pattern was of symmetrically broad meander bends to accommodate an increased flow regime. The floodplain surface included graded ponds and mound forms designed to divert surface flow away from adjacent highway infrastructure and increase water storage capacity (Fig. 9a). Mixed forest plantings were proposed largely around the boundary to contain flood waters, and these general objectives were consistent for each riverscape design, with the aim of reducing peak discharge downstream at the Bedford Place Mall site.

Riverscape scenario 2 (S2) was designed as an irregular single-thread channel pattern with variable widths and greater sinuosity compared to S1, attempting to reduce mean flow velocity. The floodplain grading design included mounds along inner bends and flat surfaces along outer bends, where flow velocity is fundamentally higher. Floodplain features also included an oxbow lake, positioned where the conceptual channel may have previously migrated and a proposed wetland to enhance water retention (Fig. 9b). The idea here was to design a floodplain that allows future channel migration with geomorphic processes responding to these forms (e.g., outer bend erosion) and allow channel migration for a more process-based approach to riverscape restoration.

Riverscape scenario 3 (S3) was the final surface generated for comparative analysis. The design included a multi-thread channel, where three separate River Builder channels were stitched to the surface data, including the main channel and two side channels of lower depths. The multi-thread planform pattern was designed to laterally spread flow to reduce mean velocity. The floodplain included similar pond features graded along the boundary of the site, while interior forms were flatter or gently sloped mounds (Fig. 9c). S3 was designed as an active floodplain, allowing future channel migration and is proposed as the most dynamic riverscape design of the dataset.

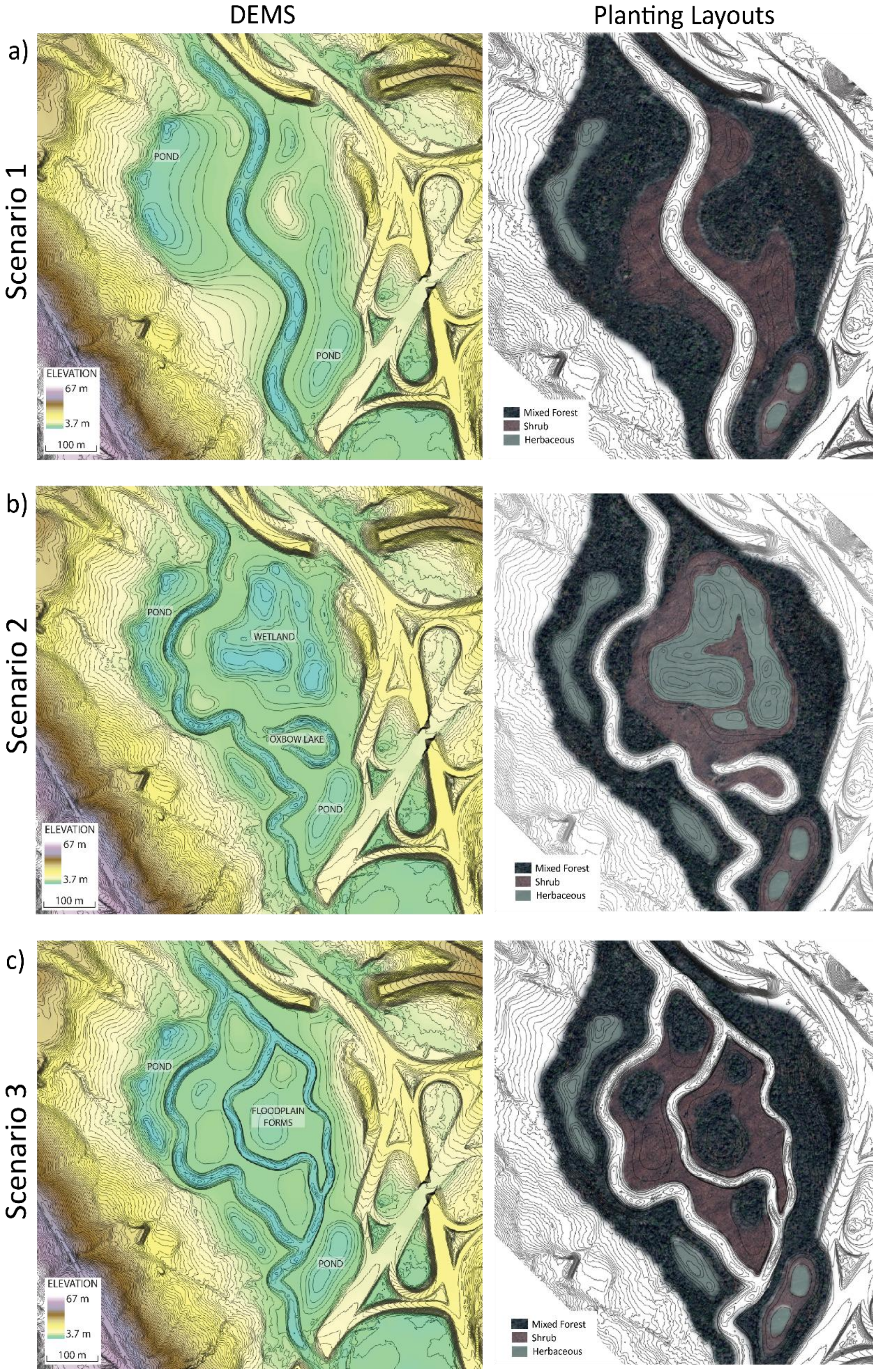

Figure 9. DEMs and planting layouts for riverscape design scenarios 1, 2, and 3.

Planting design is an important step for restoring riverscapes and enhancing habitats, while also providing surface roughness for controlling runoff and reduce flow velocities. We completed a planting design layout for each riverscape design scenario and applied corresponding Manning's roughness coefficients (n) for patches consisting of mixed forest (n = 0.12), shrub (n = 0.08), and herbaceous (n = 0.04) plantings (also see Table 1). These values defined land use classification polygons for fluvial simulations in BASEMENT and HEC-RAS modelling, providing different spatial friction inputs. Plantings were selected with reference to grading plans and keeping with the general aim of each design (e.g., NCD, wetland, multi-thread). Plant species lists for each design scenario are provided in Supplementary Material.

3.4 Simulating steady flow conditions with BASEMENT

BASEMENT software uses triangular 2D mesh and node IDs for processing fluvial simulations with a BASEmesh plugin included in QGIS. DEMs were imported to QGIS, and elevation data were used for interpolation of 2D meshing. Vector breaklines were generated along the riverbed, banks, and floodplain features including storage ponds, for example. We also generated breaklines boundaries for vegetative cover types proposed in riverscape planting designs (Fig. 9) to distinguish topographic and surface conditions for simulation processing. Region points were applied within each breakline boundary to specify maximum mesh areas and material IDs were defined to correlate with friction value inputs included for simulations. A quality mesh was generated for each case and the 2D mesh was derived from the quality mesh and DEM data. Vertices were then exported to retrieve mesh node IDs that define boundary conditions at the upstream and downstream channel cross sections.

A steady flow command prompt was used as the hydrograph input file. The discharge (Q) was set to 80 m^3/s and remained consistent for simulating each riverscape design scenario. Hydrograph data was sourced from Environment Canada, collecting data from a major flood event on July 21, 2023, and 80 m^3/s was selected because water levels surpassed the existing channel depth and indicated channel flow that overtopped bank elevations. The flow rate was estimated to simulate early flood conditions and Q can easily be adjusted to re-process different values in BASEMENT setup command files.

We used Manning's roughness coefficients (n) to define friction values for the riverbed, banks, floodplain features, and vegetative cover types. Coefficient values were greatest where dense forest plantings were proposed (n = 0.12), followed by shrub (n = 0.08), and herbaceous plants (n = 0.04). A coefficient of n = 0.05 was applied to meandering banks, while n = 0.035 was applied to riverbeds and set as the default fiction value in the setup command file. Additional setup command inputs are provided in Supplementary Information that derived the result files used for post-processing evaluation.

3.5 Assessing steady flow simulations and geomorphic variety

We exported flow velocity, water surface elevation (WSE), and water depth rasters from QGIS at a timestep of 25:00:00 and compared riverscape design conditions for each scenario. Velocity was spatially and statistically analyzed in ArcGIS to identify which scenarios showed the greatest and lowest mean velocity values, and how velocity responded to different geomorphic forms and floodplain features. DEMs were then subtracted from WSE rasters to calculate the water volume and hydraulic statistics were plotted to compare scenario conditions. The scenario showing the lowest mean flow velocity and greatest water storage volume suggests a riverscape design scenario most likely to decrease downstream peak flows (Bedford Place Mall), while an inverse relationship would suggest the least impact on discharge.

Water depth rasters were then analyzed in ArcGIS Pro, using the Focal Statistic type 'variety'. We applied the variety statistic to identify hydraulic and geomorphic complexity differences between riverscape design scenarios. Variety was also applied to additional raster input metrics including aspect, planform curvature, and flow direction. These metrics were applied to elevation data (DEMs) and may suggest designs more likely to provide habitat heterogeneity and geomorphic roughness, further reducing surface flow downstream.

3.6 Simulating unsteady flow and flood modelling with HEC-RAS

The full spatial extent, including the upstream and downstream sites (1.2 km^2), were simulated with a 2D unsteady flow simulation to model and analyze flood inundation patterns. We included a continuous DEM of the Bedford Rifle Range site and Bedford Place Mall site to investigate how peak discharge and flooding were responding to riverscape design scenarios upstream. We applied equivalent simulation inputs and applied the same approach described in Project 1 (see Sections 1.3 and 1.4), including the corresponding classification of vegetative cover types with polygon in RAS Mapper. Figure 10 shows the continuous DEM spatial extent applied (e.g., scenario 1), flood inundation map at first mall breach water level, and the 2D gridded mesh used for extracting hydraulic data.

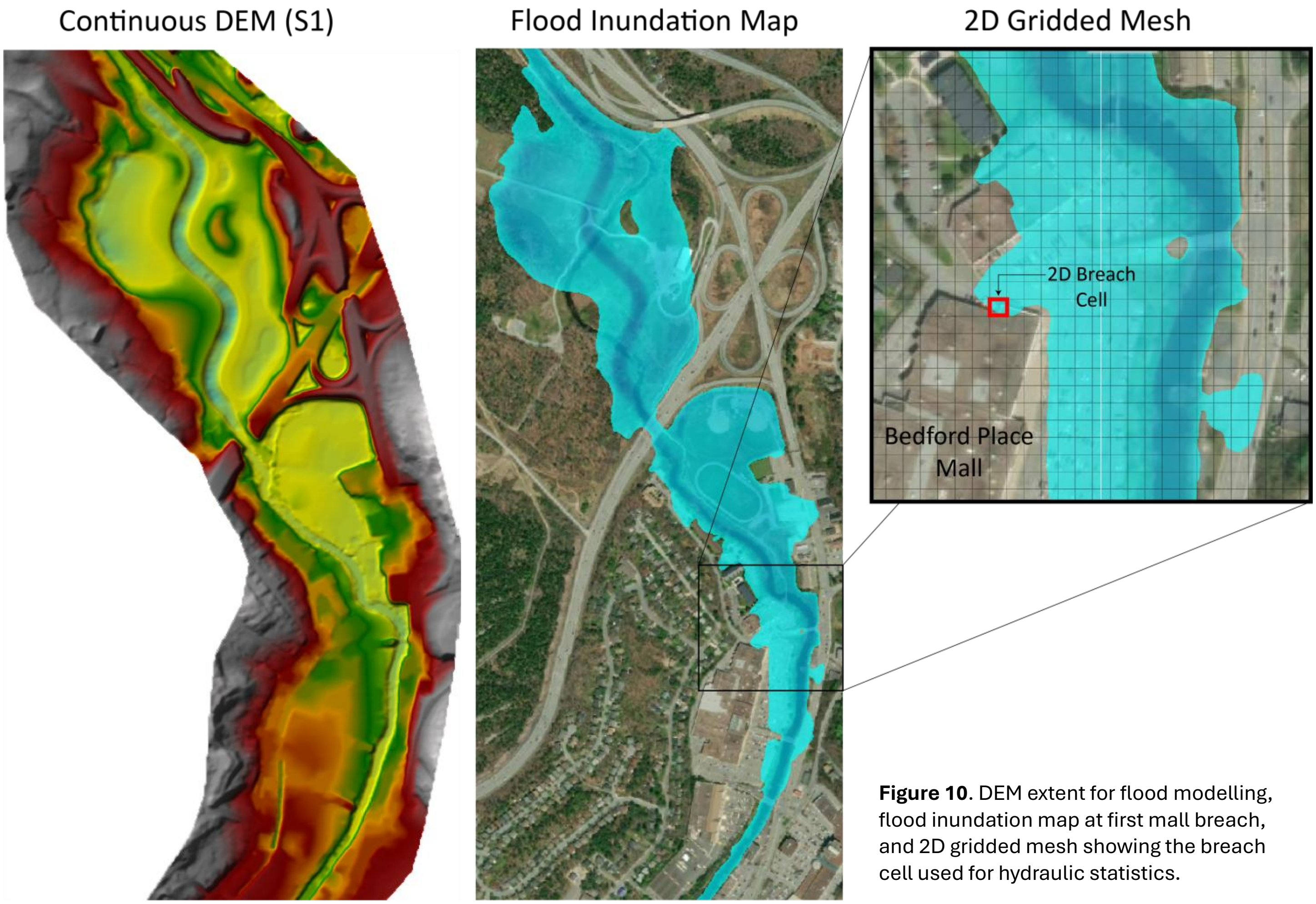

Figure 10. DEM extent for flood modelling, flood inundation map at first mall breach, and 2D gridded mesh showing the breach cell used for hydraulic statistics.

4.0 RESULTS

4.1 Comparing flow velocities and surface water volumes

We first investigated hydraulic responses to riverscape design scenarios by comparing flow velocity and surface water elevation (SWE) raters derived from fluvial simulations in BASEMENT. A main design objective was to generate synthetic 3D surfaces that reduced flow velocity and increased on-site water storage to decrease peak discharge downstream (Bedford Place Mall). Therefore, the scenario showing a low mean flow velocity and high water volume would define the preferred design option for reducing downstream flooding by slowing and retaining more water upstream. The scenario showing an inverse velocity-volume relationship would define the least preferred riverscape design option that is less likely to decrease peak discharge downstream.

Results showed scenario 2 (S2) responded with the lowest mean velocity value of 0.18 m/s and greatest water volume value of 873,205 m^3, identifying the irregular River Builder channel and wetland design as the preferred option for decreasing downstream flooding conditions (Figure 11). Scenario 3 (S3), the multi-thread channel design, showed a relatively similar relationship with the second lowest mean velocity value of 0.23 m/s and second highest water volume value of 816,583 m^3. Scenario 1 (S1) was designed with a conventional approach to river restoration, applying the Natural Channel Design (NCD) method for widening the channel with a single-thread of symmetrically broad meander bends. S1 was the least preferred design option, showing the highest mean velocity value of 0.75 m/s and lowest water volume value of 612, 742 m^3 (Fig. 11). Hydraulic conditions showed a proportional mean velocity and water volume difference of 76% and 30%, respectively, compared to the preferred design option of S2.

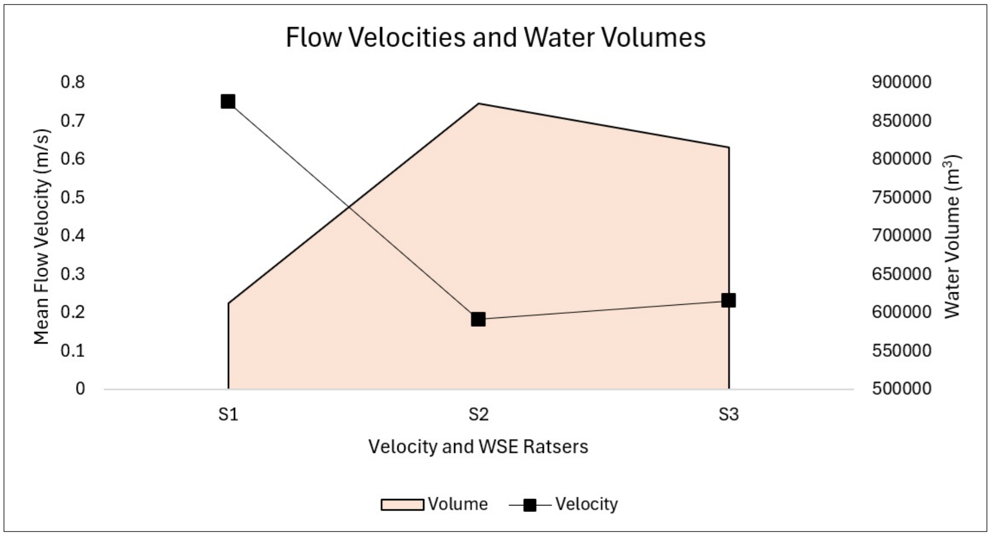

Figure 11. Plot showing mean velocity values and water volumes for each design scenario.

Hydraulic rasters were compared to understand our results and demonstrated different velocity cell patterns for each design scenario. S1 showed the highest velocity value at a downstream riverbed section near the final meander bend and pool form included in the simulation (Fig. 12a). Velocity cells largely remained within the channel boundaries, with some overtopping banks upstream form the highest velocity cells. Comparatively, S2 included showed velocity cells flowing into the proposed wetland and storage pond features (Fig. 12b), supporting our grading approach to retain flood water on-site rather. S3 (multi-thread channel) was proposed as the most dynamic of the dataset, encouraging channel migration with a more process-based approach to riverscape restoration. Rasters showed the greatest quantity of velocity cells flowing out of the channels and into the gently sloped interior floodplain features (Fig. 12c). While S2 was defined as the preferred design option, velocity rasters illustrated that hydraulic conditions were responding as intended for both S2 (wetland design) and S3 (multi-thread design).

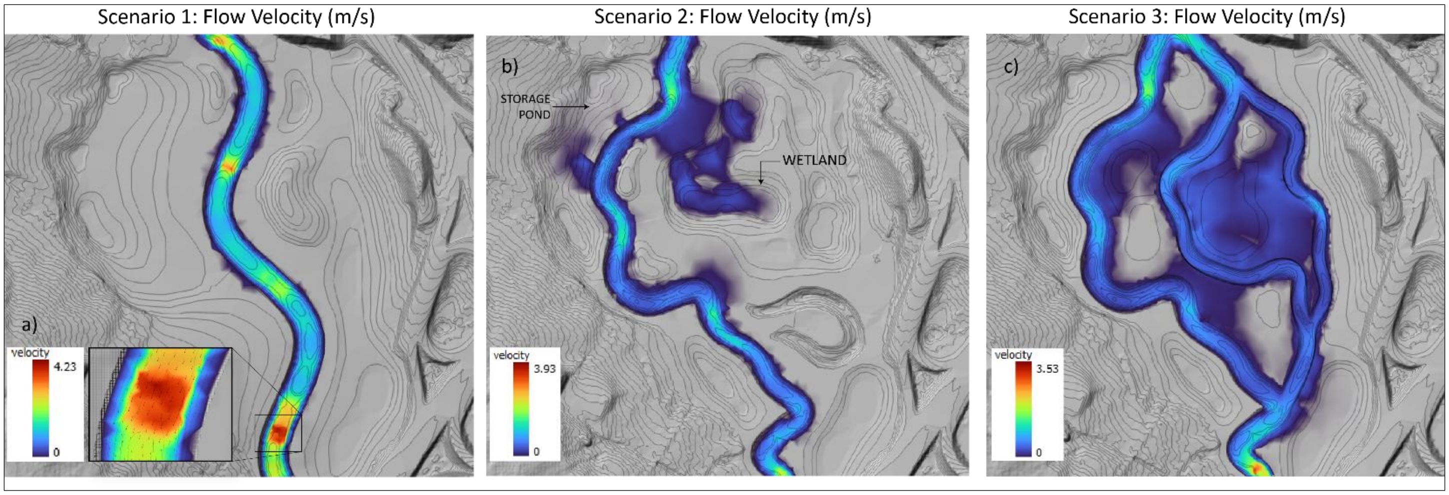

Figure 12. Velocity rasters showing cell distributions for a) scenario 1, b) scenario 2, and c) scenario 3.

4.2 Comparing hydraulic and geomorphic complexity

Hydraulic and geomorphic complexity are important measures for habitat heterogeneity and surface water management. Topographic diversity, and vegetation cover, allows for ecological microclimate development and contributes to surface roughness that reduces flow velocities, and increases water retention and infiltration. To investigate the hydraulic and geomorphic complexity of riverscape design scenarios, the Focal Statistic type 'Variety" was applied to water depth rasters derived through fluvial simulations in BASEMENT and surface-form metrics applied in ArcGIS Pro, including aspect, planform curvature, and flow direction.

S3 showed the greatest complexity for each raster metric applied, with a mean value of 3.9. S2 showed the second highest variety values with a mean value of 3.4, while S1 showed the lowest complexity for each raster metric with a mean variety value of 2.8 (Figure 13). Like velocity and volume findings (Fig. 11), the proportional value difference between S3 and S2 was relatively small (12%), compared to difference between the greatest (S3) and lowest (S1) mean values, showing a proportional difference of 29%. Of the analyzed rasters, water depth showed the greatest proportional variety value difference of 37%, followed by flow direction (36%), planform curvature (32%), and aspect (20%).

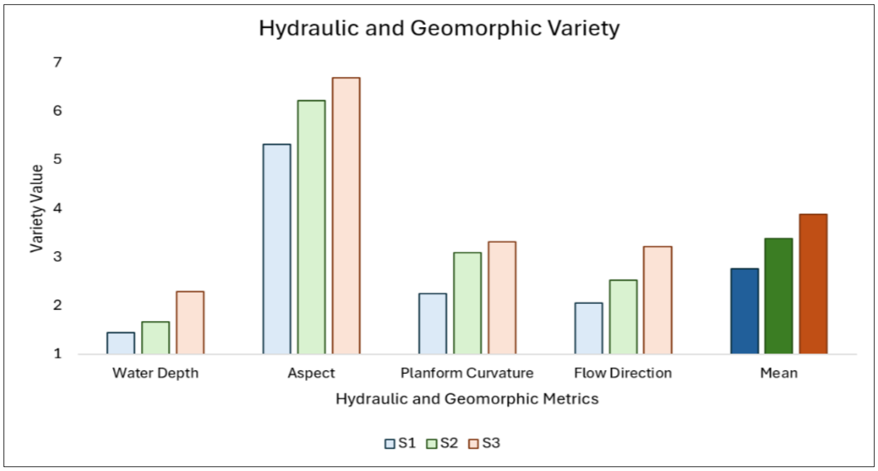

Figure 13. Bar graph showing variety values for each raster metric and mean variety values.

Water depth rasters were further investigated to understand spatial cell distributions for each riverscape design scenario. Water depth distributions were similar to velocity rasters (Fig. 12), where cells were largely contained within the channel in S1 while S2 and S3 showed cells flowing on to the floodplain features. Of the dataset, S1 showed the lowest maximum water depth of 3.37 while S3 showed the greatest water depth of 4.96 (Figure 14), suggesting a potential correlation between flood water overtopping banks and greater variety values resulting from floodplain grading designs (S2 and S3). This process-form linkage highlights the value of 'thinking outside the channel' for restoring rivers with process-based approach and can point to quantifiable measures for design decision-making methods with 3D riverscape surface models.

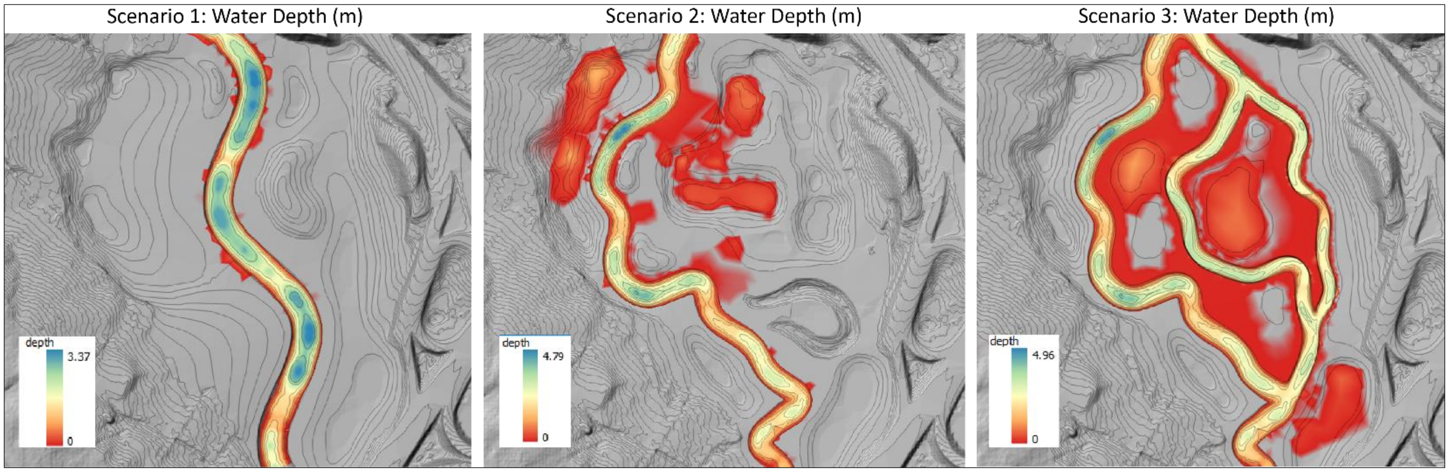

Figure 14. Water depth rasters showing cell distributions for each scenario simulated in BASEMENT software.

4.3 Comparing flood inundation patterns

Flood models were derived in HEC-RAS software and design scenarios were compared to evaluate how upstream restoration methods impacted downstream flood inundation. Water depth and simulation time were compared to determine the lag time of each scenario reaching the breach water level at the first saturated 'breach' cell in the 2D mesh (Fig. 10). Results show S1 was the first to breach the mall infrastructure at the downstream site at 11:05 (Figure 15). S3 was the second scenario to reach the flood breach water level with a lag time of ~ 20 minutes, while S2 showed a lag time of ~ 35 minutes. These findings support velocity and water volume raster comparisons derived from BASEMENT simulations, where S2 showed the lowest mean velocity and highest water volume (Fig. 12), correlating to a delayed peak discharge compared to S1 showing an inverse relationship.

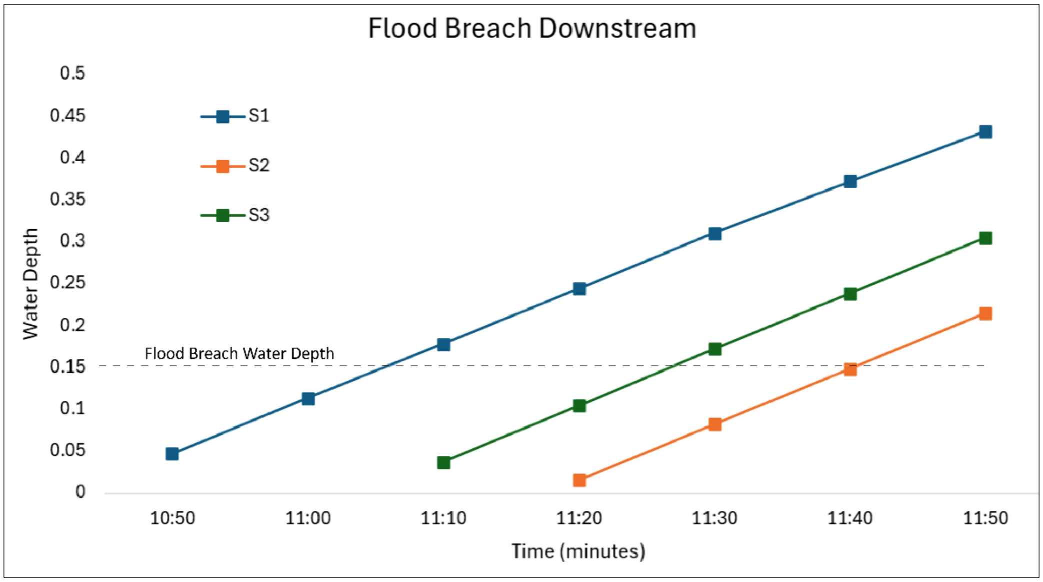

Figure 15. Line graph showing scenario water depths vs time for flood models derived in HEC-RAS.

4.4 Presenting riverscape design scenarios with V-Ray, ParaView, and RAS Mapper

Finally, here we present 3D model renderings and animations with a series of software applications to support design communication to professionals and the public. These presentation methods provide more visual data for general comprehension compared to conventional 2D drawings such as plans and sections. Sketchup and V-Ray were used to render two perspectives of S1 from a human perspective, while Generative AI tools were used for additional plant types in Photoshop (Fig. 16a). ParaView was used to animate a series of perspectives showing flow velocity data on a 3D model for S2 (Fig. 16b), while RAS Mapper was used to animate 3D flood inundation patterns for S3 (Fig. 16c). These is all a move to increase the efficiency of multidisciplinary collaboration through the planning phase of landscape design and allow more comprehensive approaches for presenting and adjusting continuous synthetic surfaces.

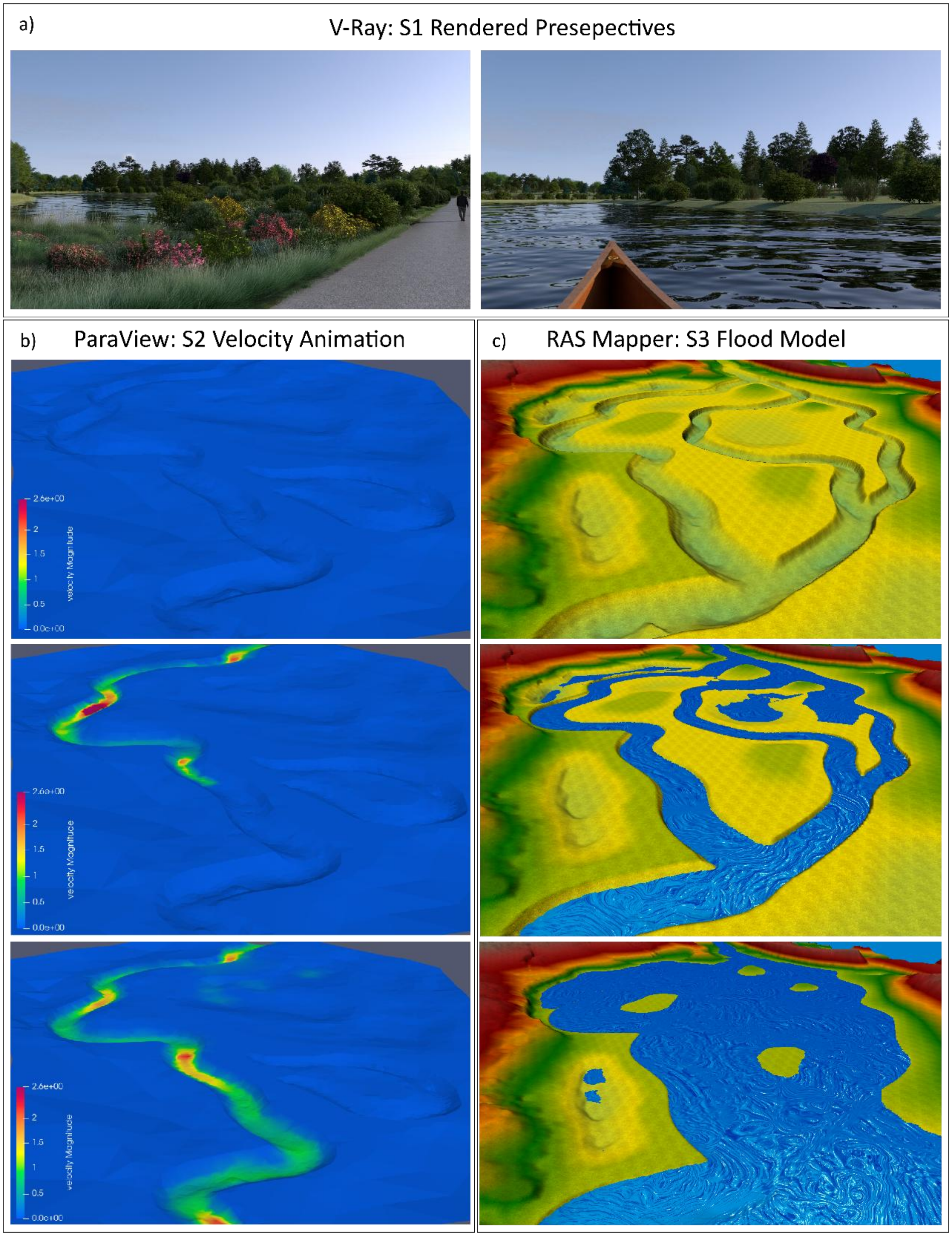

Figure 16. 3D models showing a) rendered perspective, b) velocity animation, and c) flood animation.

CONCLUSION: Project 1 and 2

This study presents a new approach for integrating geomorphic principles into green infrastructure and river restoration design by generating synthetic channels for multidisciplinary collaboration. By deriving different channel geometries with River Builder design functions and vegetative covers, a new methodology was presented for evaluating hydraulic, geomorphic, and flood mitigation strategies with 3D channel design scenarios to offer an interactive planning strategy for sustainable surface water management. Project 1 findings highlighted how planform irregularity, width variability, cross-sectional asymmetry, in-channel forms, and vegetative cover roughness can delay flood inundation and reduce flow velocities. Project 2 suggests that conventional Natural Channel Design methods may not be the optimal approach for river restoration. Findings showed that irregular channel planforms, wetlands, storage ponds, and multi-thread channel approach may lend to superior hydraulic and geomorphic conditions, while reducing or delaying flooding at downstream urbanized landscapes.

This approach offers a flexible process-based framework that allows landscape architects, engineers, ecologists, and planners to visualize, communicate, and adjust designs interactively, emphasizing the role of synthetic 3D models as decision-making tools for complementing climate-adaptive green infrastructure. By embracing these innovative tools and applying additional site-specific metrics, urbanized riverscape designers can better address the challenges of climate change and evolving flow regimes, ultimately contributing to more sustainable urban ecosystems and social acceptance. While further research is needed to customize the general methodology for real-world applications, the combination of River Builder software and LiDAR data offers a potential component for advancing nature-based solutions to stormwater management in urbanized riverscapes.