HYDROLOGY AND HYDRAULICS OF URBAN FLOODPLAINS

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Abstract. Urban waterways often suffer from a particular form of structural and ecological degradation resulting from urbanization and associated land use changes. Impervious surfaces such as roads and rooftops direct runoff into stream channels, generating powerful flood waves that pose threats to infrastructure, property, and valuable ecosystem services (Leopold, 1968; Walsh *et al.*, 2005). Stormwater mitigation and stream restoration may help protect urban stream integrity, but the relative effectiveness of these measures is still not well understood. While stormwater mitigation typically focuses on controlling the velocity and intensity of runoff at the watershed scale, stream restoration involves direct morphological interventions to improve channel stability and slow further degradation.

In this study, a two dimensional hydraulic model was developed for a portion of the Minebank Run watershed in Baltimore County, Maryland, to characterize the sensitivity of flood wave properties to geomorphic changes within the channel simulating restoration techniques. Several restoration projects have been carried out along much of Minebank Run between 1999 and 2013 primarily concerned with improving geomorphic stability and reconnecting a deeply incised channel to the floodplain (Doheny *et al.,* 2012). Two alternative versions of channel-floodplain terrain, one representing the channel topography in 2015 and one representing an altered terrain with a raised channel bed, were created using the two dimensional hydraulic modeling HEC-RAS 5.0 software developed by the U.S. Army Corps of Engineers. Five different flood hydrographs, representing a range of peak flow magnitudes, were extracted from the U.S. Geological Survey (USGS) Minebank Run stream gage record and routed through each terrain model. Comparisons of maximum water surface elevation time series and dynamic floodplain inundation mapping between terrains indicated such a restoration effort could significantly increase local overbank flow and floodplain inundation, particularly for high flow events, and thus may be an effective approach for achieving channel reconnection with the floodplain. Effects on maximum water velocity may be variable along the reach and dependent upon the size of flow, extent of floodplain inundation, and vegetation in the floodplain. When comparing flow patterns for different channel terrains at the same discharge, areas experiencing increased overbank flow following channel alteration also achieved lower maximum water velocity in the channel than that achieved in the unaltered channel for the same discharge. Overall, observed changes in flood wave properties tended to be local changes, with minimal effect on reaches downstream of the channel alteration.

Future research may build upon the modeling techniques developed in this study to simulate the response of urban streams to various geomorphic channel alternations, including restoration projects, channel degradation, or failure of restoration structures. Ultimately, comparison of the relative impact of physical channel restoration with complementary watershed-scale controls on runoff volume may better inform sustainable stream restoration and flood mitigation design.

INTRODUCTION

Urbanization and associated land use changes impact local hydrology in a variety of ways. The most common effects include changes in peak flow characteristics, changes in total runoff, water quality degradation and altered stream channel morphology. Generally, as urban development increases impervious cover and connects impervious surfaces to waterways with hydraulically-efficient stormwater drainage systems, precipitation is intercepted and swiftly transported to channels and streams. Water thus runs off the urban landscape rather than infiltrating soil and groundwater, contributing to both lower base flows and much higher peak flows (Leopold, 1968; Walsh *et al.*, 2005). Stormwater runoff often carries nutrients and pollutants from the urban landscape that degrade water quality (Leopold, 1968; Walsh *et al.*, 2005; Mayer *et al.*, 2003) and the high peak flows exert shear stress on stream banks, causing long-term channel widening and incision, scouring and bank failure (Hammer, 1972; Booth, 1990; Doheny *et al.*, 2012).

The hydrologic and morphologic effects of urbanization threaten the sustainability of urban water networks. High peak flows endanger infrastructure and property (Walsh *et al.*, 2005; Doheny *et al.*, 2012) and decrease the aesthetic and recreational quality of streams and water bodies (Leopold, 1968). Sediments and pollutants carried by runoff and flood waves degrade water quality by several measures, including turbidity, nitrate and phosphate concentrations, and dissolved oxygen (Leopold, 1968; Walsh *et al.*, 2005). Valuable ecosystem services, such as microbial denitrification and removal of pathogenic bacteria by riparian soils, are impaired by altered hydrology and floodplain ecology (Leopold, 1968; Mayer *et al.*, 2003).

The severity of consequences from urban stream degradation requires effective, sustainable solutions to both repair damaged systems and prevent further impairment. Stormwater mitigation and stream restoration will be important components of sustainable urban design, but the relative impact of such measures is still not fully understood. Stormwater mitigation typically addresses watershed-scale constraints on stream hydrology and ecology, including total catchment imperviousness and connection of impervious surfaces to streams via stormwater pipes (Walsh, Fletcher & Ladson, 2005). Stream restoration, in contrast, focuses on reach-scale constraints on stream hydrology and ecology, including channel shape and geomorphic stability, riffle-pool sequences, and channel connection to riparian vegetation (Doheny *et al.*, 2006). Novel hydraulic modeling techniques for assessing the relative sensitivity of urban waterways to different types of intervention will be critical in evaluating the impact of morphological interventions designing effective solutions for urban stream degradation.

In this study, a two dimensional hydraulic model was developed for a portion of the Minebank Run watershed in Baltimore County, Maryland, to characterize the sensitivity of flood wave properties to geomorphic changes within the channel simulating restoration efforts. Since the early 1990s, several Maryland streams have been physically restored to improve geomorphic stability and combat erosion (Doheny *et al.*, 2006). From 1999 to 2005 Minebank Run, a small tributary to the Gunpowder River in the Chesapeake Bay watershed, was the focus of a four million dollar restoration effort carried out in two phases by the Baltimore County Department of Environmental Protection and Resource Management (Lutz, 2006). The project was monitored both before and after restoration by the U.S. Geological Survey (USGS), Cary Institute of Ecosystem Studies (CIES), and U.S. Environmental Protection Agency (USEPA) for changes in hydrology, ecology, and various measures of water quality. In addition to channel stabilization and revegetation of riparian zones, efforts were made to reconnect the channel to the floodplain and increase overbank flow in several sections of the reach (Doheny *et al.*, 2012). This study made use of sophisticated two-dimensional hydraulic modeling to examine the effect of such efforts on flood wave behavior under equivalent upstream discharge conditions.

METHODS

Modeling was performed in the two dimensional version of the Hydraulic Engineering Center River Analysis System (HEC-RAS) 5.0 software. Topographic information derived from a high-resolution light detection and ranging (LiDAR) 2015 dataset was used to create a digital elevation model (DEM) of a portion of Minebank Run draining an approximately 80% urban area, which was restored in 2005 as part of the second phase of restoration projects in the watershed. Flow data were extracted for five different flood events representing a range of peak flows collected by a USGS stream gage at the upstream end of the study reach. These flows were then routed through the terrain and detailed hydraulic information for a series of time steps was computed to generate flow and stage hydrographs, time series of water surface elevation and two-dimensional depth-averaged velocity, maximum water surface profiles at specified cross sections, and dynamic inundation mapping of the floodplain to characterize the flood wave. Specific channel-floodplain terrain properties in the model were then altered to simulate stream restoration efforts and subjected to the same flow conditions. By measuring the resulting flood wave response, the relative sensitivity of flood wave characteristics to restoration techniques was assessed. For this paper, channel terrain was altered to simulate the effect of raising the channel bed by approximately two feet along a continuous stretch of the reach, a potential restoration technique to combat channel incision or promote channel-floodplain reconnection. Flood wave properties for identical flow inputs in the 2015 terrain and altered terrain were compared to assess what, if any, impacts on flood wave behavior could be expected from such a restoration technique.

Description of Study Area

This study developed a model for a portion of the Minebank Run watershed in Baltimore County, northeast of Baltimore City. The 3.27 square mile watershed lies approximately 4.7 miles northwest of the Piedmont Physiographic Province Fall Line (see **Figure 1**), with headwaters in eastern Townson, Maryland, flowing northeast and draining into Gunpowder Falls, 0.3 miles downstream of the lower dam on Loch Raven Reservoir, as shown in **Figure 2** (Doheny *et al*, 2012).

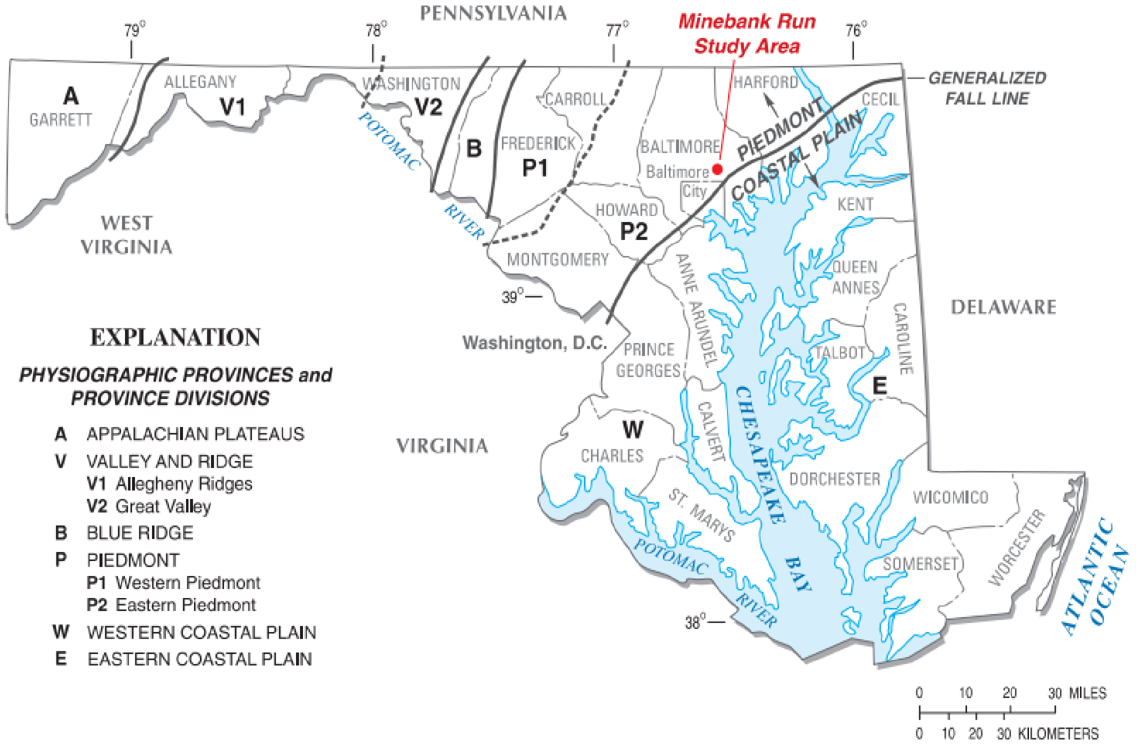

FIGURE 1. Map showing physiographic location of Minebank Run in Baltimore County, Maryland. Image courtesy of U.S. Geological Survey Scientific Investigations Report 2012-5012.

The portion of the channel upstream of the Baltimore Beltway (I-695), draining a 0.80 square mile catchment area, was the focus of the first phase of restoration efforts in 1998 and 1999. The lower portion, draining a 2.47 square mile catchment, was restored in the second phase from 2004 to 2005. Rock weirs were selectively placed to create riffle and pool sequences and control sediment supply, floodplains were created to diffuse flood flows, channel bank slopes were decreased in areas and connected to revegetated riparian areas. In selected areas, banks were hardened with riprap rock walls to protect sewer infrastructure and sinuosity was controlled throughout the restored reach to prevent lateral bank erosion (Doheny *et al*., 2012) See **Figure 2** below for a map of the watershed and study reach.

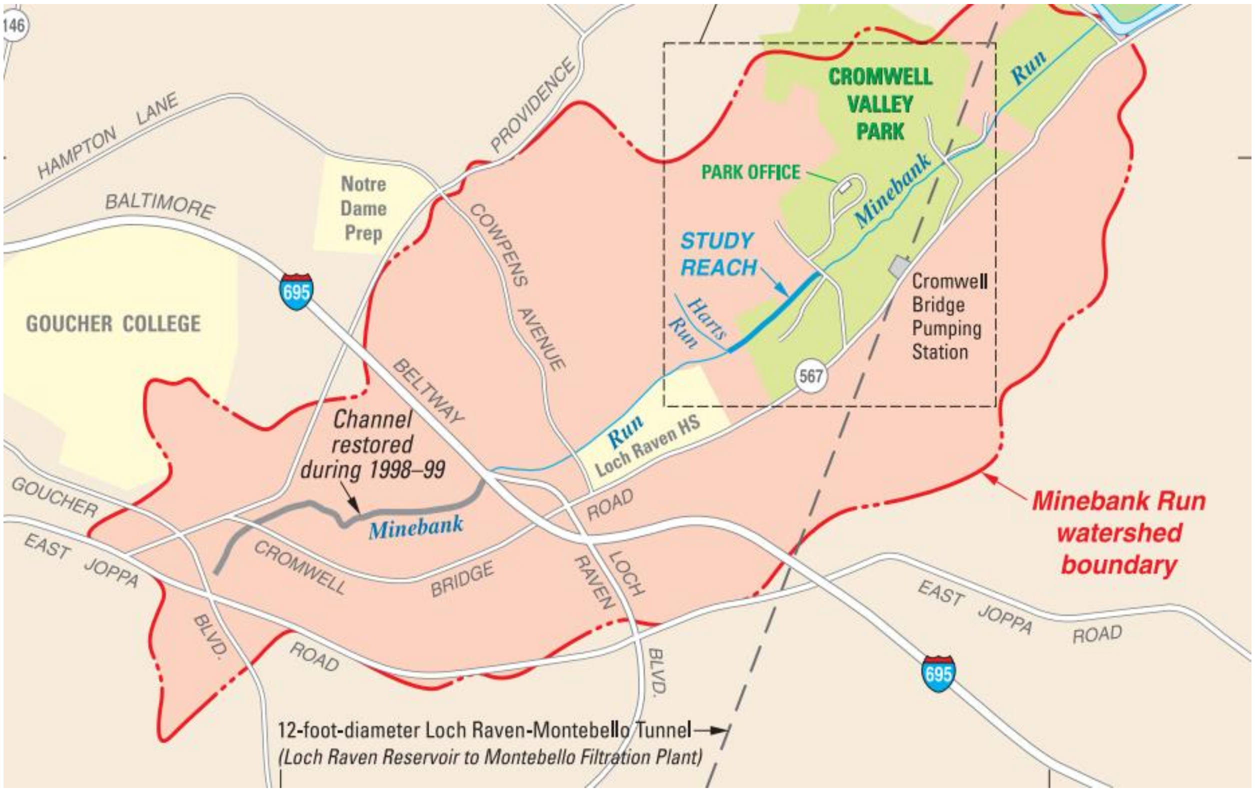

FIGURE 2. Map of Minebank Run watershed and study reach. Image courtesy of U.S. Geological Survey Scientific Investigations Report 2012-5012.

The reach of Minebank Run captured by this study is contained in the lower portion of the watershed restored in 2004-05. Land use in the region is approximately 80.6 percent urban and 16.9 percent forested or open space, with the largest percentages of urban land use and impervious cover located in the headwaters of the watershed. Prior to restoration, much of the channel was incised and over-widened, with steep bank slopes and several large meanders corresponding to unstable banks and a mobile channel bed. Within this particular reach the channel bed was reconstructed with gravel and small cobbles, riprap walls and rock weirs were placed in sections, and the channel was redirected in two locations to control sinuosity and the original channel was left in place as an overflow channel and oxbow wetland, (Doheny *et al*., 2012).

FIGURE 3. Pre-restoration photograph of Minebank Run (2003). View looking upstream from the confluence with the Harts Run tributary at the upstream end of the study reach. Image courtesy of U.S. Geological Survey Scientific Investigations Report 2012-5012.

FIGURE 4. Restored section of Minebank Run (2005). View looking upstream from the confluence with the Harts Run tributary at the upstream end of the study reach with the original channel visible in the background. Image courtesy of U.S. Geological Survey Scientific Investigations Report 2012-5012.

Since October 2001 a continuous-record streamgage (USGS station number 0158397967, Minebank Run near Glen Arm, Maryland) has provided five-minute, unit-value stage and discharge data (Doheny *et al.*, 2012). The gage datum is 216.12 feet above the North American Vertical Datum of 1998 and was relocated 190 feet upstream, at the same gage datum, following a large storm on August 14, 2015 (*USGS NWIS,* 2016).

Methods

A two dimensional hydraulic model of the described portion of Minebank Run was created using the Hydraulic Engineering Center River Analysis System (HEC-RAS) 5.0 software, developed by the U.S. Army Corps of Engineers. HEC-RAS 5.0 is publicly available and is capable of performing a variety of river analysis computations and simulations, including steady flow surface water profile computations, one-dimensional and two-dimensional unsteady flow simulations and water quality analyses for subcritical, supercritical or mixed-flow regimes (Brunner, 2016). A high-resolution light detection and ranging (LiDAR) topographic point cloud collected for Baltimore County in 2015 was interpolated in ArcGIS and transferred to HEC-RAS to create a digital terrain model of the study reach. Several sections of the channel within the study reach were lacking adequate LiDAR coverage in the 2015 dataset, causing the software to interpolate between topographic points on the stream banks and create barriers to flow within the channel. To address this, cross-sectional terrain information was extracted from the 2015 LiDAR dataset and an overlapping 2005 LiDAR dataset. In regions lacking 2015 LiDAR data, topographic information from the 2005 LiDAR dataset was substituted, provided aerial photograph comparison indicated the channel had not changed significantly at that location between the two data collection periods. The improved cross sections were then used to interpolate a new channel terrain which was combined with the original overbank terrain model from the 2015 LiDAR dataset in HEC-RAS.

An alternative version of the study reach terrain was then created by manually altering cross-sectional terrain information from the 2015 model in HEC-RAS to raise the main channel bed elevation approximately two feet along a 1570-foot stretch of the study reach, extending from the upstream boundary of the reach to Sherwood Bridge. A new channel terrain encompassing the full study reach was then interpolated from the altered cross-sectional information and combined with the 2015 overbank terrain model in HEC-RAS. Land use regions were defined in ArcGIS from 2014 aerial photographs and Manning’s n roughness coefficients were estimated from land cover type, vegetation density, degree of inundation for relevant flood sizes, and channel bed grain size distribution data collected for several cross sections within the reach (Doheny *et al.*, 2012) using guidelines from the U.S. Department of Transportation *Guide for Selecting Manning’s Roughness Coefficients for Natural Channels and Flood Plains* (1984).

Five flood events identified in the USGS Minebank Run stream gage record, representing a range of flows from approximately 237 cubic feet per second (cfs) to 1310 cfs, were routed through each terrain model in HEC-RAS. Discharge hydrographs collected for storms on August 13, 2011 (peak discharge of 1060 cfs), June 1, 2012 (1310 cfs), June 10, 2013 (1170 cfs), August 7, 2013 (689 cfs) and April 28, 2014 (237 cfs), were used to define upstream boundary conditions. Normal depth was used to define downstream boundary conditions, assuming an average channel slope of one percent along the reach from USGS post-restoration monitoring (Doheny *et al.,* 2012). Hydraulic information was then computed in HEC-RAS in one-second computational time intervals and detailed hydraulic outputs were generated in five-second time intervals. Four key cross sections were identified for data comparison: an upstream station approximately marking the location of the stream gage before August 14, 2015 (river station 3218.115), a station intersecting the downstream overflow channel and oxbow wetland left by the restoration (river station 2540.912), a station directly upstream of Sherwood Bridge (river station 2036.928) and a station at the downstream end of the reach (river station 529.5025). For each identified cross section, time series of water surface elevation and two-dimensional depth-averaged velocity, maximum surface water profiles, and maximum velocity profiles were extracted. Stage and flow hydrographs were also extracted from an upstream cross section, a cross section directly upstream of the Sherwood Bridge (approximately the middle of the study reach) and a cross section at the downstream end.

RESULTS

Visual representations of flood wave behavior and floodplain inundation for qualitative comparison between terrains were generated with HEC-RAS dynamic mapping of water surface elevation and two-dimensional depth-averaged velocity along the reach, computed in one-second time intervals. Images of maximum inundation and velocity for the 1170 cfs flow event are displayed for the 2015 terrain (**Figure 5**) and the altered terrain (**Figure 6**) below.

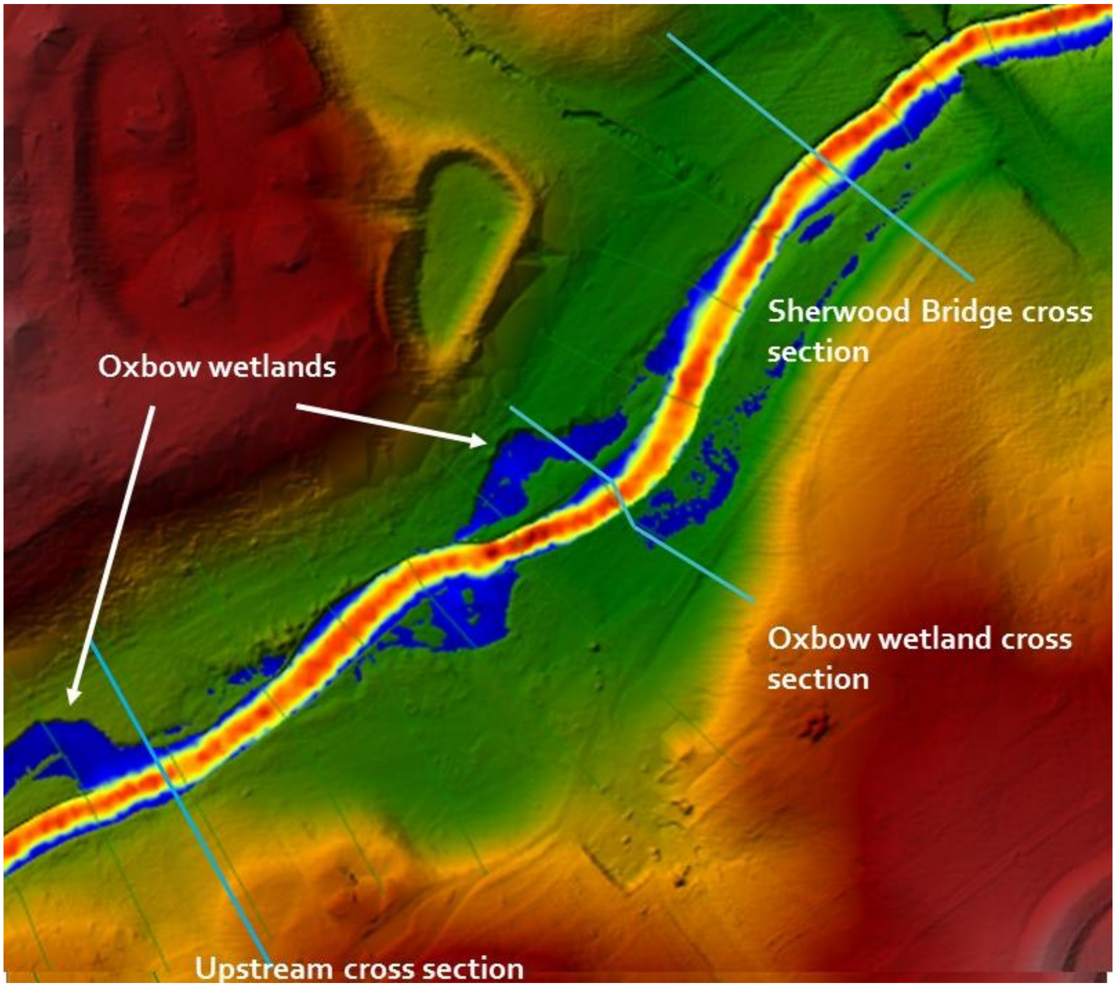

FIGURE 5. Maximum stage and velocity for an 1170 cfs flood event in the 2015 terrain model. Maximum stage and velocity display from HEC-RAS dynamic mapping of an 1170 cfs peak flow flood event in the 2015 terrain model of Minebank Run upstream of the Sherwood Bridge. Inundation mapping generated from two dimensional unsteady flow analysis in HEC-RAS 5.0. Color-coded velocity scale increases from dark blue to dark red.

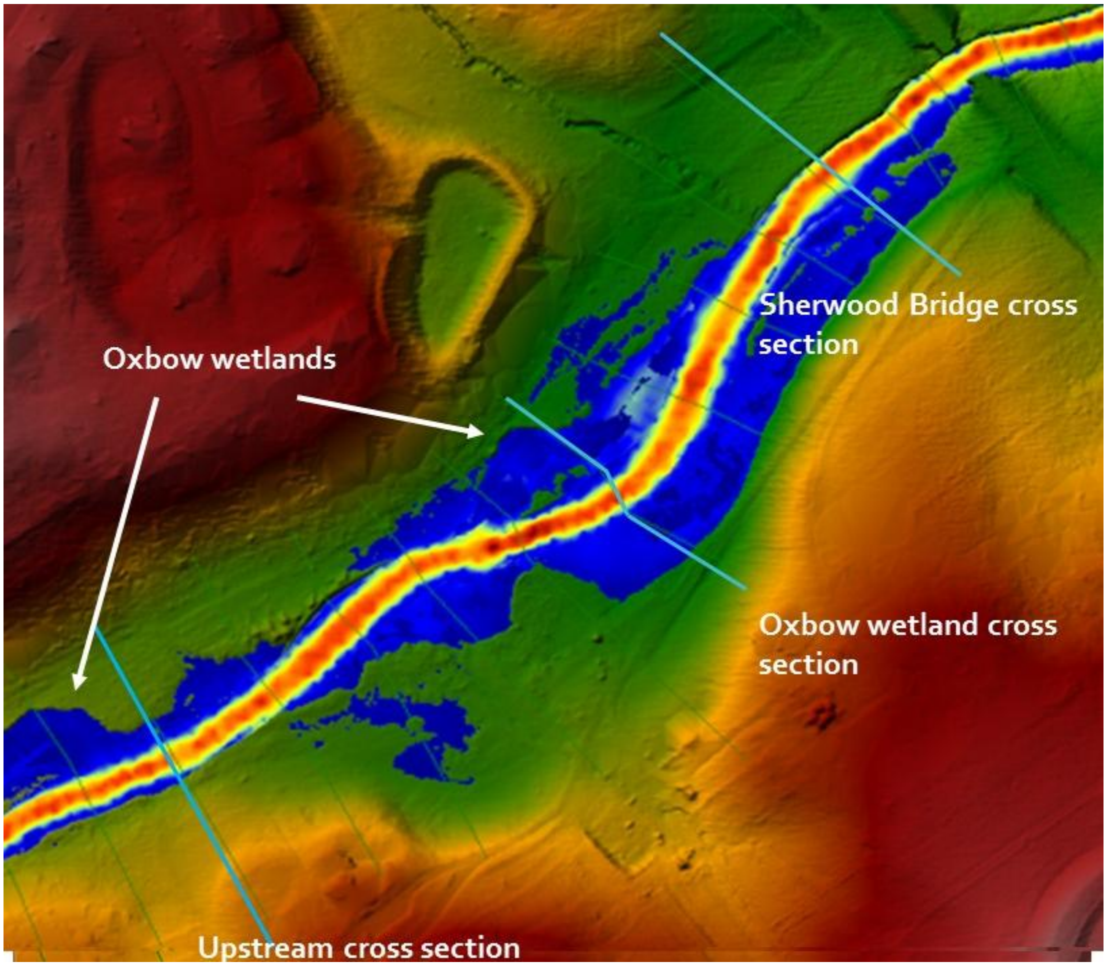

FIGURE 6. Maximum stage and velocity for an 1170 cfs flood event in the altered terrain model. Maximum stage and velocity snapshot from HEC-RAS dynamic mapping of an 1170 cfs peak flow flood event in the altered terrain model of Minebank Run upstream of the Sherwood Bridge (see the Methods section for description of terrain alteration). Inundation mapping generated from two dimensional unsteady flow analysis in HEC-RAS 5.0. Color-coded velocity scale increases from dark blue to dark red.

Comparison of **Figure 5** and **Figure 6** indicates degree of floodplain inundation at maximum stage was notably increased in the altered region of terrain upstream of Sherwood Bridge. In **Figure 5** it appears overbank flow in the 2015 terrain model was mostly confined to the oxbow wetland channels, remnants of the pre-restoration channel intended to capture stream overflow. In contrast, **Figure 6** suggests the pattern of floodplain inundation at maximum stage differed markedly in the altered terrain for the same flood event, extending farther beyond the channel boundaries and more completely flooding the vegetated areas surrounding the oxbow channels, although the highest water velocities were still concentrated in the main channel (regions of red and orange in both figures). **Figure 7** provides another demonstration of the difference in pattern of floodplain inundation for the two terrain models, illustrating the profile plot of maximum water surface elevation at river station 2540.912, the oxbow wetland cross section in **Figures 5 & 6**, for each terrain.

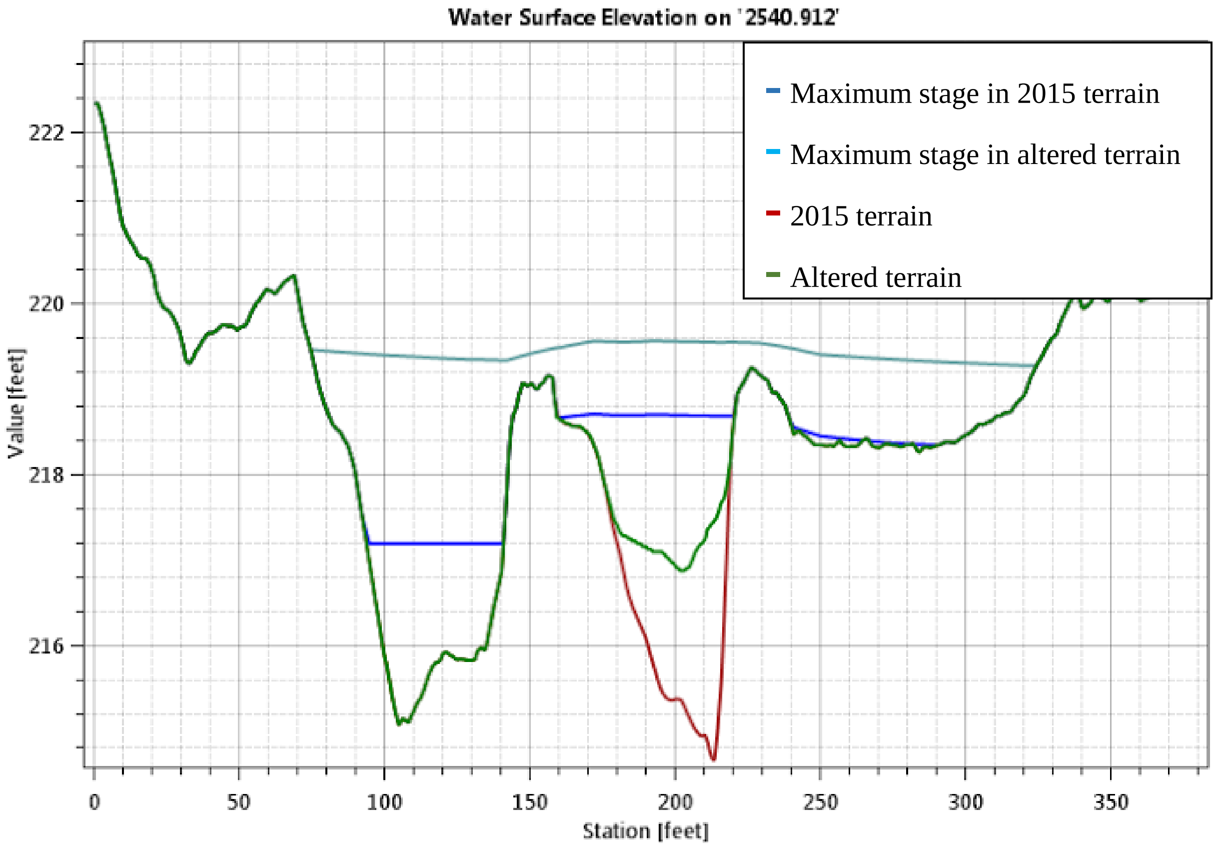

FIGURE 7. Maximum water surface elevation for an 1170 cfs flood event in the 2015 and altered terrain models at river station 2540.912. Maximum water surface elevation profiles for both the 2015 and altered terrain models as well as topographic profiles of the 2015 terrain and altered terrain plotted as elevation above the North American Vertical Datum of 1988 on the vertical axis and distance from the left extent of cross section 2540.912 facing downstream. Note the terrain models differ only in channel bed minimum elevation, approximately between cross sectional station markers 180 and 220. The left channel, located approximately between cross sectional station markers 80 and 150, is the remnant of the pre-restoration channel, left by the restoration project as one of three overflow oxbow wetlands. Plots generated in RAS Mapper, a feature of HEC-RAS 5.0 software.

Detailed water surface elevation and two-dimensional depth-averaged velocity time series, computed in five-second intervals, were collected from four select river stations along the reach. River stations were identified by distance, in feet, upstream of the downstream boundary of the study reach. Station 3218.115 is located at the upstream end of the study reach, station 2540.912 is located at the downstream oxbow wetland, station 2036.928 is located immediately upstream of the Sherwood Bridge at the boundary of terrain alteration, and station 529.5025 is in the downstream portion of the reach and was not directly altered by the terrain adjustment. From the time series, maximum water surface elevation and velocity for each terrain in each flow scenario were extracted, and maximum water depth was calculated as the difference between maximum water surface elevation and minimum channel bed elevation at a given river station in the appropriate terrain model to account for differences in channel bed elevation between terrain models. Differences in maximum water surface elevation, water velocity, and water depth at each river station between the 2015 terrain and altered terrain are shown in **Figures 8, 9 and 10** below.

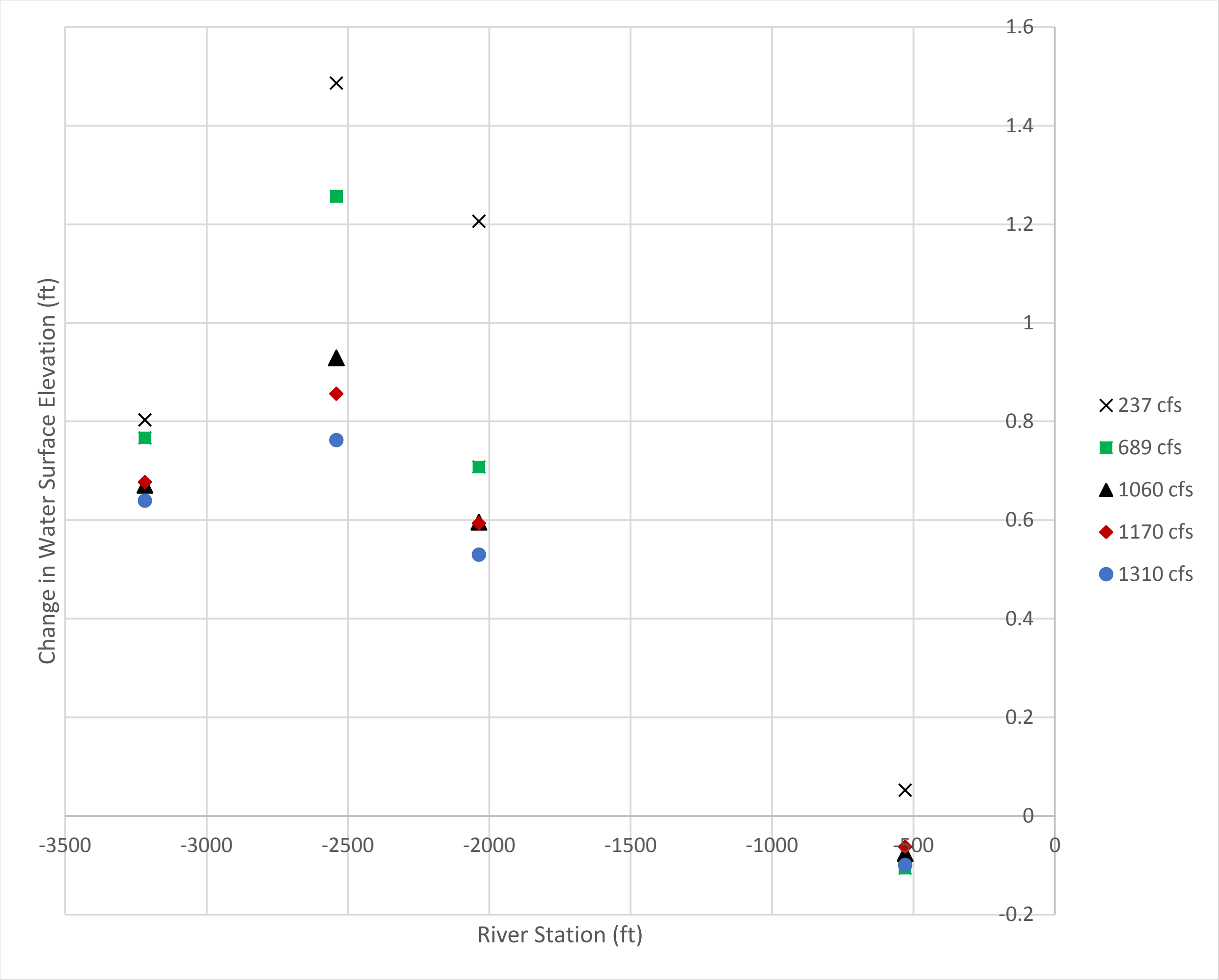

FIGURE 8. Difference in maximum water surface elevation at select river stations following terrain alteration for identical flow events. River station identification is defined as distance, in feet, from the downstream boundary of the study reach. Note in this figure river station has been defined in the negative so the upstream boundary is on the left of the figure and the downstream boundary on the right. Change in water surface elevation (WSE) was calculated by subtracting maximum WSE in the main channel of the 2015 terrain from maximum WSE in the main channel of the altered terrain; thus a negative change in WSE indicates a water elevation decrease at that river station following terrain alteration and a positive change in WSE indicates a water elevation increase at that river station following terrain alteration (see the Methods section for a description of terrain alteration). Flow events are defined in the figure legend by peak discharge in cubic feet per second.

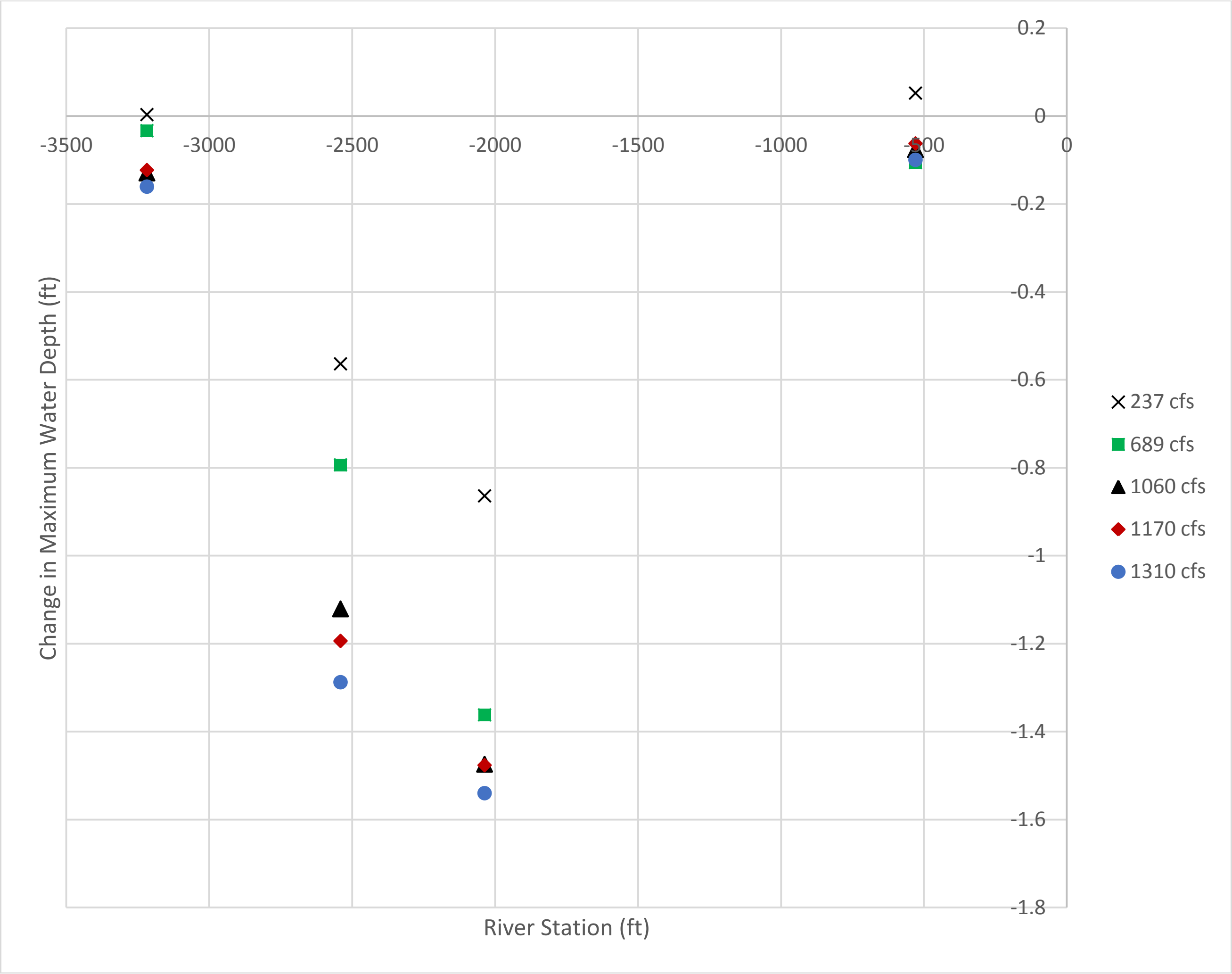

FIGURE 9. Difference in maximum water depth at select river stations following terrain alteration for identical flow events. River station identification is defined as distance, in feet, from the downstream boundary of the study reach. Note in this figure river station has been defined in the negative so the upstream boundary is on the left of the figure and the downstream boundary on the right. Water depth was calculated as the difference between maximum water surface elevation and minimum channel bed elevation in the main channel for a given river station and terrain to account for differences in main channel bed elevation between terrains. Change in water depth was calculated by subtracting maximum depth in the main channel of the 2015 terrain from maximum depth in the main channel of the altered terrain; thus a negative change in depth indicates a water depth decrease at that river station following terrain alteration and a positive change in depth indicates a water depth increase at that river station following terrain alteration (see the Methods section for a description of terrain alteration). Flow events are defined in the figure legend by peak discharge in cubic feet per second.

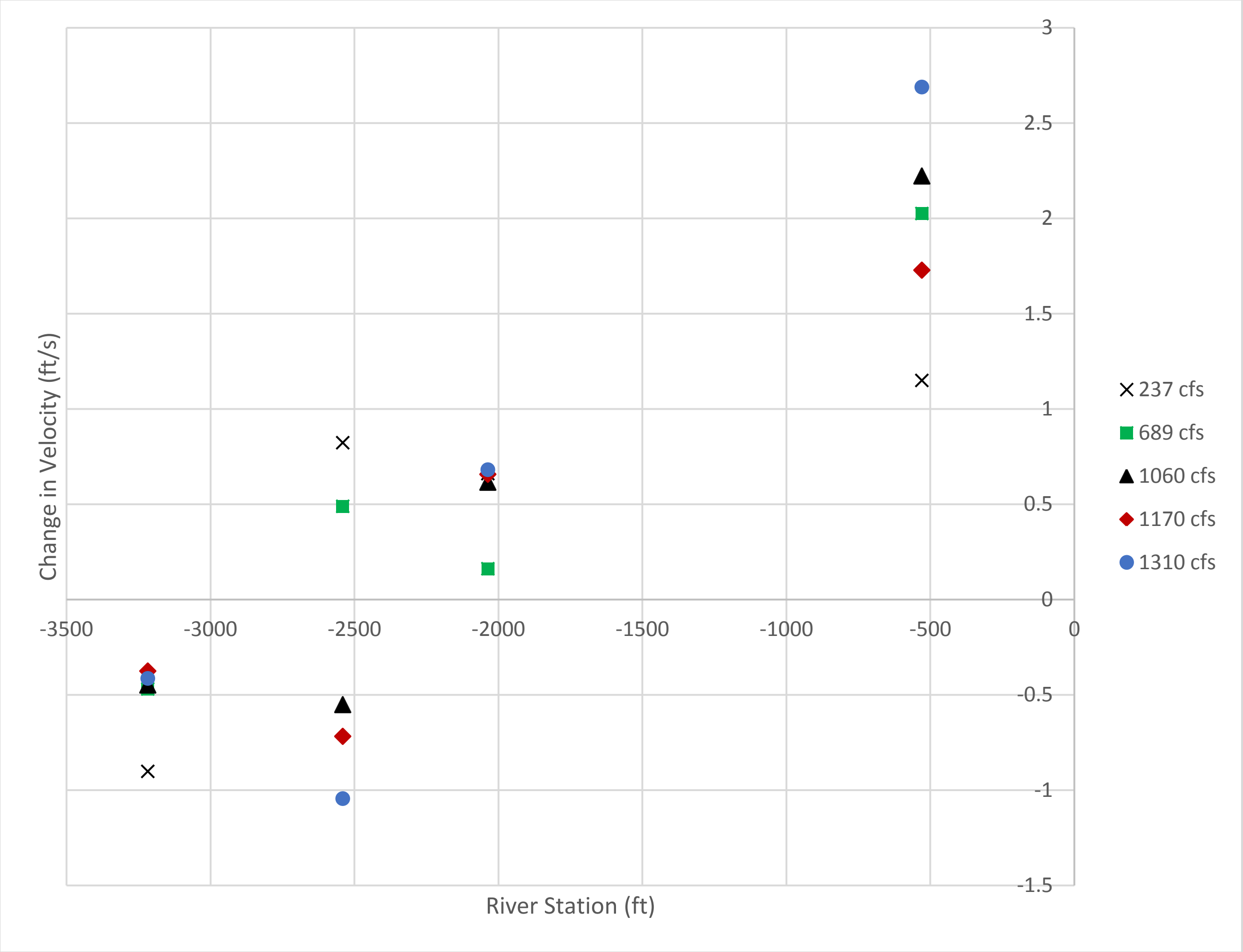

FIGURE 10. Difference in maximum two-dimensional depth-averaged velocity at select river stations following terrain alteration for identical flow events. River station identification is defined as distance, in feet, from the downstream boundary of the study reach. Note in this figure river station has been defined in the negative so the upstream boundary is on the left of the figure and the downstream boundary on the right. Change in velocity was calculated by subtracting maximum velocity in the main channel of the 2015 terrain from maximum velocity in the main channel of the altered terrain; thus a negative change in velocity indicates a water velocity decrease at that river station following terrain alteration and a positive change in velocity indicates a water velocity increase at that river station following terrain alteration (see the Methods section for a description of terrain alteration). Flow events are defined in the figure legend by peak discharge in cubic feet per second.

Figures 8, 9 and 10 demonstrate similar effects of terrain alteration on flood wave characteristics across flow events, with the exception of water velocity change at river station 2540.912, located at the downstream oxbow wetland. The two lowest flow events of 237 and 689 cfs showed an increase in maximum water velocity in the altered terrain, while the higher flow events of 1060, 1170 and 1310 cfs showed a decrease in water velocity in the altered terrain. The difference in water velocity at river station 2540.912 is modeled as a function to peak flow in **Figure 11**.

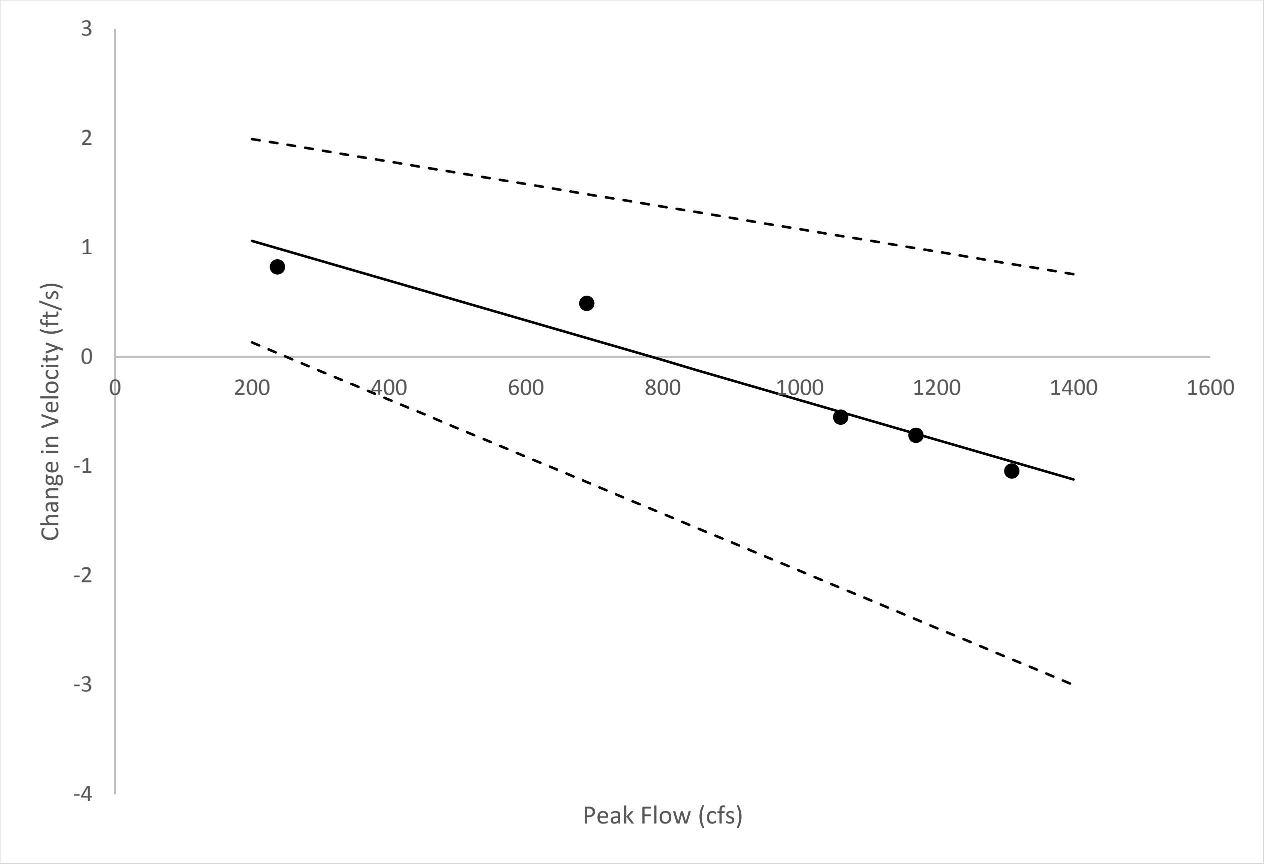

FIGURE 11. Difference in maximum two-dimensional depth-averaged velocity at river station 2540.912 following terrain alteration as a function of peak flow. Change in velocity was calculated by subtracting maximum velocity in the 2015 terrain from the maximum velocity in the altered terrain; thus a negative change in velocity indicates a water velocity decrease at river station 2540.912 following terrain alteration for that flow event and a positive change in velocity indicates a water velocity increase at river station 2540.912 following terrain alteration for that flow event. Data was characterized with a linear regression best fit model: change in velocity (ft/s) = (-0.00182 ± 0.00079)ft^{-2} * peak flow (ft^3/s) + (1.425 ± 0.773)ft/s; $R^2 = 0.9467$. Linear fit is shown as a solid line, upper and lower 95% confidence intervals are shown as dashed lines and measurements for differences in maximum velocity between models are shown as filled in circles.

DISCUSSION

Patterns of change in maximum water surface elevation at each river station between the 2015 terrain model and the altered terrain model were consistent across flood events. Absolute change in water surface elevation was greatest for low flow events, which may reflect a direct impact of changes in the channel bed elevation on water surface elevation for in-channel flow, as flow remained mostly in the channel for events under 1000 cfs in both terrain models. The three river stations upstream of Sherwood Bridge subjected to terrain alteration all showed an increase in maximum water surface elevation following terrain alteration, but maximum water surface elevation downstream of the terrain alteration was mostly unaffected, indicating the increase in channel bed elevation had a substantial effect on local water surface elevation and floodplain inundation, but little effect on water surface elevation downstream.

Maximum water depth, similar to maximum water surface elevation, showed consistent patterns of change at each river station between the 2015 and altered terrain across flow events. Unlike change in maximum water surface elevation, however, the absolute change in maximum water depth was greatest for high flow events. Maximum water depth was defined as the difference between maximum water surface elevation and minimum channel bed elevation for a given river station in the relevant terrain model; it thus appears low flow events showed the greatest change in water surface elevation but smallest change in depth, perhaps because terrain alteration did not significantly increase overbank flow for these events. River stations 2540.912 and 2036.928, located approximately at the downstream oxbow and upstream of Sherwood Bridge, respectively, showed a decrease in maximum water depth across all events, while river stations 3218.115 and 529.5025, located at the upstream and downstream ends of the study reach, respectively, showed relatively little change in maximum water depth.

Differences in cross sectional inundation profiles, maximum water surface elevation and maximum water depth indicate that as the raised channel bed allowed the flood wave to spill over the banks sooner in the altered terrain model, flow was spread across more of the floodplain. Thus, while absolute water surface elevation was higher in the altered terrain than the 2015 terrain, the shape of the water column was shallower and wider when extending into the floodplain, particularly for high flow events. At the upstream river station (see **Figures 5 & 6** for location of the upstream river station along the reach), absolute maximum water surface elevation increased in the altered terrain model, yet maximum water depth remained relatively unchanged, indicating the change in water surface elevation is mostly reflective of the change in channel bed elevation. As with changes in maximum water surface elevation, changes in maximum water depth appear mostly confined to areas of terrain alteration, with the downstream river station experiencing little change in maximum water depth between terrain models.

Unlike maximum water depth and water surface elevation, patterns of change in maximum velocity at each river station between the 2015 and altered terrain models were not constant across flow events. The change in maximum velocity for river station 2540.912 appears to show a negative correlation with peak discharge, shown in **Figure 11**, while river station 529.5025 appears to show the opposite trend, as seen in **Figure 10**. Further investigation is needed to determine if this is a result of differences in the speed at which waters flow through the channel in cases of overbank flow versus in-channel flow, changes in the backwater effect when overbank flow is increased, or other controls on velocity. For high flow events in which terrain alteration did result in a significant change in overbank flow (see **Figures 5, 6 & 7** for visual comparisons of floodplain inundation between the 2015 terrain model and altered terrain model), the observed decrease in maximum water velocity within the channel may reflect the impact of overbank flow exerting drag on flow within the channel and slowing the entire flood wave. At the upstream river station (3218.115) velocity decreased across all flow events, while the Sherwood Bridge river station (2036.928) and the downstream river station (529.5025) both showed increases in velocity across all flow events. The velocity increase at the Sherwood Bridge river station may have been partially related to an increase in local channel bed slope between the altered terrain upstream of the bridge and the unaltered terrain downstream of the bridge. Velocity changes were greatest at the downstream river station, potentially also reflective of the local increase in channel bed slope at the bridge or due to compounding effects of water velocity changes in upstream portions of the channel.

Particularly for high flow events, the results of this study indicate a restoration effort to raise the channel bed approximately two feet in the selected portion of Minebank Run could have a significant effect on local patterns of floodplain inundation and overbank flow. By increasing maximum water surface elevation while decreasing depth of the flood wave across most flow events, such a restoration effort may successfully reconnect the channel with the floodplain and potential restore riparian habitat and associated ecological services, although overbank flooding may also have negative effects on riparian habitats if flows are powerful enough to cause damage. Effects on maximum water velocity may be variable along the reach and dependent upon the size of flow, extent of floodplain inundation, and vegetation in the floodplain. Overall, observed changes in flood wave properties following an increase in channel bed elevation along the upstream portion of the study reach tended to be local changes, with minimal effect on reaches downstream of the channel alteration.

While this model was designed to gauge the relative sensitivity of flood wave properties to channel alterations, it was not fully calibrated to predict actual response of the stream under different flooding scenarios. Thus results from the model used in this study may not accurately reflect true peak stage, velocity or flow in a flood event, although the model may be further calibrated to achieve this level of accuracy in the future. Model accuracy was also limited by topographic information of the channel. While the LiDAR dataset provided high-resolution, high-accuracy topography of the majority of the region, several stretches of the channel were lacking data and had to be interpolated between cross sections completed mostly with data collected from a 2005 LiDAR dataset. This may have introduced additional discrepancies between the 2015 terrain model and the actual study reach terrain in 2015, as aerial photographs suggest significant geomorphic change has occurred throughout the study reach between 2005 and 2015. The results of this study are limited to the study reach, but similar methods may be applied to other urban watersheds, and comparison of the sensitivity of flood wave properties to specific physical channel alterations across watersheds may give valuable insight for stream restoration theory and practice. Where detailed pre-restoration and post-restoration topographic information is available, the modeling techniques described in this study may be used to assess the response of an unrestored and restored urban stream to identical flow scenarios to quantify the effect of restoration beyond traditional post-restoration monitoring techniques. Ultimately, comparison of the relative impact of physical channel restoration with complementary watershed-scale controls on runoff volume may better inform future stream restoration and flood mitigation design and provide effective, sustainable solutions for urban stream degradation.

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