Reliability of Two-Dimensional Hydrodynamic Models in Stream Restoration: Evaluation using Flood Evidence and Application in Future Climate Analysis

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Authors:
Jesse Robinson, P.E.[1]
jrobinson@wetlands.com
Arthur Parola, Ph. D, P.E.[1]
aparola@wetlands.com

Contributors:
Michael Croasdaile, Ph. D[1]
Bill Vesely[1]
McKenna Jobe[1]
Clayton Mastin, P.E.[2]

1. Wetland Studies and Solutions, Inc. Formerly with University of Louisville Stream Institute, Department of Civil and Environmental Engineering.
2. United States Army Corps of Engineers Louisville District

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Study partners and collaborators:

MD DOT SHA: Ryan Cole, Nora Bucke, Kevin Wilsey
MDE: Bill Seiger, Deb Cappuccitti, Jeff White
MD DNR: Ari Engelberg
Anne Arundel County: Erik Michelsen, Nasrin Dahlgren, Bryan Perry, Karen Jennings
Prince Georges County: Joanna Smith, Jerry Maldonado, Mark McKibben, Frank Galosi
Montgomery County: Kenny Mack
SERC: Cynthia Gilmour
Straughan Environmental: Drew Altland
Greenvest: Laura Kelm, David Merkey, Dana Cooper, Brett Berkley
Biohabitats: Joe Berg
Underwood & Associates: Keith Underwood, Chris Becraft, Keith Binsted, Heather Johnson, Beth Zinecker
RK&K: Jason Coleman, Tom Earp
Tetra Tech: Mark Sievers, Jasmine DunhamTyson
Berrywood Community: Molly LaChapelle, Bob Royer
Arundel Rivers: Jennifer Carr
McCormick Taylor: Scott Lowe
EQR: Katrina Davis
PA DEP: Dave Gorman
USACE Hydrologic Engineering Center: Chris Nygaard, Kristy Riley, Alex Sanchez
USACE Baltimore District: Nick Ozburn
BMT Ltd.: Rusty Jones
University of Louisville: Erin Gerber

Chesapeake Bay Trust Funding Partners:

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EXECUTIVE SUMMARY

Stream and wetland restoration projects are an important part of the effort to restore the Chesapeake Bay and its tributaries. Within the Chesapeake Bay watershed and beyond, there is concern that the design of restoration projects may be inadequate under current and future climate conditions, given increasing flood flow magnitudes. Inadequate design may result in flood damage that can include a loss of vegetation, erosion of topsoil, removal of habitat materials, channel straightening or incision, outflanking or loss of hydraulic structures, and the downstream transport of excess sediments and nutrients. Flood damage can lead to a partial or complete loss of ecological functions, necessitating costly redesign or repairs, or a downward adjustment in the expected project benefits.

Restoration practitioners, regulators and other stakeholders have identified two-dimensional hydrodynamic models (2D models) as an analytical tool that is well suited to assessing the vulnerability of restoration sites to damage during major flood events. 2D models are an effective companion to the computer aided design of restoration terrain. These models can be used to guide design to a robust configuration through iterative terrain modifications, so that flood flow velocities (or boundary shear stress) are below threshold levels for substantial damage. Where terrain modifications alone cannot be used to mitigate the vulnerability to flood damage, or local constraints prevent terrain modifications, 2D model output can also be used to determine where the installation of rock or erosion control protection measures are necessary. Design guided by modeling can be used for impact minimization and avoidance, including reducing land disturbance, tree removal, and other non-essential impacts to existing resources.

2D models are widely used in designing restoration projects within tributaries of the Chesapeake Bay. Although 2D model use is widespread, minimal information is available to assess the reliability of these models for identifying flood vulnerabilities of restoration projects. **This research project was initiated to evaluate the reliability of 2D models for restoration design in typical streams contributing flow to the Chesapeake Bay.** The project was conceived in two phases. Phase I was a field scale examination of 2D model reliability during flood events at five sites. Phase II was an evaluation of the vulnerability of these five restoration sites under a future climate scenario. These two phases of the project are used to address a key research question initiated by the Chesapeake Bay Trust related to the use of techniques which reduce the impacts of future climate change events.

The findings of Phase I include:

- <u>2D models in all sites were found to be reliable for the general purpose of evaluating flood vulnerability</u>. Areas where 2D models predicted high velocities showed consistent evidence of flood modified vegetation on stream banks and floodplains, bare soil, exposed basal gravels, minimal retention of organic matter, and channels with disturbed substrates and eroded banks. Areas with low predicted flood velocities showed the opposite: minimally altered vegetation, stable banks and floodplains, observable accumulations of organic matter, and stable channel substrates.

- Within the floodplain and along shallow stream banks in a stream-and-wetland complex site, Furnace Creek, the differences in flood evidence described above were organized into a flood intensity classification system that is associated with observed 2D model velocities. This classification system allows for conversion of 2D model output, which is typically limited to specialist interpretation, into descriptions of the post-restoration environment that are accessible to all stakeholders. While the results are based on one site, they show that 2D models may have great utility in predicting where different types of floodplain ecosystems are likely to develop – from low-velocity, carbon-rich areas which retain sediments and process nutrients to higher stress and eroding areas.
- The flow direction surrounding beaver dam analog (BDA) structures at one site, Bacon Ridge, was effectively predicted by 2D models, including regions of high and low velocity and the locations where flow exits the channel into the floodplain upstream of the BDA structure and returns to the channel downstream of the BDA structure.
- 2D models had more limited value in the Bear Branch restoration site, where the channel remains incised post-restoration. Within scour pools below structures and near eroding banks, 2D models frequently predicted low velocities, despite the observation of high velocities in these areas during the study. In these areas the flow contains highly non-uniform vertical velocity profiles, and vertical flow separation is likely. In this site, <u>specific areas</u> - 10 to 20 feet in length - of the channel bed and banks that are vulnerable to erosion could not be defined using 2D models, as they can be for sites with shallow flows over the channel and floodplain. 2D models were useful for identifying <u>general areas</u> of the Bear Branch restoration that are vulnerable to erosion due to the presence of high flood velocities.
- The observed rock and sediment stability within channels was effectively predicted by 2D model velocities using the Isbash (1936) stability curves for reference.

The results of Phase I combine multiple methods to evaluate 2D model reliability under varying degrees of flood intensity at five sites. The confirmation of general reliability of 2D models from Phase I allowed for the exploration of vulnerability due to flood damage under a future climate scenario in Phase II.

The findings of Phase II include:

- <u>Areas of restoration sites that are vulnerable under current climate conditions show the greatest vulnerability under the future climate scenario</u>. Each restoration site is distinctive, and the factors that define the present vulnerability also determine future vulnerability.

- Areas within sites that have the greatest vulnerability under the future climate scenario include pinch points due to landscape contraction or obstacles, areas where flow is concentrated without landscape contraction, large vertical steps around hydraulic structures, and locally steep slopes in the channel and floodplain.
- The most effective approach to reducing the vulnerability to flood damage is to spread flood flows over wide, roughened by vegetation floodplains, which effectively dampens high flood velocities. Restoration methods that achieve this, including floodplain restorations, will have a greater resilience to flood damage than sites which confine and entrench flood flows.
- Infrastructure plays an important role in the vulnerability of sites under the future climate scenario. Elevated flood velocities downstream of culverts, bridges, and due to road overtopping within the restoration area have the potential to cause significant damage. Bridges and culverts which backwater restoration sites, among other hydraulic effects, can provide protection to restoration sites during major flood events.

This research included a range of restoration methods and environments within the relatively low valley slopes of the coastal plain in the lower Chesapeake Bay watershed. The results provide important insights into model reliability and add confidence to their use in restoration design and assessment. We recommend additional research into 2D models in restorations on steeper sloped valleys sites within the Chesapeake Bay, to further evaluate their reliability and develop practical knowledge on the environments where 2D model use is recommended for flood vulnerability assessment.

RESEARCH QUESTION

This research project was initiated in response to a key question identified by the Chesapeake Bay Trust pooled monitoring initiative during the 2020 pooled monitoring funding cycle, abbreviated here:

How can different restoration approaches or techniques and/or site conditions reduce the impacts of future climate change?

This research was divided into two phases to effectively address this key research question. Both phases focus on a restoration technique widely used throughout the Chesapeake Bay in stream and wetland restoration design: flood vulnerability assessment through the application of two-dimensional hydrodynamic models. Because there is limited information on the reliability of 2D models applied to flood vulnerability assessment in restoration design, the first phase of this study focused on the collection of field data and the development of 2D models to evaluate reliability in different areas of 5 restoration sites. The first phase provided evidence for the general reliability of 2D models. This general reliability permits an exploration in the second phase of how changes associated with future climate change scenarios – through elevated major flood flows – will impact the future vulnerability of stream restoration sites.

1. INTRODUCTION

1.1. Background

Stream and wetland restoration projects are vulnerable to damage during flood events. Flood damage to restoration projects can be severe, and may include the loss of habitat materials and structures due to undermining, aggradation or outflanking (Miller & Kochel, 2013; Radspinner et al., 2010), channel avulsion (Buchanan et al., 2012), and removal of floodplain topsoil and vegetation by scour (Smith & Prestegaard, 2005).

Project failures can undermine public confidence in stream restoration as a best management practice, produce poor ecological outcomes, and ultimately fail to improve conditions in the Chesapeake Bay and its estuary. The vulnerability of stream restoration projects to flood damage is likely to increase under future climate conditions as more frequent and intense storms are predicted to occur in the Chesapeake Bay watershed. Restoration stakeholders will need tools to consider "climate resilience" (Williams et al., 2017) in the design process, a cornerstone of which should be the application of flood vulnerability assessment.

Hydrodynamic modeling of proposed restoration design provides a method implementing flood vulnerability assessment, and can be used to identify vulnerable areas, allowing for design revisions which mitigate the risk of project failure and underperformance. Hydrodynamic modeling has widespread but uneven adoption in stream restoration design in the Chesapeake Bay at present. Due to the nature of flood flows within restoration sites, which vary significantly across types of restoration and within each restoration site, it is important that the chosen hydrodynamic model can simulate the essential physics. Two-dimensional, depth integrated hydrodynamic modeling (2D models) provides a relatively straightforward approach to estimating these spatially varied hydraulic characteristics throughout entire restoration sites (Parola, 2016).

2D models have been used for more than 20 years to evaluate damage at bridges due to erosion and scour (Biglari & Sturm, 1998). They are a standard tool in the assessment of stream, floodplain, and infrastructure hydraulics (Crowder & Diplas, 2000; Papanicolaou et al., 2010; Sawyer et al., 2010). Recently, their use in stream restoration has increased because of several developments: software advances that reduce the burden of assembling input data; increased computer processing speeds; new tools for analyzing results; and the availability of detailed terrain data necessary to run the models. Multi-million cell 2D models can be run over large areas of sites in minutes to hours (Pasternack & Hopkins, 2017).

Despite the advantages offered by 2D models and their present use in the Chesapeake Bay, there is limited information on the reliability of 2D models applied to restoration design. Model benchmarking studies provide useful information on the general capacity of 2D models to replicate the hydraulics of flow in a variety of environments and conditions (Néelz & Pender, 2010), but these studies are lacking in environments which are analogous to stream restoration sites. Field research focused on applications of 2D modeling generally occurs under base flow, not flood flow conditions, with few exceptions (Abu-Aly et al., 2014; Noorbakhsh, 2020).

This research was initiated to accomplish two goals: (1) to assess the reliability of 2D models applied to flood vulnerability assessment in restoration design and (2) to evaluate how 2D models may be used to provide insight into changes in flood vulnerability in a future climate change scenario. The first goal is addressed in Phase I of this research through the development of 2D models at five post-construction restoration sites. At each site, data was collected to evaluate model reliability during observed flood events. Model development was combined with instrumentation and monitoring over three years to permit calibration of 2D models to observed flood events and associate these events to changes in soil, vegetation, and installed rock and sediments at each site. Phase I is divided into research evaluating the floodplain and shallow streambanks, and research evaluating the restored channel.

The second objective is addressed in Phase II, where the same set of restoration sites were evaluated under current flooding conditions and a future climate scenario developed by elevating the current 100-year flood event. Within each site, an area that was vulnerable during Phase I modeling was identified and evaluated under the future climate scenario flow.

The five restoration sites selected include two floodplain restoration sites, also described as valley restorations or stream-wetland complexes (Parola, 2016), one natural channel design site (Rosgen & Silvey, 1996), one beaver dam analog site (Wheaton et al., 2019), and one regenerative stormwater conveyance site (An, 2018). 2D models were developed using high resolution terrain datasets which reflected the field conditions which existed at each site during the study.

The two research phases and the research efforts that are a part of each phase are discussed below. Research objectives are described within each section. The report organization is described following the description of research efforts.

1.2. Phase I: Evaluation of 2D Model Reliability Using Bank and Floodplain Indicators

The purpose of this research effort was to develop a relationship between flood intensity, determined through 2D model velocities, and observable evidence of flooding found in changes to the ground and living vegetation on shallow stream banks – those with heights less than one foot above the base flow water surface - and in floodplains. Removal of vegetation and erosion of soils or basal gravels can lead to project underperformance and failure. Practitioners and regulators reviewing 2D model output evaluate the depth-integrated velocities (or boundary shear stress) to determine if material and vegetation thresholds are likely to be exceeded during major flooding events (Fischenich, 2001). The research in this chapter evaluated the general reliability of these predictions by looking for flood indicators on shallow stream banks and in the floodplain of Furnace Creek following a major flood event and developing a relationship between these flood indicators and 2D model results.

Furnace Creek was constructed as a floodplain (or stream and wetland complex) restoration (Kaushal et al., 2014). The site included streamside wetlands throughout the floodplain. Of the three sites which contained shallow stream banks and an active floodplain (Furnace Creek, Cat Branch and Bacon Ridge), Furnace Creek experienced two major flood events in the summer of 2021 that activated the floodplain throughout the site and produced a range of flood disturbance evidence.

Research Objectives:

- Develop a flood intensity classification system which describes the range of flood related evidence that was observed on shallow channel banks and in the floodplain.
- Categorize areas into the flood intensity classification system and evaluate the statistical distribution of 2D model velocities in and between classification categories.

1.3. Phase I: Evaluation of 2D Model Reliability in Restored Channels

This research effort addressed the reliability of 2D modeling in three applications within restored channels, with the first application consisting of an examination of rock and coarse sediment stability, the second application addressing the reliability of 2D models in an incised channel environment containing natural channel design grade control structures, and the third application evaluating the reliability of 2D model flow direction predictions surrounding beaver dam analog grade control structures. Each application is discussed below.

Rock and Sediment Stability. The stability of coarse channel sediments, consisting of native basal gravels or installed rock, are important for the success of restoration projects. Coarse sediments provide shelter for fish, invertebrates, and microorganisms, and may form the primary grade control in the channel. Scouring flood flows which disturb coarse sediments can alter the density and assemblage of aquatic organisms living within those sediments (Hemphill & Cooper, 1983; Lake, 2000). During the design process, 2D model output can be used to evaluate the stability of coarse sediments which will be installed in the proposed channel. Model output can be compared against published thresholds for the stability of coarse sediments to determine if those thresholds are likely to be exceeded during flood events. Four research sites were used in the evaluation of coarse sediment stability: Cattail Creek, Cat Branch, Bear Branch, and Furnace Creek.

Modeling in Incised Channels. Incised channels are defined by their high streambanks and disconnection from the floodplain (Darby & Simon, 1999). Disconnection from the floodplain leads to the confinement of floodwaters in the channel, increasing flow depth over the channel bed while limiting the horizontal extent of flow. This "trapping" of flow creates a challenge for the application of 2D models, which are based on the shallow water equations. The shallow water equations are derived through several simplifying assumptions. The first of these is that the width of flow is large compared to the depth of flow. In areas that have a low ratio of flow width to flow depth - including incised channels - the vertical component of velocity may be large relative to the horizontal component, *which can lead to a loss of accuracy in the prediction of local velocities and flow patterns*. The shallow water equations are also based on the assumption of a hydrostatic pressure distribution - where pressure is assumed to increase proportionally with water depth. This assumption will *not be met* in areas where there is vertical separation of flow, including, for example, where a fast-moving jet of water is formed by flow plunging over a natural channel design structure (Kang et al., 2016). Despite these limitations, 2D model output in incised environments may still provide useful information about the general and specific flood vulnerabilities in the restoration site, provided that the model user is cautious in their interpretation of results, primarily at vertical steps, abrupt expansions and contractions of the bed, and low-radius bends. The Bear Branch restoration site was used in the evaluation of 2D models in an incised channel.

Flow direction. The ability of 2D models to resolve both the magnitude and direction of velocity is important to their effective use and interpretation. During the design process, 2D model output can be used to evaluate the stability of grade control structures by examining peak velocities on the structure (and near it) and by evaluating the expected direction of flow surrounding the structures, which may lead to the identification of areas which are vulnerable to flood damage. This research effort was an evaluation of the reliability of flow direction predictions in a site where grade control structures created non-uniform horizontal flow patterns around and through each structure. These structures, described as beaver dam analogs, were constructed using irregular pieces of wood that made each structure unique in its influence on flood flows. The deflection of flow into the surrounding floodplain and channel banks left evidence of flood flow direction in fine sediment deposits and the streamlining of vegetation. The evaluation of flow direction surrounding grade control structures was completed at Bacon Ridge.

<u>Research Objectives in Chapter</u>:

- Evaluate 2D model predictions of rock and coarse sediment stability on the restored channel bed.
- Demonstrate 2D model limitations in incised channels and develop recommendations for appropriate use of 2D models in these channels.
- Compare 2D model prediction of flow direction upstream and downstream of grade control structures to observed flow direction.

1.4. Phase II: 2D Modeling in a Changing Climate

The second phase of this research applies 2D modeling to evaluate how the flood vulnerability of restoration sites may change under future conditions where major flood events including the 100-year flow are elevated above their current estimates. The spatially distributed output generated by 2D models allows for comparison of flood vulnerability across multiple scenarios. 2D models that are run using different flow inputs can be compared at specific locations which are known to be vulnerable and across the entire flooded area. Practitioners and restoration stakeholders can use 2D model output derived from multiple scenarios to develop knowledge about the site and its possible trajectories under different future climate conditions. Model output can also be applied to a formal risk assessment of restoration site vulnerability (Niezgoda & Johnson, 2007) which incorporates probable design failure modes indicated by 2D model output under different scenarios.

The impact of climate change on regional precipitation is typically quantified by downscaling the results of global climate models. Downscaling can be through statistical (Pierce et al., 2014) or "dynamical" (Giorgi & Gutowski, 2015) means, with each including multiple methodological decisions which will impact the prediction of future values. The choice of statistical downscaling method has been shown to lead to a 10% difference in the 100-year 24-hour rainfall estimate in the Chesapeake Bay (Butcher et al., 2023); different choices of emissions scenarios, time period, and location will further increase the uncertainty in estimates. These uncertainties are imposed onto the uncertainty which is already present in current estimates of precipitation values.

Few studies have attempted to predict how changes to the frequency, duration and intensity of rainfall will impact major flow events within the Chesapeake Bay or elsewhere (Morsy et al., 2024). The estimate of major flows which are dependent on first downscaling precipitation data and subsequently estimating flow increases through hydrologic modeling or statistical adjustment to existing streamflow estimates leads to layering even greater uncertainty on already uncertain values. Major flow estimates for the western coastal plain where all research sites are located are provided by Thomas and Sanchez-Claros (2019). These estimates have a standard error of 35% at the 100-year event. Statistical methods which extrapolate from these or similar estimates to determine future conditions will begin with estimates that are uncertain.

The uncertainty in major flow estimates under current and future conditions is a consideration in developing reliable 2D models. This uncertainty does not preclude the effective use of 2D models, and does not modify model output in the same way at each site. The research in this chapter will provide important context for evaluating 2D models across a range of major flood flows and show the extent to which flood velocity changes across major events and under a climate change scenario. This analysis is conducted at all five research sites, which represent a range of design methods, basin and site characteristics.

Research Objectives in Chapter:

- Determine how the vulnerability of each restoration site may change under a future climate with an elevated 100-year flow. Floodplain, channel, and areas pre-determined as vulnerable were evaluated.
- Determine the trajectory of restoration sites under a future climate scenario to facilitate the development of general conclusions about restoration site vulnerability which can be applied to the planning of future 2D modeling efforts.

1.5. Organization of Report

This report is divided into chapters that are organized around the individual research efforts that are a part of Phases I and II.

Chapter 2. Methods. The methods that are shared by all research efforts are defined in Chapter 2. This includes site selection criteria, terrain data collection, 2D model setup and 2D model calibration approach. Methods that are specific to each research effort are provided at the start of Chapters 3 – 5.

Chapter 3. Research Phase I. Evaluation of 2D Model Reliability Using Bank and Floodplain Indicators. Chapter 3 is an evaluation of the reliability of 2D models on the vegetated floodplain and shallow stream banks at Furnace Creek, a stream-and-wetland complex research site.

Chapter 4. Research Phase I. Evaluation of 2D Model Reliability in Restored Channels. Chapter 4 explores three applications of 2D model reliability analysis in channels. Analysis includes an examination of rock and sediment stability following flood events at all five research sites, evaluation of 2D model reliability in an incised channel environment at Bear Branch, and a comparison of observed and predicted flow direction surrounding beaver dam analog structures at Bacon Ridge.

Chapter 5. Research Phase II. 2D Modeling of Major Flood Events in a Changing Climate. Chapter 5 is an analysis of flood vulnerability at all five research sites under a future climate scenario. The results for the future climate scenario are compared to current conditions for channels, floodplains, and areas identified as uniquely vulnerable.

Appendix A. Effective 2D models for Reliability Research. Appendix A is an abbreviated summary of research conducted as part of this grant to develop effective 2D models which are used throughout the report. This research is related to the choice of modeling software (HEC-RAS 2D or TUFLOW), model grid resolution and choice of turbulence model coefficient.

Appendix B. 2D model figures for readers with color vision deficiency. Appendix B includes reprints of figures used in the report with alternative symbology for readers with color vision deficiency.

Appendix C. 2D model output for all flow events at research sites. Appendix C includes the modeled, depth-integrated velocity results for all flows at the 5 research sites. This includes the 2-, 10-, 50-, and 100-year recurrence interval flows, the climate change scenario flow and the estimated peak flood flow observed at each site during the field data collection period of March, 2021 through March, 2024.

Appendix D. 2D Model output for all flow events at research sites for readers with color vision deficiency. Appendix D is a reprint of Appendix C with alternative symbology for readers.

2. METHODS

2.1. Site Selection Criteria

Candidate sites were identified primarily through consultation with project partners and examining public databases of restoration projects to find sites that were post-construction in the coastal plain physiographic region of Maryland. 33 candidate sites were identified (Figure 1) and the majority were walked to evaluate suitability for inclusion in the study. The inclusion criteria are identified in Table 1. In addition to the listed criteria, it was a priority to select sites that were constructed using a range of commonly applied restoration design methods.

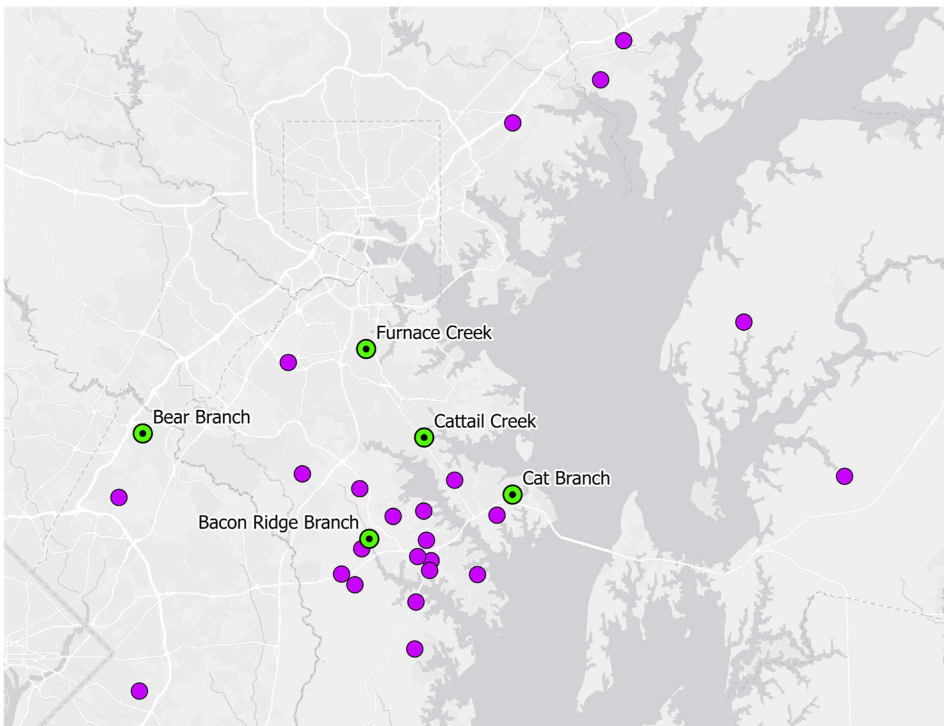

Figure 1. Restoration Sites Evaluated for Study Inclusion. Sites evaluated for use in study are shown in purple with selected sites in green.

Table 1. Site Selection Criteria. P defines priority, S defines supplemental criteria.

P1.	*Local valley slope*. Only projects with local, downstream valley slopes less than 10% were considered for this study to ensure that the assumption of a hydrostatic pressure distribution in the model is valid (Chow, 1959).
P2.	*Drainage area*. Project sites with watersheds greater than 0.2 square miles and under 10 square miles were prioritized. This ensured that the study sites represent the typical watershed size where most projects are constructed.
P3.	*Project length*. To reduce the complexities of transitions into and out of restorations, restoration projects that were longer than the effect of the transitions were selected. A minimum project length of 500 feet was the goal. Longer projects have greater potential for constructing statistically robust samples and were prioritized.
P4.	*Tidal influence*. Only project reaches above the mean high water tidal elevation were included.
P5.	*UAV restrictions*. Data collection efforts included the use of an un-manned aerial vehicle (UAV), therefore projects in restricted/no-drone zone areas were not included.
S1.	*Low coarse sediment inputs*. Project sites with inferred high coarse sediment loads were excluded. Modeling of the transport and deposition of bed material sediment is sometimes required to comprehensively evaluate sites with high coarse loads. Although coarse sediment loads may damage restoration components by altering local hydraulics, modeling them is beyond the scope of this project.
S2.	*Date constructed*. Projects completed within the past 5 years were given preference over older sites so that the design methodology was close to the prevailing practice.
S3.	*Project data availability*. The availability of project data including as-built and/or design topographic data was considered.
S4.	*Site accessibility*. Safe, legal access to project sites was required. Access was facilitated by Ann Arundel County, Prince Georges County, the community of Berrywood, and project design consultants.
S5.	*Distance from infrastructure*. Sites with bridges and culverts were considered for inclusion provided that a substantial portion of the project is outside of the backwater influence or downstream flow expansion area of the hydraulic structure.
S6.	*Discharge data availability*. Sites with nearby stream gages were preferred.

2.2. Selected Sites

Table 2 includes the location and restoration method applied at each study site. Additional information about each site is provided below with the layout of research sites shown in Figure 2. Information on site drainage areas and percent impervious cover were determined using StreamStats (U.S. Geological Survey, 2019) and is provided in this section for general context. The percent cover data obtained from StreamStats may vary significantly from cover estimates obtained through hydrologic analysis completed during project planning and design phases.

Table 2. Restoration Method and Study Components

Site	Latitude and Longitude (decimal degrees)	Restoration Method
Furnace Creek	39.16673, -76.61613	Floodplain Restoration and Stream-Wetland Complex
Cat Branch	39.03369, -76.44674	Floodplain Restoration and Stream-Wetland Complex
Cattail Creek	39.08696, -76.54879	Regenerative Stormwater Conveyance (RSC)
Bear Branch	39.09164, -76.87920	Modified Natural Channel Design (NCD)
Bacon Ridge	38.99557, -76.61346	Beaver Dam Analog and Stream-Wetland Complex

Furnace Creek. Sponsored by Anne Arundel County. Prior to restoration, much of Furnace Creek was a concrete lined, trapezoidal channel. Restoration was completed in 2020 and includes 4,300 linear feet of stream restoration and 6 acres of emergent and shrub-scrub floodplain wetlands. The upstream drainage area is 0.6 square miles and the impervious cover is 55%.

Bacon Ridge. Sponsored by Maryland Department of Transportation. The site faced severe channel incision and headcutting prior to restoration and was subject to years of extensive rooting by pigs. Construction was completed in 2019 with 17,970 linear feet of stream restored. The upstream drainage area at the confluence with the major tributary entering at valley left is 7.2 square miles with a 10% impervious cover in the basin.

Cat Branch. Sponsored by Anne Arundel County and the Maryland Department of Natural Resources. Prior to restoration, the site experienced intense erosion, poor water quality and minimal habitat. Construction was completed in 2019 with 1,492 linear feet of stream restoration, 3.5 acres of wetland restoration, and improvements to stormwater storage and conveyance structures. The drainage area upstream of the site is 0.4 square miles and the impervious cover of the basin is 35%.

Cattail Creek (Berrywood). Sponsored by Ann Arundel County and the Maryland Department of Natural Resources. Prior to restoration, Cattail Creek was a deeply incised ditch with minimal floodplain inundation. Restoration was completed in 2019 with 650 linear feet of stream restored. The upstream drainage area is 2.4 square miles and the impervious cover of the basin is 33%.

Bear Branch. Sponsored by Prince George's County. The site was a deeply incised channel prior to restoration. Construction was completed in 2010 with 1,800 linear feet of stream restored. The drainage area upstream of the site is 1.2 square miles with an impervious cover of 34% in the basin.

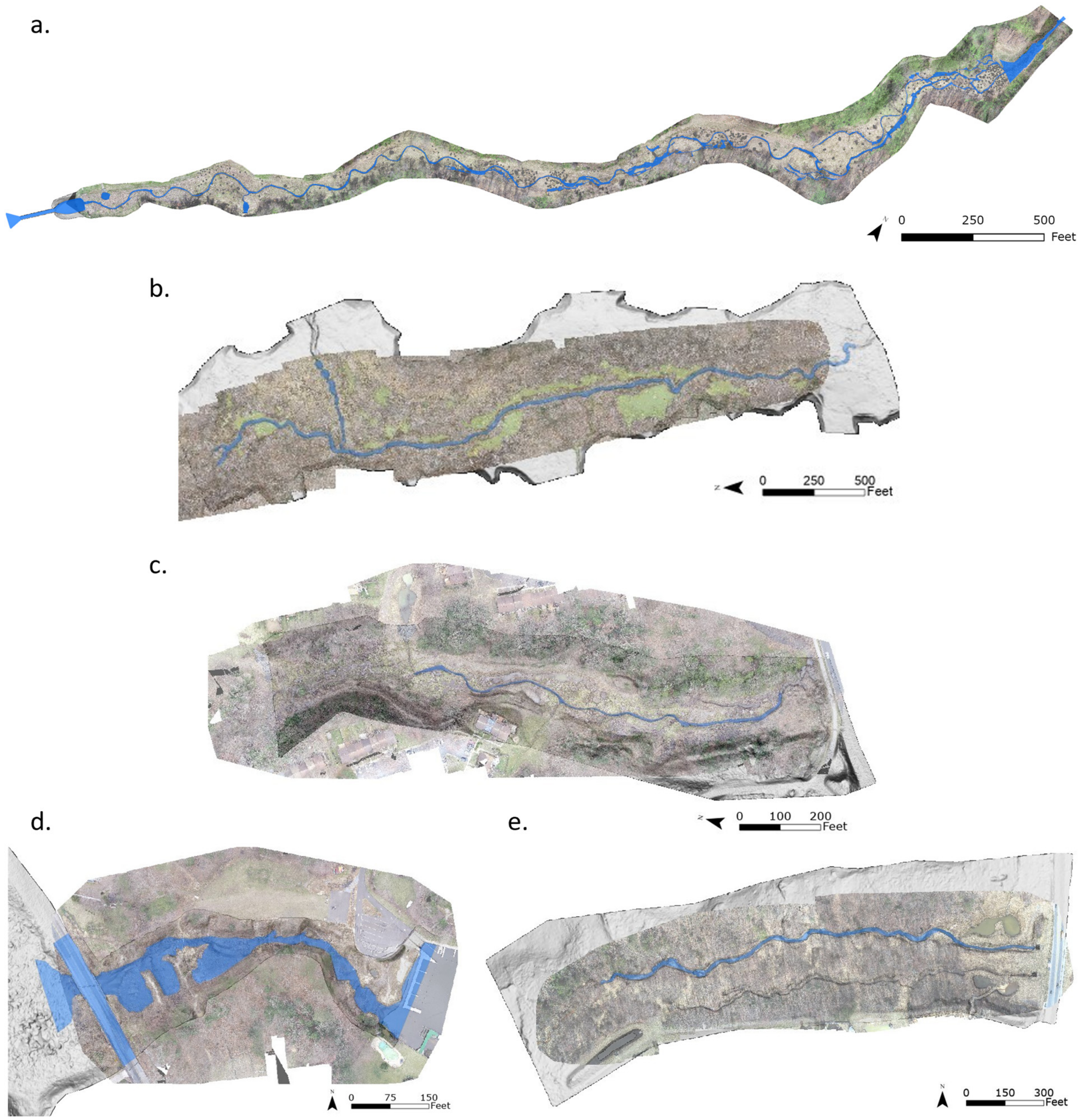

Figure 2. Layout of Research Sites Used in Study. Sites include Furnace Creek (a), Bacon Ridge (b), Cat Branch (c), Cattail Creek (d) and Bear Branch (e). Light blue boundaries are the boundaries of channel areas at each site. Flow is from left to right.

2.3. Terrain Development

Site terrain datasets were defined by integrating publicly available light detection and ranging (LiDAR) data (Maryland Department of Information Technology, 2017), aerial structure from motion surveys collected using a DJI Phantom 4 on March 15, 2021, and field-run ground survey using a Trimble SX10 robotic total station and a Trimble R12i global navigational satellite system (GNSS) receiver for real-time kinematic (RTK) survey. The primary use of LiDAR data was to define the edges of valleys and hillsides surrounding the restoration areas. At Bacon Ridge and Bear Branch, LiDAR was used to develop terrain in areas of the floodplain that were away from the channel. The field-run ground survey was used to collect channel and floodplain breaklines where they were not well defined in aerial structure from motion datasets. Ground survey was completed with RTK precisions set to 0.1 foot and lower. The aerial structure from motion survey was used to define the location of large woody debris at Furnace Creek and to permit breaklines to be surveyed from the georeferenced point cloud. Terrain quality was verified through a set of above water check points collected in bare earth and near-bare earth locations. Check points were used to ensure that the root mean square difference between the check point and terrain dataset was less than 0.164 feet (5 centimeters) which is the standard for high-quality, QL0 level LiDAR data (Heidemann, 2018) and reflects an appropriate level of accuracy for this research.

2.4. 2D Numerical Model

2.4.1. Model Setup

2D numerical modeling was completed using the hydrodynamic modeling software package TUFLOW HPC (Heavily Parallelized Compute), version 2023-03-AE (WBM Pty Ltd., 2024). TUFLOW HPC solves the shallow water equations over a uniform cartesian grid. TUFLOW has been extensively tested and benchmarked (Collecutt & Syme, 2017; WBM Pty Ltd., 2012) and is capable of massively parallelized simulations on computer or graphical processing units. TUFLOW HPC engine uses the mass conserving, explicit finite volume solution scheme. The 2nd order spatial scheme was used for all models. Additional 2D numerical modeling was completed using the U.S. Army Corps of Engineers model HEC-RAS 2D, version 6.4.1 (G. W. Brunner, 2024) to permit comparison between HEC-RAS 2D and TUFLOW HPC. Results from this comparison are available in Appendix A.

Orthoimagery collected on March 15, 2021 at each site was used to define the channel bottom boundaries and areas of pooled water lacking dense vegetation. Manning's *n* roughness coefficients were assigned to landcover classes as shown in Table 3. The Manning's *n* coefficients are used within areas that have a similar roughness, including vegetated areas of the floodplain, and are used to calculate the loss of energy experienced by flow over the restored landscape. The 2D model grid size was set to one foot with output set to half a foot. The sub-grid sample distance was set to a quarter of a foot. Models used the "3D" method (WBM Pty Ltd., 2020) for eddy viscosity turbulence modeling which is based on the product of the local shear velocity, lower of the water depth or distance to dry boundary, and the user specified turbulence coefficient. The user specified turbulence coefficient was set to 0.5 for all 2D models. Interpretation of 2D model output typically includes velocity magnitude and direction as well as boundary shear stress, as a force per unit area. For simplicity, all results and discussions were based solely on velocity magnitude and velocity direction. Model boundary conditions, which were used to determine flow inputs to the model and define the hydraulic conditions where flow exits the model, were separated from the locations where analysis was conducted by a sufficient length to ensure that results were not altered by proximity to the boundary condition.

Each flow in the model domain was allowed to achieve steady state conditions before model output was exported. Model input regions and development lengths were verified by iterative adjustment of the upstream boundary condition until identical results were obtained downstream in areas which were the focus of research.

Table 3. Landcover Classes Used in 2D Models

Landcover	Manning's *n* roughness coefficient
Floodplain and channel banks	0.06+, 0.07*
Channel Bed	0.04
Rock Protection	0.055
Culvert Bottom and Sidewalls: Concrete, Smooth HDPE	0.012
Culvert Bottom and Sidewalls: Concrete and Brick	0.017

+ Value for Furnace Creek, Cattail Creek and Bear Branch as a result of model calibration.
* Value for Bacon Ridge and Cat Branch as a result of model calibration.

2.4.2. Model Calibration to Observed Events

Calibration of 2D models to observed flood events which occurred during the study was accomplished through multiple methods. At two sites - Cattail Creek and Bear Branch – the culvert headwater and tailwater depths during floods were observed using pressure transducers; flood flow was estimated using Federal Highway Administration culvert analysis software HY-8 and those observations. At Furnace Creek, flood flows were estimated at the upstream end of the project area by instrumenting the culvert with a pressure transducer and combining with depth integrated velocity data provided by Ann Arundel County. Flood flow and floodplain roughness calibration at Cat Branch and additional calibration at Furnace Creek was performed using water depth and velocity estimates derived from timelapse imagery and video. Calibration at Bacon Ridge was accomplished by estimating water depth from timelapse imagery.

At Furnace Creek instrumentation of the culvert provided an estimate of flow at the upstream end of the site that was increased to account for additional flow inputs which occur along the reach, including in the reach upstream of the area where timelapse imagery allowed for estimation of water surface and surface velocity at multiple locations. Calibration was performed at flows which were increased proportional to drainage area by a factor of 0.5, 1.0 and 1.5. To provide a greater calibration range, additional models were run at 70% of the flow estimated at the culvert (lowest tested flow) and 130% of the flow estimated at the culvert (highest tested flow). For Furnace Creek calibration results were reported through bias, as the average difference between observed and predicted water surface (or velocity), and root mean square difference (RMSD) for water surface and velocity. The selected flow and roughness coefficients at Furnace Creek minimized the bias for velocity and water surface and had low RMSD for both parameters.

3. PHASE I: EVALUATION OF 2D MODEL RELIABILITY USING BANK AND FLOODPLAIN INDICATORS

3.1. Supplemental Methods

Methods are supplemental to the methods described in Section 2. The research site used in this chapter is the floodplain restoration site Furnace Creek.

3.1.1. Classification of Flood Evidence

The collection of flood evidence was completed within the floodplain of Furnace Creek and along streambanks. The streambanks were shallow throughout the site, with heights less than one foot above the base flow water surface in all but a few locations. To facilitate classification of flood related changes, aerial imagery was collected in Furnace Creek on March 15, 2021 and April 15, 2022. The site was walked regularly and geotagged photos were collected starting on January 18, 2021 and ending on March 15, 2024.

The flood classification framework is based on different levels of apparent flood intensity. To develop the categories and use the classification system, a series of ground and vegetation indicators were determined through field examination. Flood evidence in each category was summarized into short narrative descriptions.

The following considerations were developed during the classification process and used to establish boundaries with common flood classification throughout Furnace Creek:

- Classification was limited to living vegetation. Wind action and very low flood velocities can streamline dead vegetation. Velocity thresholds linked to the ability of vegetation to withstand flood forces that are used in stream restoration design – see Fischenich (2001) as an example - are based on living vegetation.
- Boundaries surrounding classified areas were made as continuous features until one of the following occurred: (1) a change in indicators warrants a change in category, (2) the polygon was bounded by edge of valley and channel (boundaries should not cross channels), (3) a primary channel bend apex was reached.
- Areas were excluded from classification if: 1) they were not represented in the 2D model. This included areas in the influence of downed trees or areas where the geometry changed since the initial survey. 2) erosion control blanket was installed and not biodegraded. 3) insufficient data in the form of field notes or ground and aerial photography was available to classify the area.
- Evidence of erosion was not collected in highly erodible sandy soils which are mobilized across a wide range of velocities. This includes portions of the lower Furnace Creek restoration. In these areas, if the evidence provided by vegetation was sufficient the area was classified, otherwise it was excluded.

- Areas of the floodplain where the growth of vegetation was suppressed due to persistent surface flow or pooling of water were not classified as bare areas.

3.1.2. Statistical Methods

To evaluate whether the differences in median velocities between categories were statistically significant, a Kruskal-Wallis rank sum test was used. Significance levels between individual categories was determined using a Wilcoxon rank sum test with the Bonferroni p-value adjustment method. Statistical analysis was performed on the median velocities of each classified area, with significance testing occurring between areas which share the same classification category.

Figure 3. Flood (left) and Post-flood (right) Imagery During July 2021 Event at Furnace Creek. Observation posts used for model calibration are visible in both images.

3.2. Results

Several major flood events occurred during the study, with the largest occurring September 1, 2021, due to Hurricane Ida. An event of similar magnitude dating to July 27, 2021, which occurred during daytime hours, is shown in Figure 3. Flow data at the upstream culvert from this July 27th event, Hurricane Ida on September 1st, and flow estimates from intermediate points on the rising and falling limb of the hydrograph are shown in Figure 4. The estimated peak flow from Hurricane Ida was 475 cubic feet per second (cfs), which was close to 569 cfs, the 50-year event predicted from the hydrologic model TR-55 which was provided by RK&K, the project design consultant. 2D model calibration to Hurricane Ida can be seen in Table 4 for the monitoring station located at the midpoint of the site. Calibration was used to determine the floodplain vegetative roughness and to determine the increase in flow from the upstream culvert to the monitoring station at the midpoint of the site. The events dating to July and September of 2021 provided significant evidence of flood disturbance to the ground and vegetation; this evidence was used to develop and apply the flood classification system.

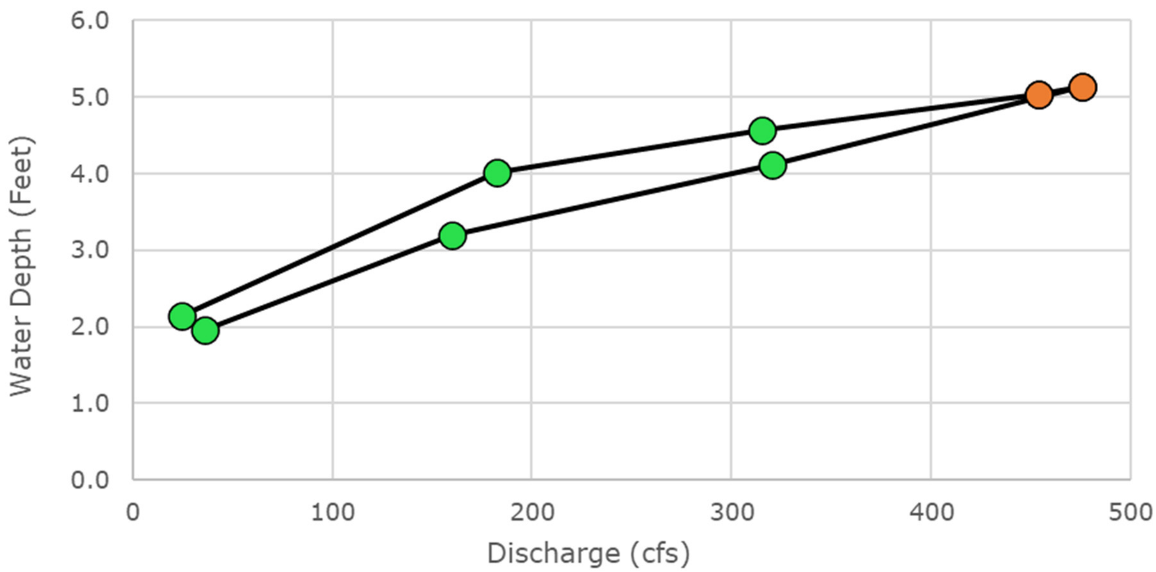

Figure 4. Flow Estimate at Upstream Culvert. 2021 Events on 7/27 (right) and 9/1 (far right, Hurricane Ida) are shown in orange. The event shows typical hysteresis, with increasing and decreasing flow shown by line connecting points in a counter-clockwise direction.

The flooding classification framework can be seen in Table 5, with photographic evidence linked to the flooding categories in Figure 5. The Furnace Creek floodplain was dominated by herbaceous vegetation and saplings due to the wetland character of the floodplain and the age (less than 2 years old) of the restoration. For this reason, the flooding classification system should be viewed as having been developed in an environment dominated by herbaceous vegetation. The grouping of shallow stream bank and floodplain areas together was justified based on the similarity of channel bank and near-bank floodplain velocities. The similarity of velocity data was evaluated by developing non-parametric distributions of velocity data found within one channel top width of the left and right channel banks to the velocity data found an additional top width outside of these areas. The quantiles of the velocity distributions from these two areas were compared and found to deviate by less than one tenth of a foot per second.

Two forms of evidence were essential to the development of the classification system. The first form of evidence was in the streamlining or deformation of living vegetation tissue. The hydrodynamic forces acting on vegetation during floods lead to bending of vegetation in the direction of flow. Vegetation may fully recover from the effect of these hydrodynamic forces if the basal area of the plant was free from noticeable erosion and the individual blades retained enough elasticity to spring back to a vertical orientation. If vegetation had returned to a vertical orientation, flow direction could not be determined. Where hydrodynamic forces were higher, the vegetation did not recover from bending, and the growth of the plant following the event maintained the evidence of streamlining. The classification of living vegetation was not based on vegetation removal due to floodplain erosion. The density of vegetation pre- and post-flooding events was similar. The sedges and rushes which were found within the floodplain in category 3 areas were resistant to uprooting. The focus of the classification system is on the evidence visible in rooted, living vegetation.

The second form of evidence was in the eroding or retentive character of the flooded area. Where hydrodynamic forces are low, organic matter and fine sediments were likely to deposit or be trapped by living vegetation, trees, and woody debris. At higher velocities and greater hydrodynamic forces, organic matter and sediment were likely to be transported downstream through vegetation, and erosion of soil around vegetation down to the resistant materials, including basal gravels or installed rock, may have occurred.

Table 4. 2D Model Calibration Results

Peak Flow (cfs)	CH *n*	FP *n*	Water Surface Bias (ft)	Water Surface RMSD (ft)	Velocity Bias (ft/s)	Velocity RMSD (ft/s)	Flow Estimation Method
428	0.04	0.055	0.5	0.6	0.3	1.1	70% of 610 cfs
428	0.04	0.06	0.5	0.5	0.5	1.2	70% of 610 cfs
428	0.04	0.07	0.4	0.4	0.7	1.3	70% of 610 cfs
544	0.04	0.055	0.3	0.4	0.0	1.0	$Q_{US} + Q_{US}*0.5\Delta DA$
544	0.04	0.06	0.2	0.3	0.2	1.1	$Q_{US} + Q_{US}*0.5\Delta DA$
544	0.04	0.07	0.1	0.3	0.4	1.2	$Q_{US} + Q_{US}*0.5\Delta DA$
610	0.04	0.055	0.1	0.3	-0.1	1.0	$Q_{US} + Q_{US}*1.0\Delta DA$
610**	0.04**	0.06**	0.0	0.2	0.0	1.0	$Q_{US} + Q_{US}*1.0\Delta DA$
610	0.04	0.07	-0.1	0.3	0.3	1.1	$Q_{US} + Q_{US}*1.0\Delta DA$
679	0.04	0.055	-0.1	0.3	-0.3	1.0	$Q_{US} + Q_{US}*1.5\Delta DA$
679	0.04	0.06	-0.2	0.3	-0.1	1.0	$Q_{US} + Q_{US}*1.5\Delta DA$
679	0.04	0.07	-0.3	0.4	0.1	1.1	$Q_{US} + Q_{US}*1.5\Delta DA$
794	0.04	0.055	-0.3	0.4	-0.5	1.1	130% of 610 cfs
794	0.04	0.06	-0.4	0.5	-0.3	1.1	130% of 610 cfs
794	0.04	0.07	-0.6	0.7	-0.1	1.0	130% of 610 cfs

Abbreviations: CH, channel; FP, floodplain; *n*, Manning's *n*; ΔDA, difference in drainage area between US flow monitoring at culvert and calibration region. **Selected flow and roughness coefficients.

Table 5. Flooding Classification Framework: Shallow Banks and Floodplains

	Category 1	Category 2	Category 3	Category 4
	Stable & Retentive	**Stable & Mostly Retentive**	**Locally Eroding and Unstable**	**Widespread Erosion and Instability**
Description	*Vegetation and surrounding ground are free from disturbance by flood forces.*	*Vegetation and surrounding ground shows evidence of non-destructive surface flow with material sorting.*	*Areas of scour are present but limited to well defined areas. The density, type and growth of vegetation is modified by disturbance from flood forces.*	*Scour is widespread. The density, type and growth of vegetation is significantly modified by disturbance from flood forces.*
Evidence	Ground evidence: * Wracking and debris accumulation limited to deposition due to wave action or flotation. * Ground shows last year's litter and decaying organic matter. Vegetation evidence: * Flow direction is not evident. Vegetation is upright or bent due to causes unrelated to flood forces. * Vegetation lacks evidence of the influence of hydraulic stress on growth patterns.	Ground evidence: *Flow direction is evident from the wracking of debris on the upstream side of obstacles. * Variation in velocity is evident in the patchy distribution of leaf litter and fine sediments. Accumulations are greatest at the downstream side of obstacles or due to trapping by dense vegetation * Minimal ground is bare, unless due to other causes, including suppression of growth due to the presence of surface water. Vegetation evidence: * Flow direction is evident in the streamlining of some stems and leaves.	Ground evidence: * Scour is localized to areas where flow is concentrated or pinch points, including topographic low points in the channel and around obstacles. * Resistant subsurface material including roots and basal gravels are exposed in areas of scour. * Leaf litter and organic matter accumulations are limited and transient. Vegetation evidence: * Most stems and leaves are streamlined. * Hydrodynamic loading on vegetation is leading to minor, permanent deformation. * Vegetation is dominated by species capable of living in environments with scouring flow, including sedges and rushes.	Ground evidence: * Scour is extensive where flow is concentrated, including topographic low points and around obstacles. * Resistant subsurface material including roots and basal gravels are exposed throughout the area. * Areas lacking evidence of scour are limited to those in the wake zone of obstacles. Vegetation evidence: * Most to all stems and leaves are streamlined. Hydrodynamic loading is evident in bent stems, scarred, or broken stems and uneven branching patterns * Vegetation is sparse and limited to species that are adapted to high stress environments.

Categories 1 and 2 represent areas within restoration site that were stable and retentive. Categories 3 and 4 represent areas that were eroding and may be un-stable without sufficient protection through rock installation or other methods. In Furnace Creek, many areas that were classified as category 3 were protected through the installation of rock in the floodplain and channel, which was visible during site visits. No areas of category 4 were observed at Furnace Creek.

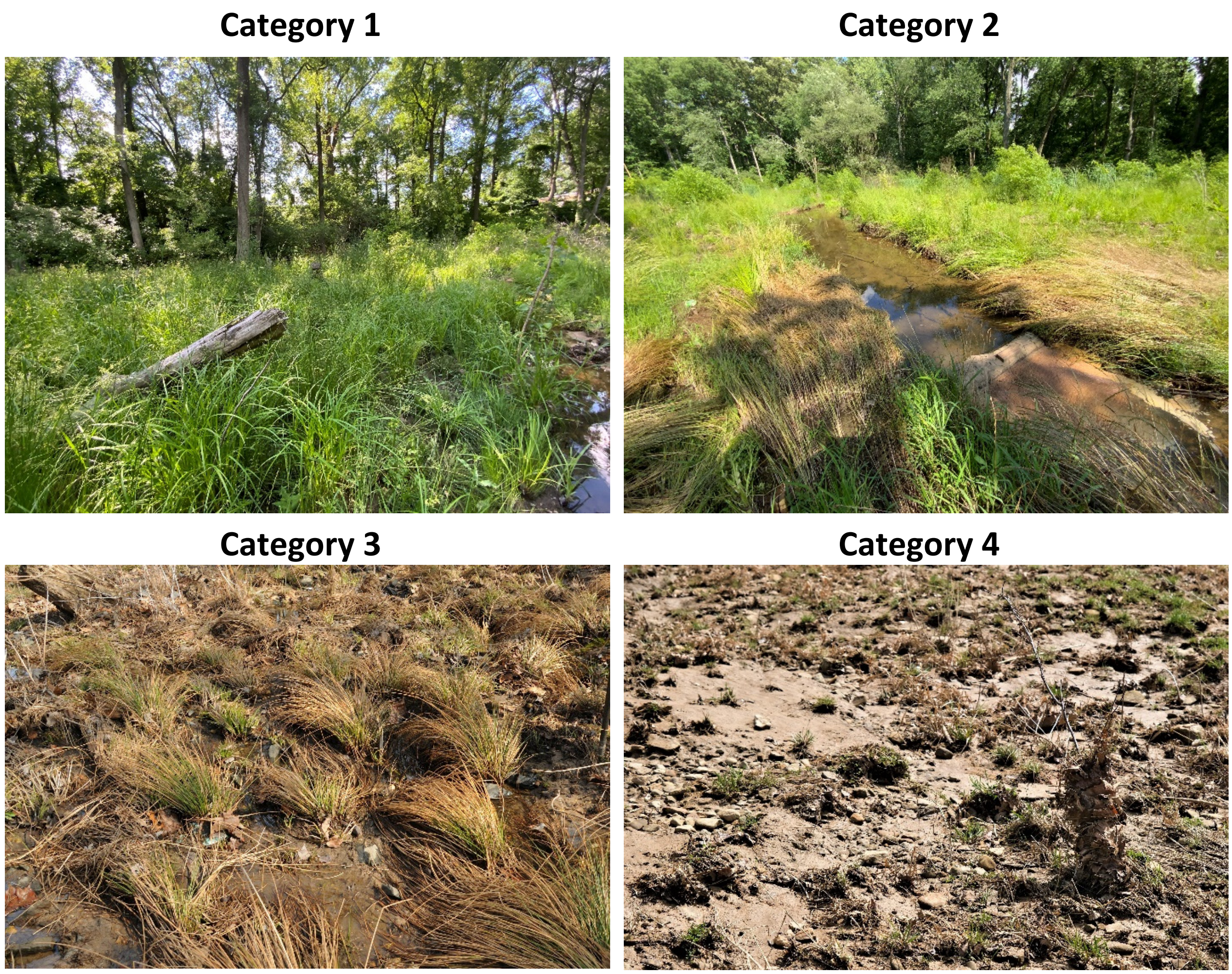

Figure 5. Representative Photos of Flooding Categories described in Table 5. Photos for categories 1 – 3 are from Furnace Creek. The photo in Category 4 is from a restoration site in Kentucky.

Figure 6 shows the classification boundaries at the lower end of Furnace Creek and the 2D model velocities predicted within each classified area. The area outlined in black is excluded from analysis due to the presence of a large, downed tree that is partially in contact with the floodplain. The patchy distribution of velocity around obstacles can be seen throughout the lower area. Obstacles to flow generate velocities that were higher and lower than the median for the area due to, respectively, acceleration of flow around the sides of the obstacles and the generation of wake zones due to flow separation. These small areas of flow acceleration/de-acceleration were not evaluated separately. Instead, the larger area surrounding the obstacles was examined, including indicators that occur because of the influence of obstacles.

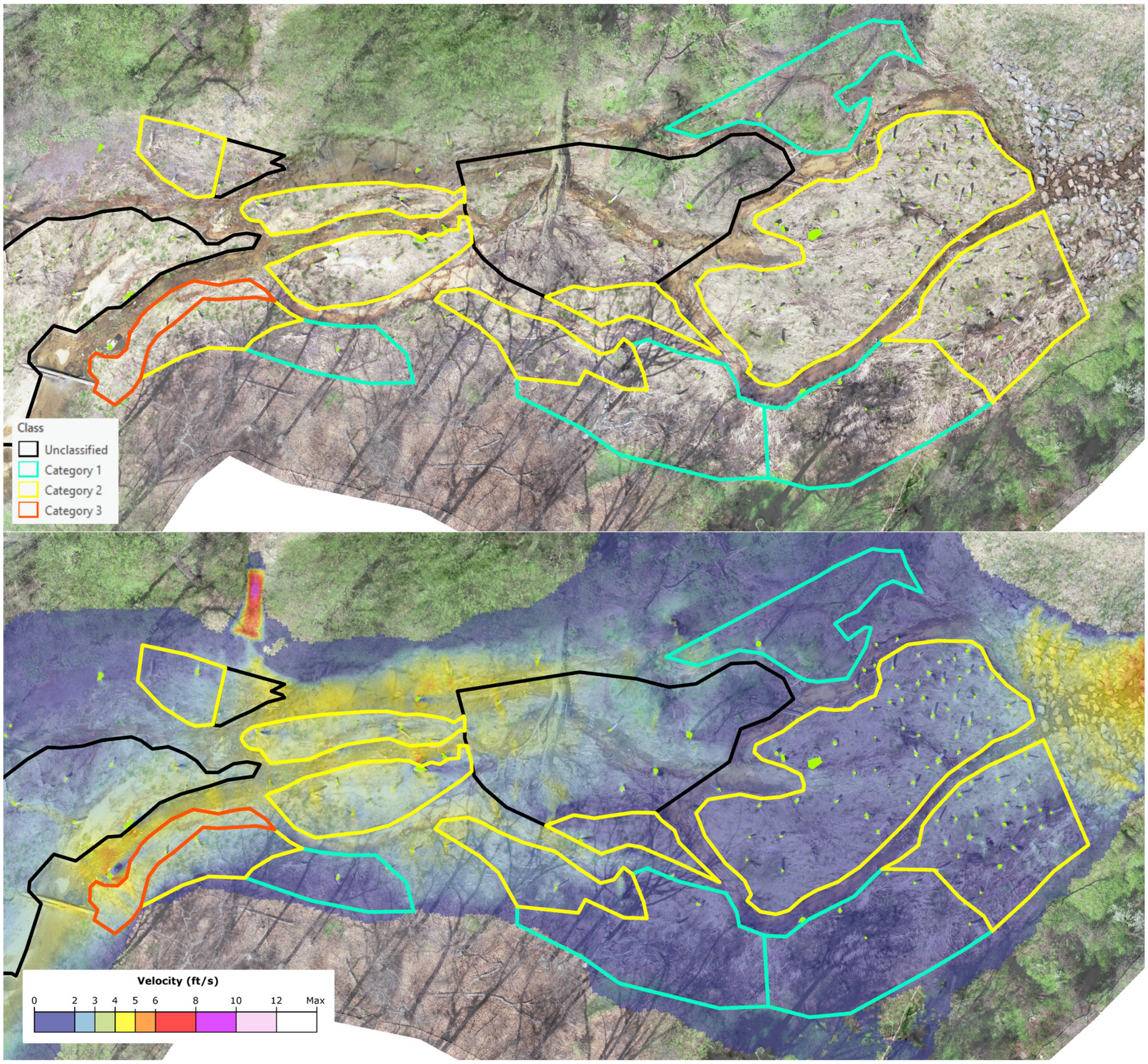

Figure 6. Classification of Floodplain Areas shown over aerial imagery (above) and 2D model velocities (below). Light green areas are large wood obstacles. Area is located at the downstream end of the Furnace Creek restoration.

The distribution of 2D model velocities within each classification category can be seen in Figure 7. The distributions seen on the left include all model velocity data assigned to each category across the entire site; the distributions on the right are the median velocities in each classified area. The difference in median velocities between categories was found to be statistically significant with p values < 0.0004 for all pairwise differences.

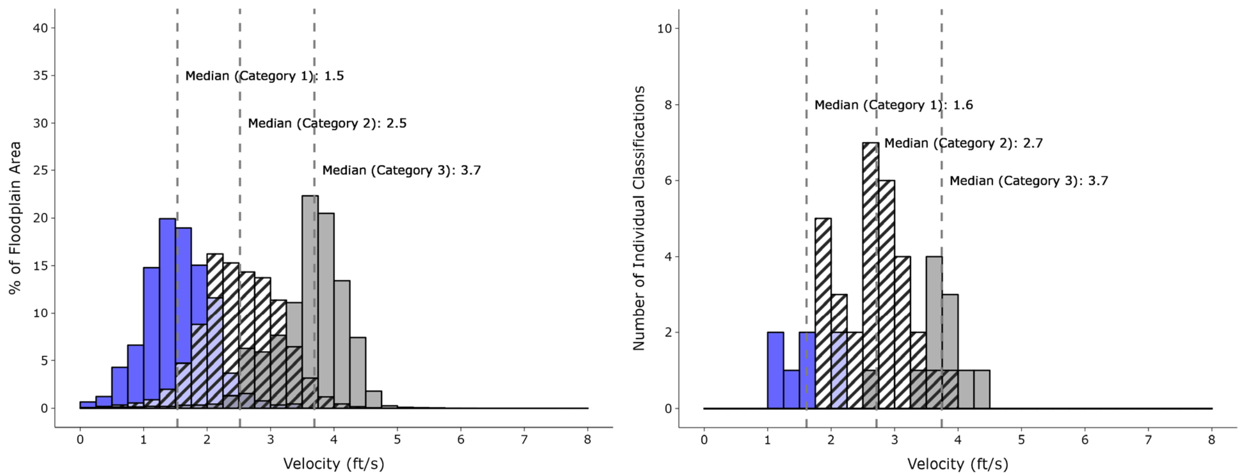

Figure 7. 2D Model Results by Floodplain Classification Category. Results for all model cells (left) and for the median velocity in each unique classification area (right).

3.3. Discussion

In this examination of flood disturbance at Furnace Creek following the major events of 2021, we found evidence for the general reliability of 2D models to predict the vulnerability to flood disturbance of shallow bank and floodplain areas dominated by herbaceous vegetation. The presence of shallow banks throughout Furnace Creek was important context to these findings. 2D models applied to streams with shallow banks are more compliant with the simplifying assumptions of the shallow water equations, which are described further in section 4.3.2 and chapter 6. We also find evidence that 2D models can effectively predict the expected function of those areas as determined by their erosive or retentive characteristics. The median velocity in category 3 - which represents the category where erosion and flood damage to vegetation are initiated - agrees well with published values for disturbance to short native and bunch grasses (Fischenich, 2001).

As conceived, the categories are semi-distinct and narrative in nature, leading to indicators which blend between adjacent categories. This ambiguity in classification increases the spread of velocity distributions about the median value in each category. Velocity distributions are also influenced by the variability of the modeled environment, including vertical obstructions, lateral contractions and expansions, and abrupt changes in terrain which occur over small areas and are embedded within larger classified areas. Reducing the number of categories from 4 to 3 could reduce the ambiguity in classification but would also reduce the effectiveness of the system by limiting the number of retentive and erosive categories, both of which have a weaker and stronger form that is determined by the intensity of flooding.

The study was initiated at Furnace Creek after the site had experience multiple flood events, both during the 2.5 years under construction and post-construction. All restoration sites are vulnerable to flood damage during and after construction; those, like Furnace Creek, with urban hydrology, sandy soils, and a lack of space to allow flood flows to bypass the work area are very vulnerable during construction and prior to vegetation establishment. These flood events led to the presence of local areas of floodplain scour where installed rock was exposed and a lower density of vegetation. The entire site was walked prior to the flood events documented during this study to determine the condition of vegetation and disturbance to the ground that was present prior to the observed flood events. The flood evidence observed in category 3 areas reflected a combination of evidence from flood events which pre-date this study and the observed events from 2021. For this reason, it was important that multiple lines of evidence were considered before classifying an area as category 3, above the threshold for erosion of the ground and permanent deformation of vegetation, and before linking the flood velocities from a specific event to the indicators present within the area following that event. The observed events of 2021 occurred in late summer, well into the growing season, and provided sufficient indicators for classification, including newly deformed vegetation with extensive streamlining, root exposure, and removal of litter and organic matter from topographic low points and deposition against and in the wake of obstacles. These indicators were not observed in category 1 or 2 areas.

One limitation of this study is the absence of category 4 data. Small areas which were consistent with indicators in this 4th category were observed, but these are the result of flow separating around obstacles. One of the areas did not justify separate delineation based on its small size, and the second is underlain with erosion control blanket.

As envisioned, the framework can be used in a backward (reconstructing what has occurred) and forward (prediction of what is likely to occur) direction. In the backward direction: is the restoration meeting stated objectives or are flood forces limiting project success? Have changes that occurred during construction altered the intended function of the restoration? In the forward direction, the classification framework may allow the conversion of quantitative data (2D model velocities) typically limited to specialist interpretation into descriptions of the post-restoration environment that can be easily understood by restoration stakeholders with different technical backgrounds. 2D models have great utility in predicting where different types of restored ecosystems are likely to develop.

We recommend that future studies explore the effectiveness of this classification system in floodplain wetland systems like Furnace Creek and with appropriate modifications in forested and shrub/scrub environments. Areas with a forested canopy will suppress herbaceous vegetation, reducing its density and promoting the growth of species adapted to conditions with more limited direct sunlight. We observed this condition at Furnace Creek under willow stands. Areas under canopy may have bare soil that occurs due to shading rather than erosion due to flooding. Collection of flooding indicators at additional sites will strengthen the classification system introduced in this chapter and identify potential gaps in the approach.

The site chosen for this research includes a range of evidence of flood disturbance, from areas which are highly retentive in nature and lacking evidence of flood disturbance to the ground or vegetation, to areas with evidence of disturbance in the form of bent vegetation, exposed roots, minor rilling in the floodplain, and limited retention of sediment and organic matter. It is typical to find a range of conditions within restoration sites which occur over thousands of feet and include a variety of human and natural constraints. In the case of Furnace Creek, most areas which were vulnerable to flood damage were protected through rock installation in the floodplain and along stream banks and through the installation of erosion control blanket.

The classification approach introduced in this study provides a useful framework for evaluating restoration sites with vegetated shallow banks and active floodplains. The results provide evidence for the reliability of 2D models applied to this type of restored environment.

4. PHASE I: EVALUATION OF 2D MODEL RELIABILITY IN RESTORED CHANNELS

4.1. Supplemental Methods

The methods described below are supplemental to the methods in Chapter 2. The research sites used in section 4.1.1 are the natural channel design site Bear Branch, the floodplain restoration sites Furnace Creek and Cat Branch, and the regenerative stormwater conveyance site Cattail Creek. Bear Branch is used in section 4.1.2. The beaver dam analog site Bacon Ridge is used in 4.1.3.

4.1.1. Rock and Sediment Stability

The reliability of 2D model predictions of coarse sediment stability was assessed using the stability curves of Isbash (1936). Isbash (1936) and similar methods which are derived from it are widely applied to determining the size of rock armoring in streams and rivers (Maryland Department of the Environment, 1999; Maynord, 1993b). The Isbash stability curves link the movement of sediment particles to a critical flow velocity in the vicinity of the particle; in practice this critical velocity is set as the depth-averaged velocity (Recking & Pitlick, 2013). The use of depth-averaged velocities at the location of the sediment particles allows for straightforward application of 2D models to sediment stability analysis, requiring only the median particle diameter, 2D model velocities at the particle location, and a determination of sediment particle condition as exposed (protruding) or protected from flow.

To evaluate 2D model prediction of the stability of native gravels, cobbles, and installed rock, repeat surveys of the four research sites were conducted. These surveys were conducted throughout the study, allowing for pre- and post-flood examination of disturbance to coarse sediments at locations throughout each research site. Surveys of sediment stability were completed using pebble counts, geotagged ground photos with the horizontal scale identified in the photo, optical scanning of bar and riffle features, and aerial imagery. Aerial imagery was used to evaluate the stability of sediments exceeding three inches in diameter.

A sampling of 100 sediment particles or greater is standard in pebble counts (Wolman, 1954), however, samples should be of sufficient number to ensure that the sample is statistically robust for the sampling objective (Bunte & Abt, 2001). In this research, the approach to defining the median sediment diameter in areas where installed rock and bar material are present, and where these particles appeared highly uniform, was to measure the intermediate axis of 15 to 20 particles. In two sites, Bear Branch and Cattail Creek, fewer than 10 sediment particles were sampled for sediments exceeding 5 inches in diameter, due to limits on the amount of available sediment. The apparent uniformity of material was confirmed by examining the coefficient of variation and sorting coefficient (Inman, 1952) of sampled sediments at each location.

Sediments were classified as stable or unstable based on evaluating the change in sediment position between repeat surveys. Their initial position was defined as protected - found within a matrix of similar size sediments with the expectation of grain locking to surrounding sediments - or exposed to the flow. The 2D model velocities used in the stability assessment were the average velocities found within the riffle or bar features assessed.

4.1.2. 2D Models in Incised Channels

Limitations to 2D model velocity predictions in the incised Bear Branch channel were evaluated by comparing observed flow patterns to 2D model predictions. The flood events used in the comparison were the two largest events that occurred during the study. For the events, timelapse imagery and videos were available to determine observed flow direction.

Areas of significant bank retreat which occurred over seven years were determined by comparing bank position in the 2021 terrain dataset developed for this study and LiDAR collected for Prince George's County dated to 2014. The bank retreat identified through terrain comparison was due to flood events of varying magnitude which occurred over the seven years, in addition to other erosive forces including freeze thaw. These areas of bank retreat provided evidence of locations where velocities were sufficiently high to cause erosion and were used in evaluating 2D model predictions. The area evaluated was selected because of an absence of observed seepage flow from the bank, which could accelerate erosion from causes other than flood damage. Other stream banks within Bear Branch were observed to have significant seepage flow.

4.1.3. Flow Direction

2D model prediction of flow direction surrounding beaver dam analog (BDA) structures was assessed by comparing observed and predicted flow direction at 16 locations. The analysis was focused on a single flood event which occurred in April 2022 at the Bacon Ridge site. Observed flow direction was determined by painting arrows onto the ground in the direction of apparent flow, collecting aerial imagery of the area using an unmanned aerial vehicle, then digitizing the flow direction angle from the georeferenced aerial imagery. Flow direction was determined from vegetation streamlined by flow and erosion patterns in the floodplain soils and channel banks. Predicted flow direction was determined from the resultant vector of the 2D horizontal velocity components. The azimuth angle from geodetic north was determined for observations and predictions of velocity direction at the same location and then compared.

Bacon Ridge flows to the south with an 11-degree deflection to the east in the study area. The channel was in a wide valley which exceeds 400 feet in width throughout the study area. The channel was historically straightened and remains straight through most of the study area. At Bacon Ridge, velocity directions around 170 degrees indicated flow parallel to the primary flow direction of the channel; direction values greater or less than 170 degrees indicated flow that was diverging from the channel.

4.2. Results

4.2.1. Rock and Sediment Stability

The coefficient variation of the median diameter from sediment samples was 0.25 or lower for most samples and below 0.3 for all samples. The Inman (1952) sorting coefficient was 0.4 or lower for most samples and below 0.75 for all samples, indicating a high degree of particle uniformity and well sorted sediments within each sample (Bunte & Abt, 2001). The primary source of sediment in this analysis differed by restoration site. At Furnace Creek, the source was installed rock in the channel and floodplain, all of which were classified as protected. At Bear Branch, sediments found in a protected position included installed rock located in the channel, both in riffles and bank protection areas, and native gravel and cobble found in point bars. Exposed sediments at Bear Branch included installed rock that was scoured during flood events which occurred prior to the start of research and had been deposited on point bars. At Cat Branch, both exposed and protected sediments were native gravels found in a depositional area of the channel. At Cattail Creek, the exposed and protected sediments were installed rock found in installed weirs.

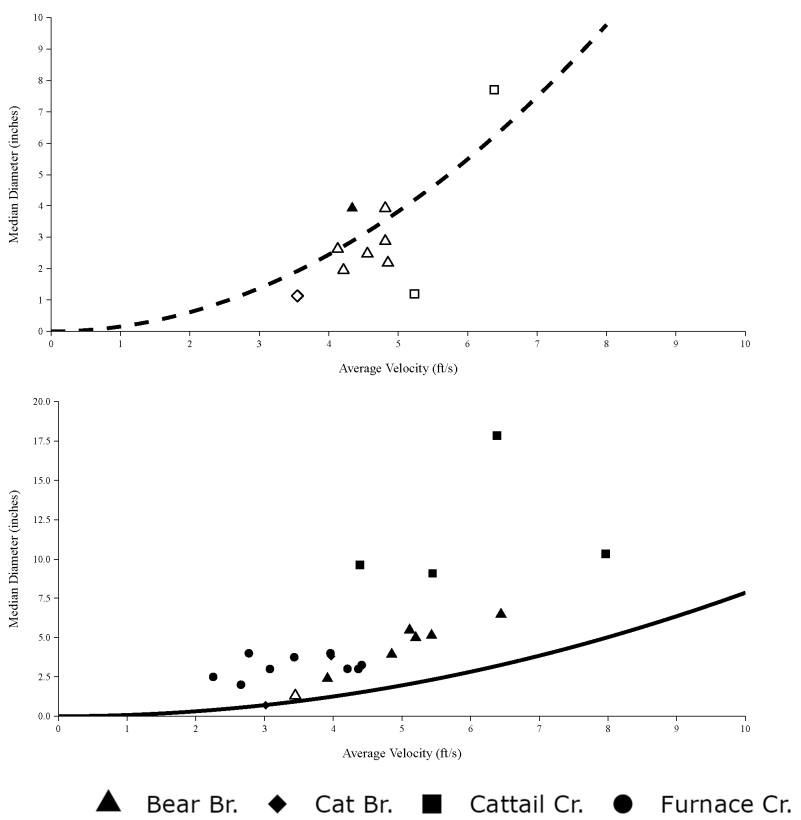

Figure 8. Relationship Between Rock and Coarse Sediment Stability and 2D Model Velocities. Exposed sediments are shown at the top with the exposed Isbash (1936) curve. Protected sediments are shown below with the protected sediment Isbash (1936) curve. Open symbols indicate sediment movement.

Figure 8 shows the results for the sediment stability analysis from the four study sites. Points below the curves are sediments where disturbance is expected to occur. The 2D model prediction of sediment stability using Isbash stability curves was correct for 7 out of 10 exposed sediments and 21 out of 22 protected sediments. Seven out of the nine sediment areas where disturbance was observed during the study occurred within Bear Branch, with one observation of disturbance at Cattail Creek and one at Cat Branch. No sediments were disturbed at Furnace Creek.

4.2.2. 2D Modeling in an Incised Channel

The largest observed flood event which occurred at Bear Branch during the study was estimated at 200 cfs, which equals the 2-year flow estimate from Streamstats (U.S. Geological Survey, 2019). Figure 9 shows this event at Bear Branch in two locations. Figure 9(a) is a series of two bends with a cross vane located at the start of the second bend. Figure 9(b) shows a section of channel where there are multiple vanes in series. Most of the vertical drop in this section of Bear Branch was over the vanes, with minimal drop over riffle features found in between the vanes. The pool depth downstream of each vane was variable, ranging from a foot to greater than three feet at baseflow. In the section of Bear Branch covered by Figure 9(b) the upper two vanes were j-hooks which do not extend to cover the entire channel. The bank retreat highlighted with green boundaries in Figure 9(a) was concentrated at the two bends. The 2D model predicted velocities within the areas of bank retreat were low during the observed flood event.

The camera located in Figure 9(a) was the source of the timelapse imagery of the cross vane that is visible in Figure 10. Multiple features from observed flow patterns are detailed at right, which were extracted from still images and video taken by the timelapse camera. The arrow at (1) was an area of concentrated flow, which originates as a jet of water at the center of the cross vane and loses momentum through the pool by expansion of flow and deflection by the wood downstream of the vane. The arrows at (2) are locations of maximum surface velocity within the channel section that are directed towards channel banks. The arrows at (3) are the outward movement of water from the area of concentrated flow at (1), visible as concentric waves which are sheared from channel center and carry momentum towards the channel boundary and into the banks. The arrow at (4) is a location of weak upstream directed flow that has detached from the area of concentrated flow at (1). The aggradation and degradation of the channel bar seen near (4) provides evidence that the fluid shearing from (1) and upstream directed flow at (4) are of sufficient velocity to disturb small cobbles present on the channel bed and left bank. This pattern of bar aggradation and degradation were confirmed through site visits pre and post flood events.

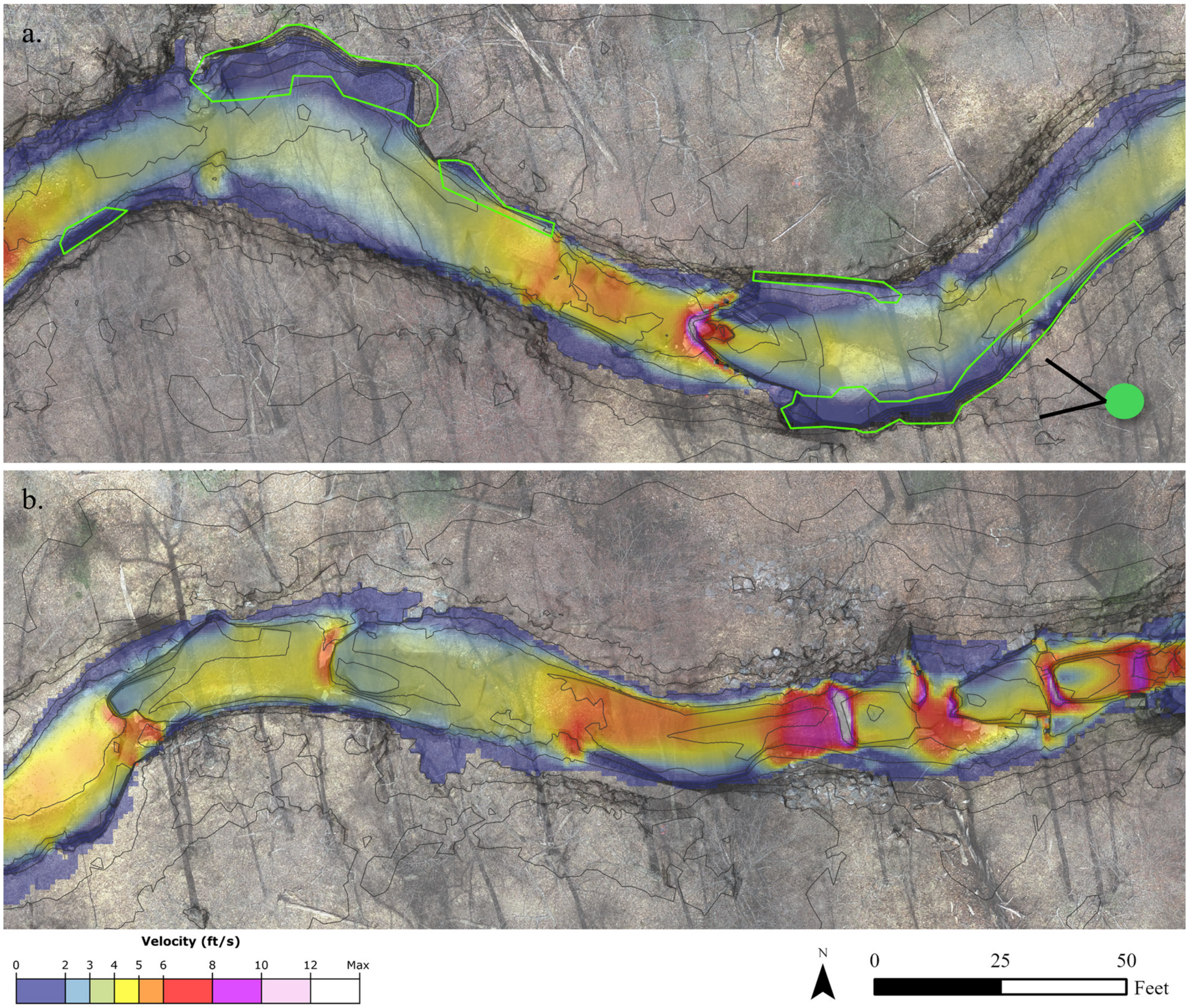

Figure 9. Largest Event at Bear Branch during Study. Monitoring area is shown in (a) with bank retreat mapped by green boundaries and camera location shown by green circle. Camera view is defined by black lines. Vane sequence is shown in (b). Contour interval is one foot.

Figure 10. Imagery of Largest Event at Bear Branch during Study. Imagery prior to the event is shown in above left with the event peak shown in above right. A second flood event with similar kinematics is shown below which highlights surface flow patterns.

4.2.3. Flow Direction Surrounding BDA Structures

Figure 11 illustrates the application of the method for comparing observed and predicted flow direction surrounding BDA structures. The structures are visible in the middle of the figure where higher velocities are concentrated. These structures are constructed to raise the channel bed control to near the top of the channel bank. As the water surface drops over each structure, flow accelerates over and through the woody elements of the structure. Flow that is not conveyed over the structure exits the channel upstream and returns to the channel downstream. The length of the flow path from the upstream location where flow exits the channel to the return location is determined by the local terrain.

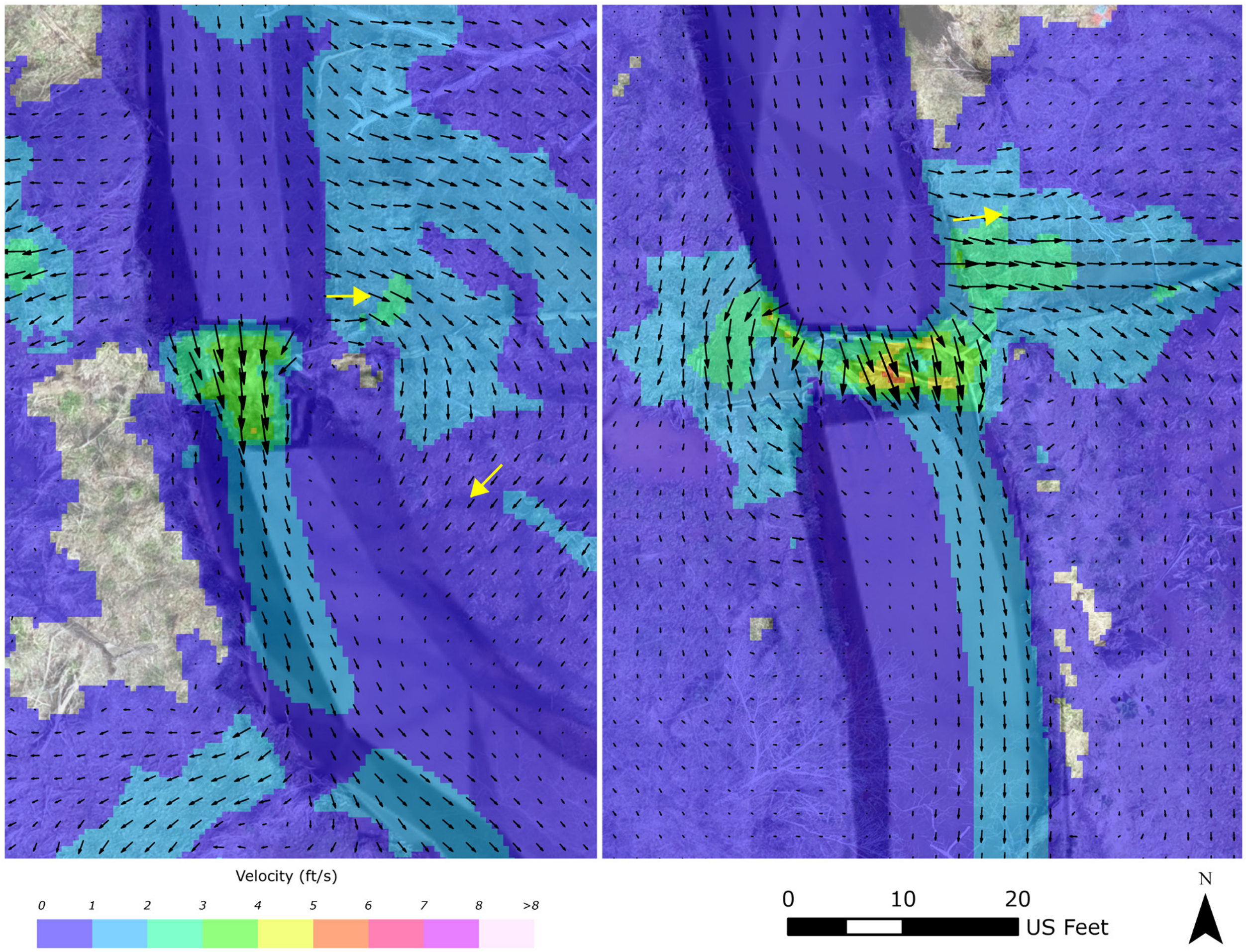

Figure 11. Planview of Flow Direction at Bacon Ridge Structures during a Small Flood Event. Black arrows show the predicted 2D model flow direction. Yellow arrows are the field determined flow directions. No field determined return flow was completed for the right image, where evidence on the ground was limited.

The relationship between observed and predicted velocity direction is shown in Figure 12. In this figure the orange and grey symbols are locations where the observed and predicted flow orientation relative to the channel are the same. Orange symbols are flow directed towards the channel and grey symbols are flow that is exiting the channel. The green symbol is a location where the predicted and observed flow orientation did not agree. The adjusted R^2 is 0.98 for all points (entering, exiting, mixed). No relationship between velocity angle error, as predicted angle minus observed, and velocity magnitude was found.

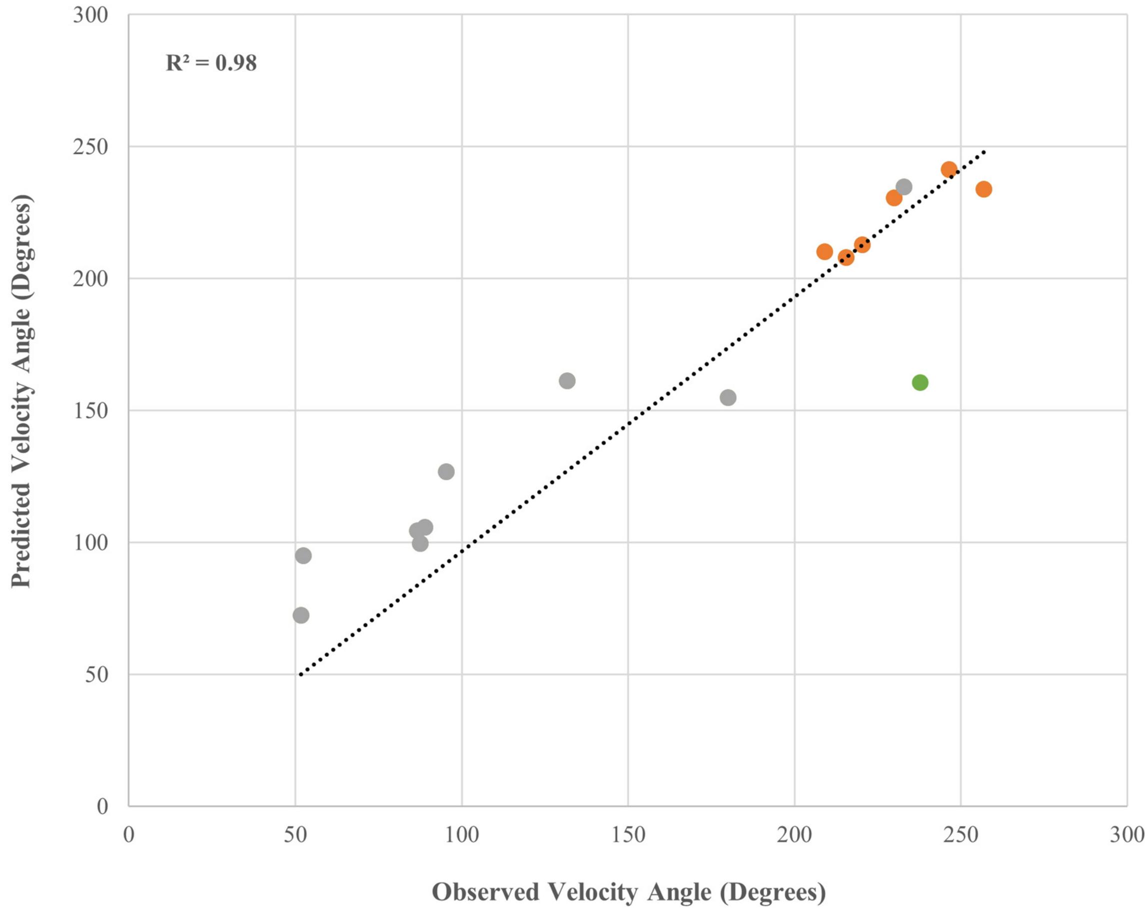

Figure 12. Comparison of Observed and Predicted Flow Direction at Bacon Ridge.

4.3. Discussion

4.3.1. Rock and Sediment Stability

The predictions of sediment stability using 2D models with reference to Isbash (1936) curves were generally reliable for exposed sediments. The misclassified exposed sediments - those where movement was predicted but not observed, or observed but not predicted - were within 20% of the predicted velocity in all cases. Protected sediments were correctly classified as stable with one exception. The stability of these protected sediments during the flood events which occurred during the study is expected; most protected sediments are installed rock, which had been sized by restoration practitioners to withstand scouring flood flows. At Furnace Creek, Cat Branch and Cattail Creek, rock sizing was completed through the use of 2D modeling.

Both the prediction of the 2D model velocity or boundary shear stress at a particular location in the streambed and the characterization of the bed sediments at the same location have uncertainties that affected the reliability of sediment stability predictions. Several factors affect the mobility of bed material, including the density of the sediment particles, shape of particles, size distribution of sediment mixtures, particle packing (particle exposure), the non-uniformity of the bed sediment mixture, and the tendency of some sediment mixtures to armor the surface. Narrowing the characterization of bed material to two parameters - median particle size and exposure - can lead to large variations in mobility for the same particle size. The prediction of flood velocity or boundary shear stress at a particular location on the streambed also has considerable uncertainty because of variability, non-uniformity and inaccuracy of the selection of roughness coefficients, topographic errors, and the inability of 2D models to represent turbulent, three-dimensional flows. The classification of particle motion, estimation of sediment texture and relative roughness, and properties of the flow all contribute to this uncertainty (Buffington & Montgomery, 1997). For these reasons, reliable 2D model predictions of sediment stability will include some misclassifications. The sediments were sampled from within areas of riffles and bars where the 2D model predictions are relatively uniform, reducing uncertainty in the determination of a flood velocity to use for stability analysis.

The agreement between predicted and observed sediment stability in this evaluation provides supporting evidence for the reliability of 2D models used to evaluate sediment stability in channels. The appropriate solution for the uncertainty in rock and sediment stability which is typical of sediment transport analysis and has been observed in this study is to incorporate a degree of conservativism in the restoration design process. If an area within a restoration has a predicted velocity at the 100-year flow of six feet per second, the rock protection that is specified for the area should be stable beyond six feet per second, to account for uncertainty described above. The best method for addressing uncertainty in the interpretation of 2D model predictions for rock and sediment stability will depend on the project objectives. Methods for addressing uncertainty can include revising the design to lower the predicted model velocities, increasing the size of installed rock, particularly where increasing the size does not significantly impact the project budget, and evaluating changes in predicted model velocities which occur due to changes in the design flow. Chapter 5 demonstrates the importance of evaluating 2D model predictions across a range of design flows; 2D model velocities may increase steadily with increasing design flow, or may increase and then decrease due to the influence of backwater.

4.3.2. 2D Modeling in an Incised Channel

Figure 10 provides evidence of features within the flood flows at Bear Branch which were responsible for the disturbance of sediments at the channel bed and contribute to bank erosion. The largest observed event shown in Figure 9 and visible in the imagery in Figure 10 is not the largest event that occurred in the site during the 7 years over which bank retreat was compared. Flood velocities were observed to increase until the 10-year event and then decrease due to the influence of backwater from the downstream culverts (see Appendix C for model exhibits of recurrence interval flows and the largest observed event). Although the largest observed event during the study was not likely to have produced the highest velocities on the areas which have experienced bank retreat, the exhibits for Bear Branch show that 2D model predicted velocities remained low at the eroded channel banks. These previously eroded banks are at risk for further erosion, and erosion of the areas where bank retreat occurred prior to 2021 was observed during this study.

2D models do not fully represent the peak local velocities that occur near the channel bed downstream of vanes, where the water surface drops abruptly. Strong three-dimensional flow features around vane structures were defined from observations collected during the largest flood event which occurred during this study. Similar three-dimensional features have been documented surrounding natural channel design structures in prior research efforts (Khosronejad et al., 2013). 2D models effectively represent flow parallel to the streambed; they do not represent vertical flow acceleration or deceleration, highly non-uniform vertical velocity profiles, or vertical flow separation. The vertical drop over the vane and vane arms creates a large step in the channel bed which leads to plunging flow, where flow is directed vertically towards rather than along the streambed. This plunging flow may cause higher velocities near the bed of channel than along the water surface. The extent of this high near-bed velocity region depends on many factors: the alignment of the approaching flow, the vertical drop height, the geometry of the vane structure, the bed topography below the vane, and obstacles to flow below the vane. Below vanes, large-scale vortices are often formed that alter large portions of the downstream channel flow pattern and will influence the location of the high near-bed velocity region. The scour of larger, coarse sediment and rock below vanes which is deposited in bars below the vane pool can alter the hydraulics of flow exiting the pool and increase local instabilities, including bank erosion.

Although the 2D models at Bear Branch effectively predict the horizontal flow pattern upstream of the vane, downstream of the vane the modeled flow is relatively uniform and hydraulically simplified, relative to the complex, observed three-dimensional patterns that are driving erosion and sediment transport in the downstream bed and banks. The deep and narrow channel of Bear Branch enhances the three-dimensional flow effects which occur below the vane. Although the local amplification of near-bed velocities in pools downstream of structures is not represented by 2D models, the 2D model velocity of the plunging flow before it enters the pool provides a reference for the maximum velocities which may exist along the bed and banks of the channel below the vane.

Similarly, 2D models do not fully represent the peak near-bed or near-bank velocities that occur in low radius bends in narrow, deep channels. 2D models have a partial accounting of the centrifugal forces which drive flow towards the outer bank in bends, the transverse pressure gradient that drives flow inward, and flow acceleration or deceleration due to bend geometry influenced by the size and orientation of the point bar and bend pool. 2D models can produce the horizontal flow separation which is observed to occur frequently along the inner bank in low radius bends (Blanckaert et al., 2013) and the coincident acceleration of flow towards the outer bend. 2D models do not represent the three-dimensional, helical pattern that drives flow towards the outer bank and bed, including the vertical separation which accompanies this flow. The three-dimensional effects on peak near-bed or near-bank velocity in bends increases with decreasing bend radius (R) to channel width (B) ratio (R/B). Where this ratio is less than 2.5 in narrow and deep channels, 2D models will more significantly underpredict peak local velocities. The amplification of near-bed velocity and boundary shear stress in tight bends has led to the development of correction factors which can be applied to estimate representative peak values. For example, velocity amplification factors have been developed by Maynord (Maynord, 1993a) for channel bends.

The above discussion should provide context for the interpretation of 2D model output. Even where the representation of velocities and boundary shear stress are incomplete, 2D model output can provide useful data for determining the general flood vulnerabilities of an area. 2D model output can also be used for comparison of areas within and between sites. Narrow and steep sections of Bear Branch where flow cascades over multiple structures (Figure 9(b)) have higher mean and maximum velocities than relatively flat sections of channel or those that are influenced by backwater. The drivers of these vulnerabilities – the degree of channel incision, the local slope, the curvature of the channel, the amount of water conveyed over the channel and floodplain – are all embedded in the 2D model output. Further discussion of interpreting 2D model outputs in incised channels can be found in Chapter 6.

4.3.3. Flow Direction Surrounding BDA Structures

The predicted pattern of flow shown in Figure 11 was typical of BDA structures at Bacon Ridge. Other restoration sites using beaver dam anolog structures to raise bed elevations to close to the top of channel banks will have similar patterns of flow. Compared to natural channel design structures or constructed riffles, BDA structures have an irregular geometry. At Bacon Ridge this irregular geometry was defined by overlapping pieces of large wood, inverting large root structures, and the protruding tops of posts that were set into the existing stream bed. The sill elevations formed by the wood components of the structure and adjacent channel banks distributed the flow along the structure and to each side in a way that was unique to each structure. This approach created the conditions for flow to diverge from the channel above the upstream end of each structure. This divergent pattern of flow can lead to areas where flow is concentrated on channel banks and the adjacent floodplain, which may cause erosion if those areas are not sufficiently protected.

The research completed at Bacon Ridge demonstrated the reliability and utility of 2D models to predict flow direction surrounding BDA structures and the areas where flow concentration was expected to occur. The observed and predicted flow directions were in good agreement in areas where flow enters and exits the channel, with closer agreement for flow entering the channel. 2D model output was developed using the high resolution terrain dataset at Bacon Ridge as an input. The terrain is of sufficient spatial resolution and accuracy to capture the general flow pattern around each structure, with some locations leading to greater flow over the structure or to the left and right sides of the floodplain. The exact distribution of flow over the structure and to the left and right sides are determined by: 1) the local geometry and roughness of materials along the sill captured in the 2D model; 2) changes in geometry and roughness due to local patterns of erosion and deposition, and woody debris recruitment or loss which were not captured in the 2D model; and 3) hydrodynamics including flow through structure materials which were not captured in the 2D model. (2) and (3) above lead to local differences in flow that were not effectively captured by 2D model predictions. The areas where flow returns to the channel are simpler to model, and typically consist of gently sloping areas of the floodplain with shallow areas of concentrated flow. The differences in complexity of the areas where flow exits and returns were the expected cause of differences in the accuracy of predicted flow direction.

Flood vulnerability assessment using 2D models can be successful in environments where the features controlling the pattern of flow and locations of maximum flood velocity have irregular geometry, provided that the resulting flow patterns are primarily two-dimensional in nature. At Bacon Ridge the vertical drop in water surface over each structure was less than half a foot in most cases, and this drop occured over a distance of five or more feet - the length of the structure within the channel - reducing the areas of plunging, vertically oriented flow.

2D models effectively captured the curved pattern of flow exiting and re-entering the channel. Practictioners should consider how variability in structure geometry will impact flood flow hydrodynamics, and work to incorporate these effects into 2D models.

5. PHASE II: 2D MODELING OF MAJOR FLOOD EVENTS IN A CHANGING CLIMATE

5.1. Supplemental Methods

The chosen climate change scenario flow was a 33% increase over the 100-year event at each of the five research sites. This increase was sufficiently large, allowing for an exploration of how the flood vulnerability of each site would change under an elevated 100-year event. The 33% increase above current estimates of the 100-year flow for the climate change scenario used in this study was close to the 39% increase predicted by Morsy et al. (2024) for small watersheds in the coastal plain of Virginia by midcentury under the representative concentration pathway (RCP) 4.5 scenario. This scenario is intermediate of the climate scenarios typically examined.

For each site the 2-year, 10-year, 50-year, 100-year and climate change (CC) scenario were modeled. The largest events at each site which were observed during the study and modeled in earlier chapters are not included in the analysis in this chapter, which is focused on a comparison of current and future flood values. Current flow estimates for each site were developed using the U.S. Geological Survey (2019) program StreamStats with regional regression estimates of flow from Thomas and Sanchez-Claros (2019).

2D model velocity changes which occurred due to increasing flow, up to and including the climate change scenario, were evaluated. At all five research sites the 2D model velocity changes within the channel were evaluated. Velocities were sampled within the floodplain for all sites except Cattail Creek, which lacks a floodplain. At all sites, a vulnerable area was selected for separate analysis; this area contained evidence from site visits or in 2D model results indicating that it was uniquely vulnerable to flood damage. These areas may have been protected from flood damage through the installation of rock or erosion control blanket. The vulnerable areas include channel grade control structures at three sites (Bear Branch, Cattail Creek, Bacon Ridge), two areas where flow is contracted (Cattail Creek, Furnace Creek), and a section of channel that is steeper than the remainder of the reach (Cat Branch).

Site abbreviations include FC for Furnace Creek, CB for Cat Branch, CC for Cattail Creek, BR for Bacon Ridge, BB for Bear Branch and BB* for Bear Branch with the influence of backwater from the road culverts immediately downstream removed. The influence of backwater is removed from Bear Branch in this scenario to demonstrate the importance of considering infrastructure effects in flood vulnerability assessment.

5.2. Results

2D modeling results for all events at each research site can be seen in Appendix C. For readers with color vision deficiency these results can be seen in Appendix D.

The median channel velocities for each site can be seen in Figure 13. Because the magnitude of peak flood flows were different between sites, in this figure the flow events are expressed as a ratio of the 100-year flow at each site. From left to right, each site includes the

2-year, 10-year, 50-year, 100-year, and CC Scenario events. The channel velocities at Cat Branch, Furnace Creek and Bacon Ridge sites were similar across flow events; these sites had a median channel velocity around two feet per second at the 2-year, which increased to between three and four feet per second at the CC scenario. For Bear Branch the channel velocity increases from the 2-year to the 10-year event and then dropped due to the influence of backwater from the downstream roadway culverts. The BB* scenario shows that channel velocities would continue to increase until the 100-year flow if the influence of backwater were removed, with most of the increase occurring below the 50-year event. Channel velocities for Cattail Creek increased consistently across flow events due to the confinement of the channel in the lower half of the site.

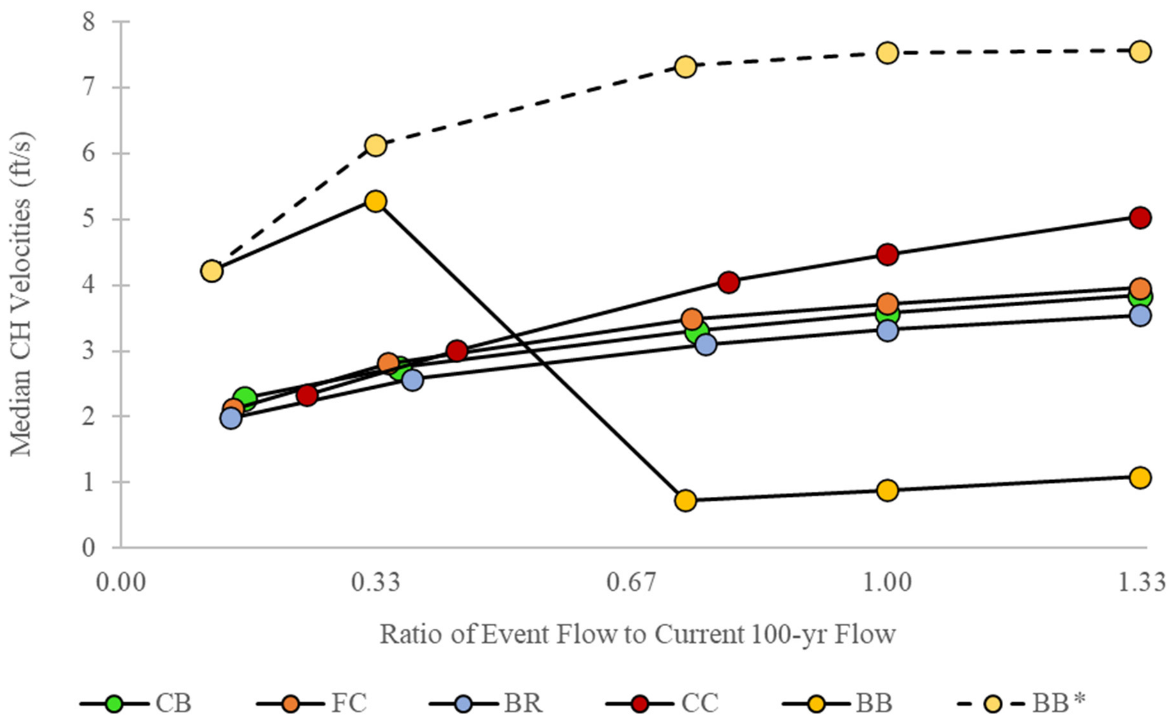

Figure 13. Median Channel (CH) Velocities Under Current and Future Conditions

The median floodplain velocities for each site can be seen in Figure 14. Results for Cat Branch, Furnace Creek and Bacon Ridge were similar in their magnitude and trend, as they are for channel velocities. Floodplain velocities at Bear Branch were low even in the absence of backwater, due to most of the flow being conveyed down the channel. The small areas of floodplain activation which occurred at lower flow recurrence intervals (2-year, 10-year) consist of shallow, low velocity flows in topographic low points on the floodplain. Bear Branch had low floodplain velocities at higher flow recurrence intervals (50-year and above) due to the influence of backwater from the downstream roadway crossings.

The maximum velocities in vulnerable areas for each site can be seen in Figure 15. The pattern for the vulnerable area at Bear Branch was similar to the channel velocity pattern for Bear Branch. This is due to the incised nature of the Bear Branch channel, which led to high velocities prevailing throughout the reach until the area was backwatered at higher flows. Vulnerable areas at both Furnace Creek and Cattail Creek were defined by sudden contraction in the flow. At Furnace Creek this contraction was due to the presence of large woody debris; at Cattail Creek this was due to the presence of a hillside on valley right and a terrace on valley left. The velocities at both sites continued to increase with increasing flow. At Bacon Ridge the vulnerable area was around a beaver analog structure where the water surface drops above and below the structure, leading to the acceleration of flow down the structure and around the left and right sides. As flow increased, the amount of backwater from downstream increased, leading to a lower drop in water surface over the structure and a decrease in maximum velocities. Cat Branch showed a very minor increase in the vulnerable area velocity within the steep section of the channel, despite a significant change in flow from the 2-year to the CC scenario. The wide floodplain at the site reduced the potential for large increases in flood velocities.

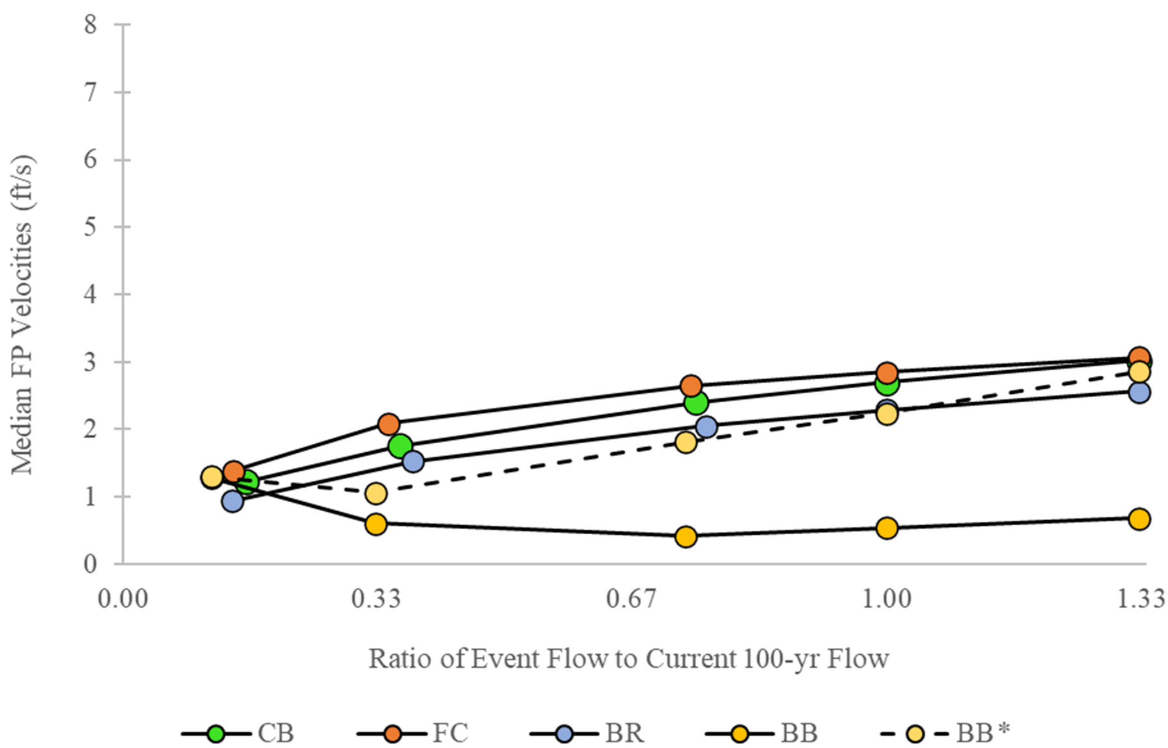

Figure 14. Median Floodplain (FP) Velocities Under Current and Future Conditions

The difference in the 100-year and CC Scenario for the two vulnerable areas within Cat Branch and Furnace Creek are shown in Figure 16. For Cat Branch the steep and curved section of channel which formed the vulnerable area ended where the channel straightens. Where the vulnerable area ended there was a small sediment splay, indicating erosion within the vulnerable area above and downstream transport of gravels. At Furnace Creek the vulnerable area was due to the installation of three large woody obstructions in the floodplain, which locally contracted the floodplain.

The kinematics of the 2D model predicted velocities were similar between the 100-year and CC Scenario events at both sites, with the higher flows in the CC Scenario reinforcing patterns in the velocity results that existed in the 100-year model results. At Cat Branch the peak velocities were centered over the left overbank region at the end of the channel bend and an area of high ground at channel right. There was a second area of relatively high velocity at the edge of the inundated area where the floodplain contracted due to encroachment of the hillside. At Furnace Creek, the peak velocities were located at the left and right edges of obstacles where flow was accelerated around the obstruction. Where flow divided around each obstacle, flow separation occurred, creating wake zones which locally reduced the area of conveyance throughout the floodplain and led to higher velocities in between.

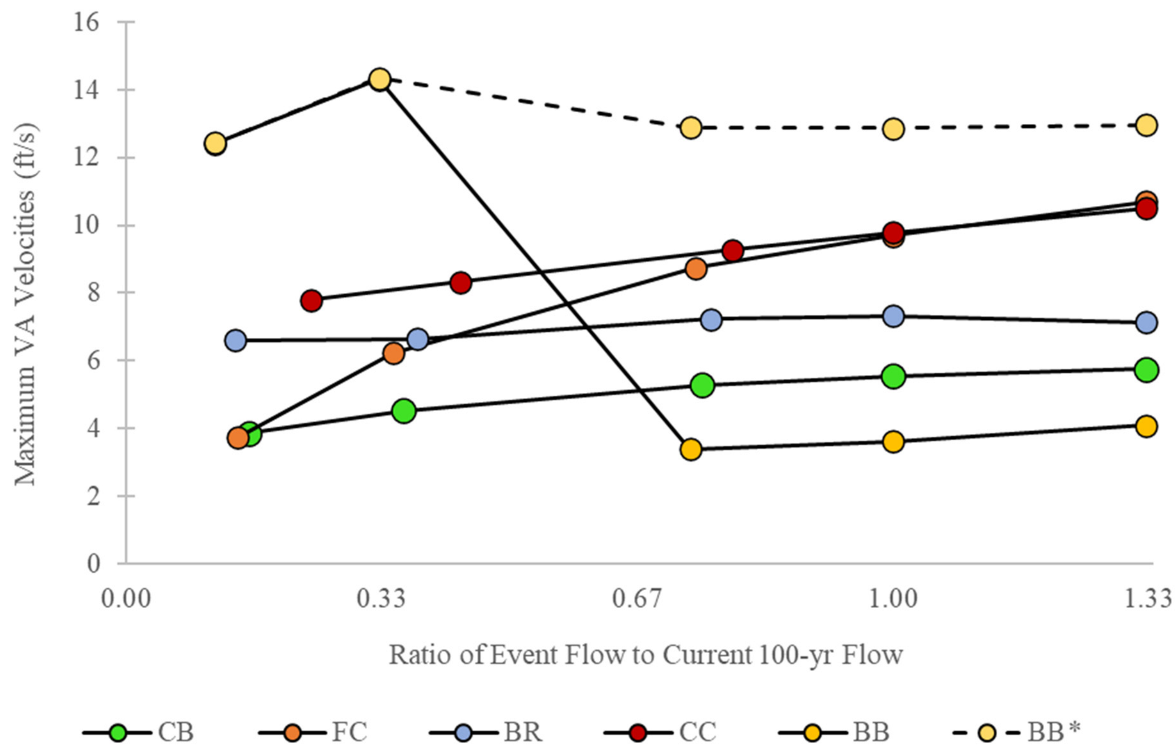

Figure 15. Vulnerable Areas (VA) Maximum Velocities Under Current and Future Conditions

The distribution of flood velocities for the 100-year and CC Scenario event at each site can be seen in Figure 17 through Figure 22. These distributions are broken down by channel and floodplain areas for all sites except Cattail Creek. Table 6 shows how the percentage of floodplain area exceeding velocity thresholds of four, five and six feet per second are predicted to change under the CC Scenario.

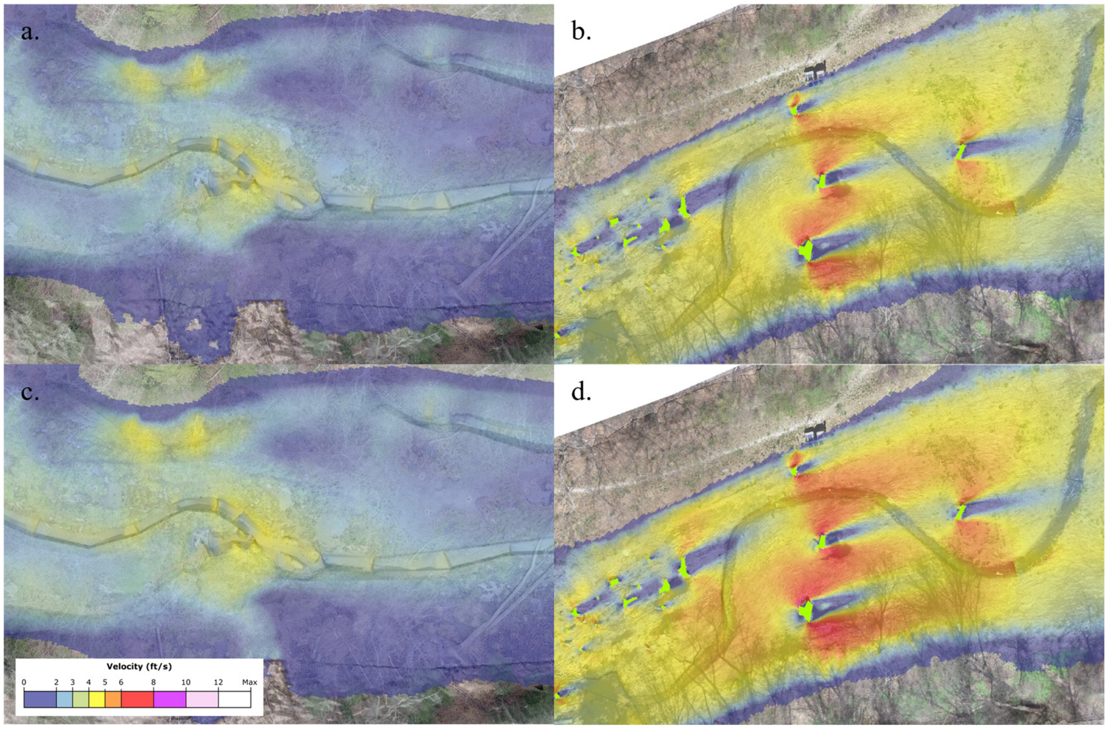

Figure 16. Velocities in Vulnerable Areas at the 100-year and CC Scenario Flows. Plots include the 100-year at Cat Branch (a) and Furnace Creek (b) and the CC Scenario at Cat Branch (c) and Furnace Creek (d).

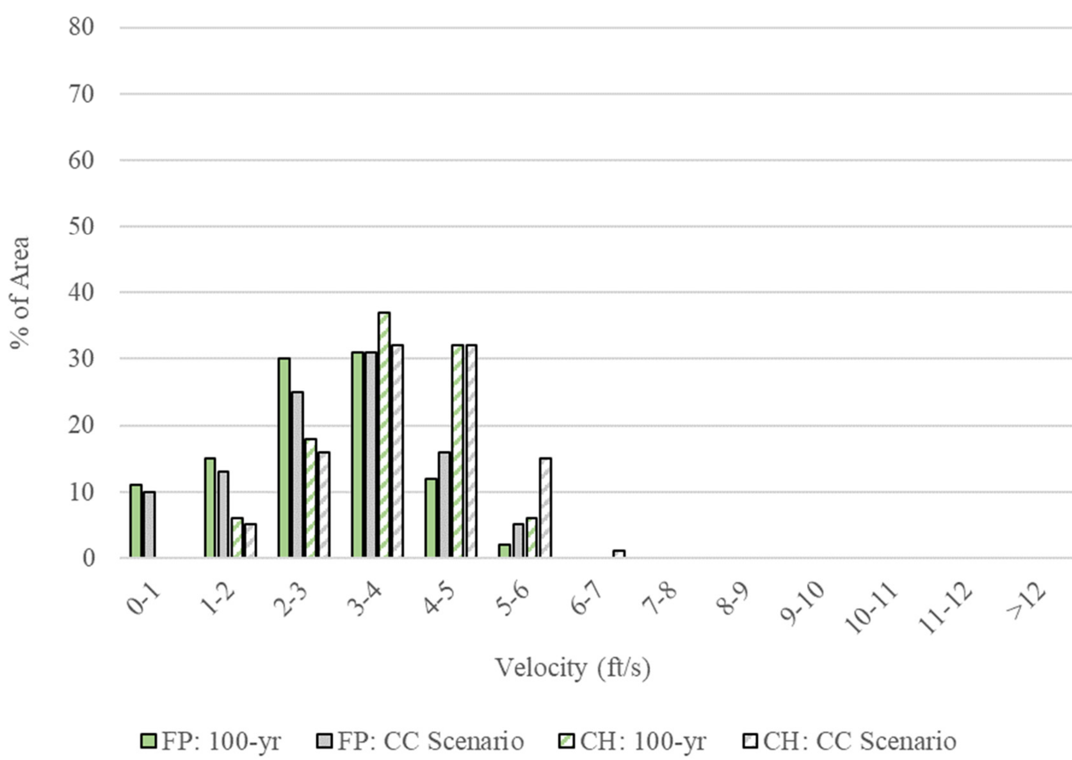

Figure 17. Furnace 100-year and CC Scenario Velocity Distributions

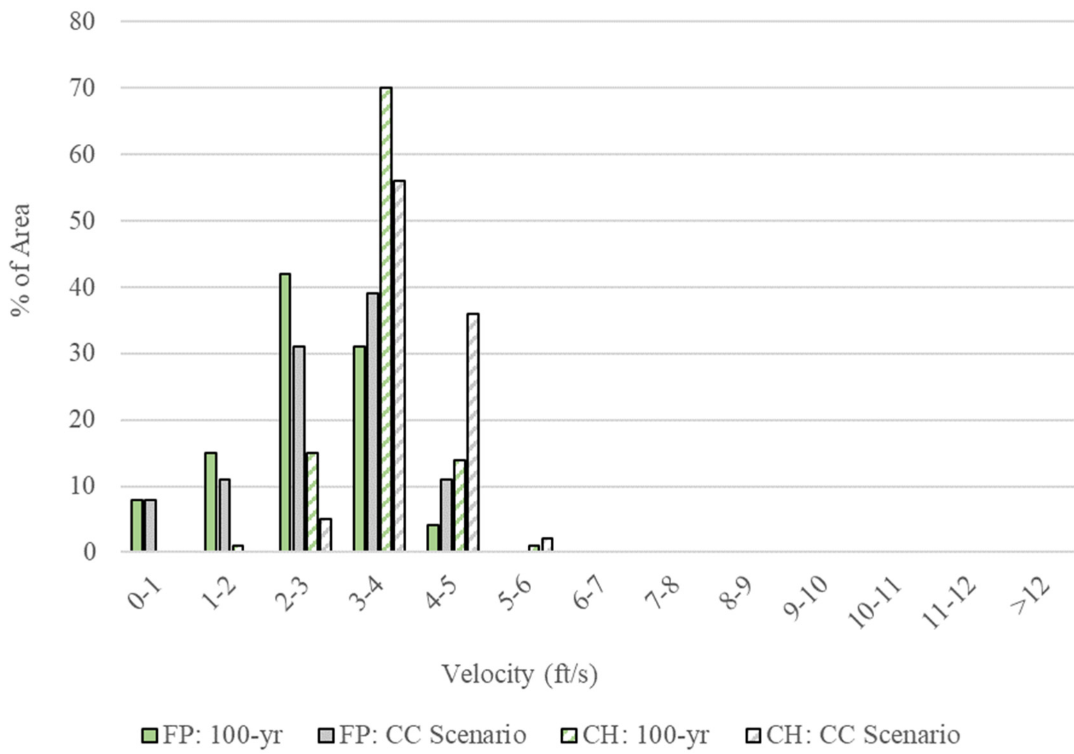

Figure 18. Cat Branch 100-year and CC Scenario Velocity Distributions

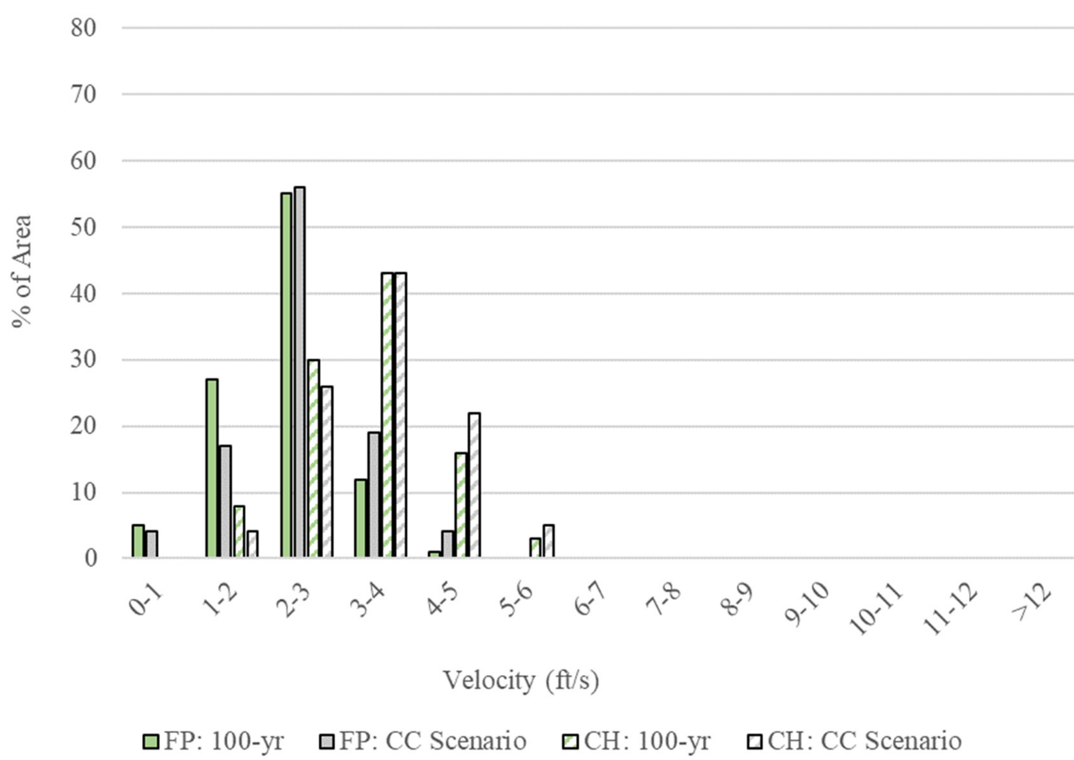

Figure 19. Bacon Ridge 100-year and CC Scenario Velocity Distributions

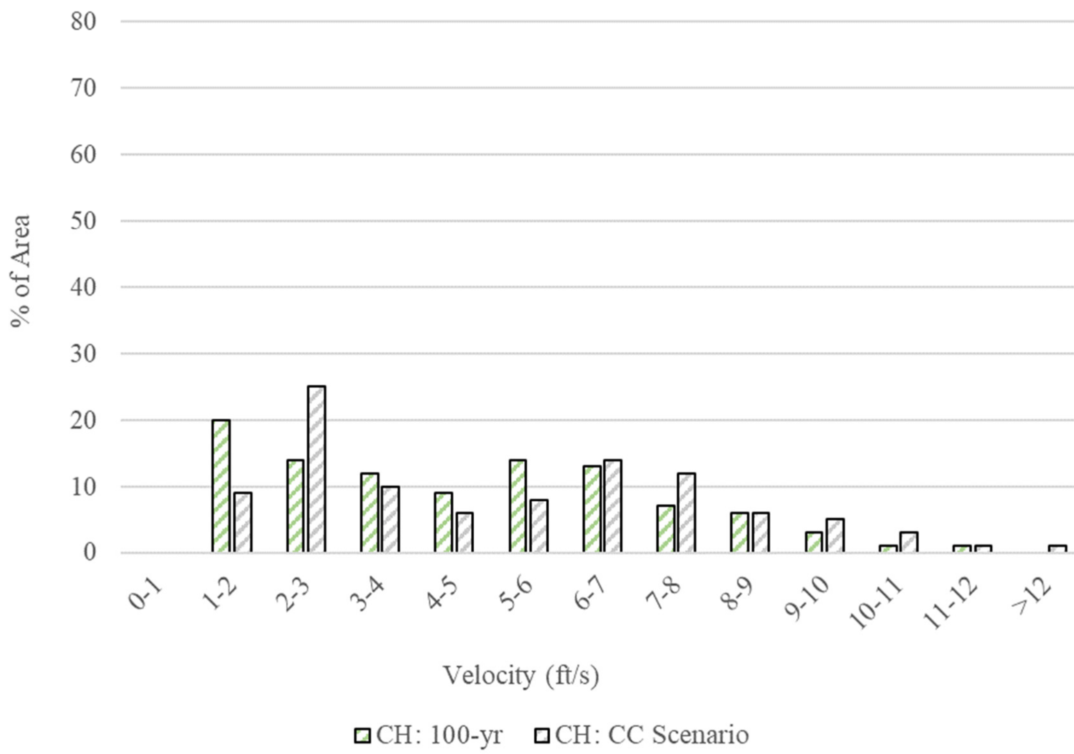

Figure 20. Cattail Creek 100-year and CC Scenario Velocity Distributions

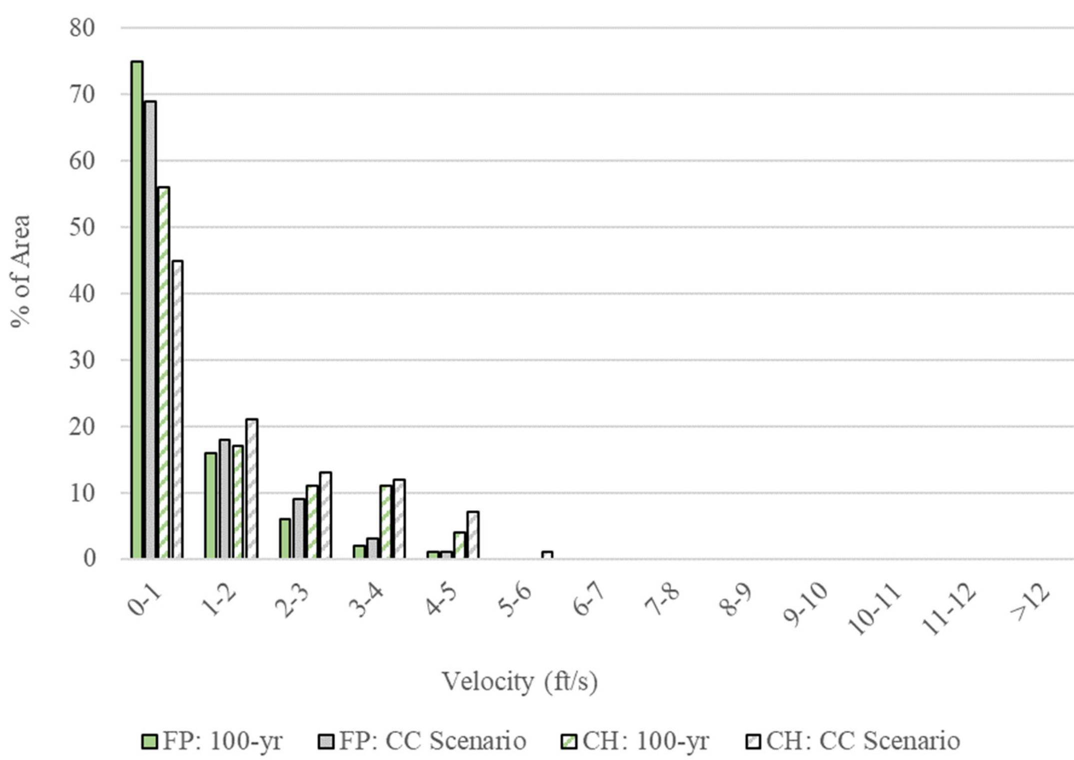

Figure 21. Bear Branch 100-year and CC Scenario Velocity Distributions with Backwater

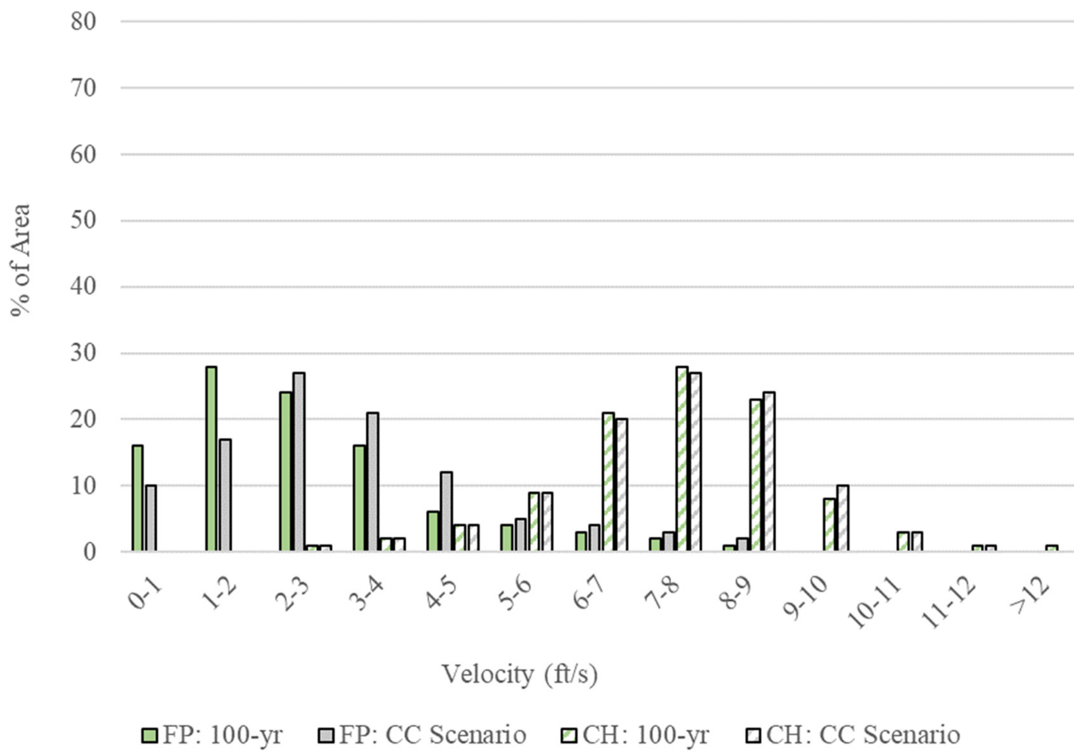

Figure 22. Bear Branch 100-year and CC Scenario Velocity Distributions: No Backwater

Table 6. Exceedance of Velocity Thresholds in the Floodplain at Four Sites

Velocity Threshold	Site	100-yr (% exceeding)	CC Scenario (% exceeding)
4 ft/s	FC	14	21
5 ft/s	FC	2	5
6 ft/s	FC	0.2	0.6
4 ft/s	BR	1	4
5 ft/s	BR	0	0
6 ft/s	BR	0	0
4 ft/s	CB	4	11
5 ft/s	CB	0.1	0.5
6 ft/s	CB	0	0
4 ft/s	BB	1	4
5 ft/s	BB	0.1	0.2
6 ft/s	BB	0	0
4 ft/s	BB*	16	26
5 ft/s	BB*	10	14
6 ft/s	BB*	6	9

5.3. Discussion

At three sites – Cat Branch, Furnace Creek and Bacon Ridge – there was a gradual increase in median velocities within the channel and floodplain as the modeled flows increased with each major event and the CC Scenario, with the largest increase in velocities occurring between the 2-year and 10-year flows. The similarity in the curves (Figure 13 and Figure 14) at these three sites was due to the similarity in configuration of the channel and floodplain geometry - all have shallow channel banks and wide, active floodplains - and an absence of downstream infrastructure causing backwater. In these sites, the additional flow in the CC Scenario was spread over the width of the area which includes both the channel and floodplain, moderating potential velocity increases.

The impact of the CC Scenario on the flood vulnerability of the floodplain for the three sites was quantified in Table 6 using velocity thresholds of four and six feet per second. The difference in the stability of restoration materials above these thresholds is significant (Fischenich, 2001). Four feet per second may result in small areas of local erosion and modification of vegetation type and density. In excess of six feet per second those same areas may experience significant erosion, loss of vegetation, and destabilization of cobble material and small riprap.

At the three sites, the percentage of the total area that exceeded a velocity threshold of four feet per second increased by less than ten percent. Bacon Ridge and Cat Branch had no areas which exceeded the threshold of six feet per second, and the percentage of area above this threshold at Furnace Creek remained below 1% under both flow scenarios. The impact of the CC Scenario on the flood vulnerability of the channel at the three sites can be seen in Figure 17 - Figure 19. Increases in channel velocities were limited at all sites. There was a 22% shift in the total area from within 3-4 feet per second to within 4-5 feet per second at Cat Branch (Figure 18), but this shift is driven by the narrow distribution of velocity data in the channel at Cat Branch, centered around a median velocity of 4.0 and 4.4 feet per second at the 100-year and CC Scenario flows, respectively. We interpreted the 2D model results at these three sites as showing that the CC Scenario would have led to a minor increase in the areas that would have required further design revisions to address, or the use of protection measures, including erosion control blanket, wood or rock. A significant change in the flood vulnerability at these sites did not occur under the CC Scenario.

At Cattail Creek, there were two areas of the site that were hydraulically distinct from one another. The upper area of the site was relatively wide, consisting of a series of two berms with rock weirs and three pooled areas. By design, flood flows passed over the rock weirs and into the pooled regions between weirs. Debris deposited over the top of the weirs led to flow over low points in the berms. The upper area of the site showed reduced velocities on the weirs and low points in the berms above the 10-year event, due to the presence of backwater from the contraction of the landscape near the middle of the site. The lower area of the site continued the pattern of berms, rock weirs, and pools, but this area was confined by the surrounding landscape, so the increased flow had minimal area to expand laterally. Velocities had a wide distribution at Cattail Creek with the median centered around six feet per second in the CC Scenario (Figure 20). This is due to large areas of low velocity in the pools between weirs in the upper parts of the site, and the higher velocities which occurred in the confined lower area of the site.

The interpretation of 2D model results from the CC Scenario at Cattail Creek was mixed; due to the presence of backwater in the upper area of the site, there was a reduction in the flood vulnerability, while the flow confinement in the lower area of the site led to higher peak velocities and an increase in the flood vulnerability. We interpret these results as showing that in the upper area using the CC Scenario instead of the current 100-year flow would not have led to the need for additional protection measures, due to the presence of backwater. In the lower area of Cattail Creek, the velocities were sufficiently high in the 100-year flood event to warrant the installation of large rock in the weirs, and rock protection in other vulnerable areas of the channel and banks. The same areas that would require protection in the 100-year flood event would have required protection in the CC Scenario. We interpreted the CC Scenario results in this lower area as moderately increasing the degree of flood vulnerability, but not significantly expanding the area of vulnerability.

At Bear Branch the interpretation of 2D model results was straightforward: above the 10-year flood event the presence of backwater from the downstream culverts significantly reduced the channel and floodplain velocities (Figure 13 and Figure 14) and the flood vulnerability of the site. Except for areas within close proximity to the upstream model boundary, velocities at the 100-year flow and CC Scenario were less than two feet per second everywhere. The upstream area within the restored has a series of interlocking vanes which do not show evidence of flood damage. Above this area, there is extensive headcutting throughout the channel and floodplain, which may be due to high flood velocities that are not moderated by backwater from the downstream culvert. There was no increase in the flood vulnerability at Bear Branch in the CC Scenario.

At Bear Branch with the influence of backwater from the downstream roadway culverts removed, the 2D model results from the CC Scenario showed that floodplain velocities continued to increase (Figure 14) while the channel velocities remained the same (Figure 13), with minor adjustment between the percentages areas in the velocity distribution above the median value (Figure 22). The interpretation of the increase in floodplain velocities is straightforward, since additional flow was conveyed over the floodplain in the CC Scenario with the influence of backwater removed. Channel velocity increases in the 2D model results were moderated by local backwater effects, as the drop in water surface over structures or structures in series was reduced in the CC Scenario compared to the 100-year flow; the water surface profile has fewer steps in the CC Scenario, dampening further velocity increases at structures. Interpretation of the statistical results at Bear Branch in the absence of backwater should be limited to general conclusions about relatively large sections of channel (sub-reaches) for reasons discussed in section 4.3.2. We interpreted the CC Scenario results at Bear Branch in the absence of backwater as moderately increasing the flood vulnerability of the floodplain. Due to the presence of high velocities in the channel throughout Bear Branch in both the 100-year and CC Scenario, the area of flood vulnerability was un-changed in the CC Scenario.

6. CONCLUSIONS

In interpreting 2D model output, we found evidence for the effectiveness of models to describe the general flood vulnerability of restoration sites, and to predict how this general flood vulnerability would change under an elevated 100-year flow. We determined the general flood vulnerability from the predicted velocities which prevailed across the site. Identifying and quantifying the general vulnerability would influence design decisions, including the extent of grading and quantity of rock required. Design decisions made to address general flood vulnerability will affect impacts to existing resources, project resilience (or sustainability), and construction costs. We evaluated the general flood vulnerability through creating and summarizing distributions of velocity data (Figure 17 - Figure 22, Table 6) and evaluating changes in the median velocity over increasing flood flows within the channel and floodplain (Figure 13 and Figure 14). These figures and table distill a significant amount of site-specific hydraulics and allowed for comparisons between flow events and across sites.

We also found evidence for the effectiveness of 2D models to determine the specific flood vulnerability within restoration sites across increasing flows. We define the specific flood vulnerability as the evidence from 2D model velocities of a localized vulnerability surrounding individual restoration structures, large obstacles, and other features that significantly modify flood velocities. These areas of specific flood vulnerability may include those that are critical to the long-term stability of the restoration site, including around hydraulic structures. Flood flows that lead to damage or loss of structures may initiate a cascading effect that ultimately degrades a large area of the restoration. In some cases, the loss of a grade control structure or the outflanking of grade control structures can lead to the rapid undermining of upstream bed or bank protection measures and the loss of restoration function.

In the sites we examined, the areas that have the greatest specific vulnerabilities are pinch points, areas where flow is concentrated, large vertical steps at grade control structures, and locally steep slopes. Pinch points are areas where the flow is narrowed or contracted due to changes in terrain or the presence of obstacles. Areas where flow is concentrated (excluding pinch points) are those where flow converges due to local geometry without lateral contraction, including eroded, linear features in the floodplain and sections of floodplain with a transverse (or cross) slope. All specific areas are impacted to a greater degree by flow increases, including under the CC Scenario we examined, than other areas within the restoration sites. Within an area that is narrow or steep, increasing the flow without expanding the flow area will lead to increases in velocity that may destabilize the environment. As flow increases within pinch points and areas where flow is concentrated, velocities will increase; these areas may also include wide and tall habitat features such as rootwads, boulders and other obstacles which occupy a large percentage of the floodplain and introduce flow separation and wake zone formation as observed in Furnace Creek (Figure 16). Large vertical steps, such as those that occurred over cross vane grade control structures at Bear Branch and the most downstream structures at Bacon Ridge, locally accelerate and redirect flow, which can lead to structures being undermined or outflanked if they are not founded sufficiently deep, protected from scour, and/or keyed-in to the bank beyond the extent of lateral erosion. The risk of damage will increase with higher flows unless the effect of the vertical step height is dampened by the presence of backwater from a downstream structure or narrowing of the valley.

The features which caused the most significant vulnerabilities in the five research sites were: (1) local steps in the bed and water surface profiles at structures and (2) a reduction in the width of floodplains, both of which accelerate flow over a small area. We can conclude that the most effective approach to reducing vulnerabilities is to reduce step heights along the flow profile, primarily through reducing vertical drops at structures, and through spreading flood flows over wide, hydraulically rough vegetated floodplains, which effectively dampens peak velocities. Restoration methods that achieve this, including floodplain restorations, will have a greater resilience to flood damage than sites that feature a deep, entrenched channel with minimal floodplain flow. Where the 100-year flow is spread out over a wide floodplain, there will be a smaller increase in velocities than for otherwise equivalent sites where flows are confined to narrow floodplains and/or deep channels.

We find that regional regression equations that assume stationary climactic conditions remain useful for estimating flow inputs even in a changing climate. Each restoration site examined had a distinct flood vulnerability which can be interpreted by examining the patterns of velocity within the site over increasing flood flows, and by comparison of sites to each other. For all the sites examined, the specific and general flood vulnerability was evident in the current conditions flow estimates, with the CC scenario providing additional context. The benefits of 2D modeling for restoration practitioners and stakeholders are best realized when applied to defining and quantifying flood vulnerabilities and serving as a communication tool to identify, highlight and address potential issues. The uncertainty in the estimation of flood flow increases under future climate conditions will impact the interpretation of vulnerability (general and specific) at restoration sites unevenly. For a site that is backwatered during all major flow events, the impact of a lower or higher estimate of the 100-year flow produces a negligible change in velocity.

To ensure that model predictions can be relied upon in evaluating project vulnerability, it is essential that 2D models are well-constructed. One of the most important factors in 2D model construction is the quality of the terrain in the channel and floodplain. Biased or incomplete representation of the ground surface, obstructions, or hydraulic structures will lead to inaccuracies in model predictions (Legleiter et al., 2011; Pasternack et al., 2006). The terrain dataset(s) used in the development of a 2D model should be assessed to ensure that the terrain is of sufficient density and accuracy. If an existing accuracy assessment is not in existence, one can be developed through establishing a set of bare-earth check points using identical survey datums as the terrain dataset(s). Representation of the proposed floodplain and channel terrain developed through computer aided design must also be of sufficient accuracy to allow for reliable modeling. Poorly constructed proposed terrain will result in high or low velocities that are not representative, leading to inaccurate interpretation of 2D model predictions and poor design decisions.

Accurate representation of upstream and downstream model boundary conditions is also critical. As demonstrated in the Bear Branch example in this study (Section 4.1.2), backwater from downstream structures can substantially reduce site vulnerability caused by high velocities which typically result from increasing flow. Assuming a low downstream slope may artificially cause backwater that may mask a high velocity vulnerability. For the purpose of identifying flood damage vulnerabilities, boundary conditions should be selected to identify high velocity or high stress vulnerabilities rather than high flood elevations. Separate 2D models can be constructed to identify the risk of elevating base flood elevations. 2D models should also include an appropriate development region upstream of the project area, so that, unless intended by the modeler, the 2D flow patterns are not heavily influenced by the upstream model boundary. In addition to the use of appropriate boundary conditions, modelers should select roughness and turbulence coefficients to ensure the numerical stability of the model without dampening high velocity predictions. This dampening effect can occur if turbulence coefficients are too diffusive or roughness coefficients are artificially high for the post-restoration environment.

How a project area conforms to 2D model assumptions should be considered, to ensure that interpretation of 2D model predictions is appropriate. 2D models perform best where flow has a hydrostatic pressure distribution, is parallel to the bed, and free of significant vertical acceleration, deceleration or separation. These conditions are best satisfied when the width of the flow is 10 or more times the depth on the floodplain or in the channel. In these conditions local velocities can be assumed to be sufficiently accurate, provided the model is well-constructed as described above. The 2D modeling completed at Bear Branch contains flow conditions in channels and downstream of structures where the 2D model does not fully represent peak near-bed or near-bank velocities and boundary shear stress. These flow conditions will be present at other sites where the channel is deeply incised and structures that cause plunging flow are in use, or in the presence of tight bends. Users of 2D models should be cautious when interpreting results in deep and narrow channels (those with width to depth ratio less than 10), around structures which induce plunging flow, in tight bends with R/B less than 2.5, and on slopes greater than 10%. Underprediction of peak velocities and boundary shear stress starts to become significant at slopes up (depth contraction) or down (depth expansion) greater than 10% and is much more important near downward steps. At depth contractions where flow is exiting the channel and entering the floodplain, our experience has been that 2D models effectively identify vulnerable banks. Although the 10% slope guidance is clearly exceeded, the 2D model's representation of the vertical flow contraction and increased local velocity match the observation of eroded banks and floodplain surfaces. In a similar manner, 2D models are also effective where flow is returning from the floodplain into the channel, especially where there is a rapid drop in water surface from the floodplain back into the channel. The accuracy of the depth-averaged velocity at these locations is unknown, although there is a clear correlation between high 2D Model velocities and bank and floodplain damage at these locations.

In cases where the project area significantly deviates from 2D model assumptions, local velocity and/or stress amplification factors may be appropriate (Maynord, 1993a) in combination with local reference velocity. An example local reference velocity at a structure (such as a cross vane) could include the maximum velocity found below the nappe of vertical steps, before the depth of flow expands in the downstream pool. This reference velocity could provide an indication of the potential near-bed or near-bank peak velocities along the bed and perimeter of the downstream pool, which may not be indicated by 2D models. This approach requires the use of 2D models in conjunction with empirical information on the vulnerability of structures and bends of various orientations and dimensions. Currently, this empirical information is present solely in the form of professional experience and does not exist in a formal, analytical format.

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APPENDIX A. 2D MODEL DEVELOPMENT

This Appendix contains research related to the development of effective 2D models used in the reliability analysis in this report. We define effective 2D models as models which are appropriately configured to represent the essential hydrodynamics in the flow environment at the physical scale of the problem of interest. In this research the physical scale of the problem includes floodplains (tens to hundreds of feet), channels (feet to tens of feet), and in the vicinity of large woody obstacles (one foot to several feet).

We examined the choice of hydrodynamic modeling software, appropriate grid resolution, and selection of the turbulence model in developing effective models. One field site and one laboratory flume case study are used in the development of effective 2D models.

A.1 2D Model Selection

The field site consists of a testing region within the Furnace Creek restoration. This testing region is shown in Figure A-1.

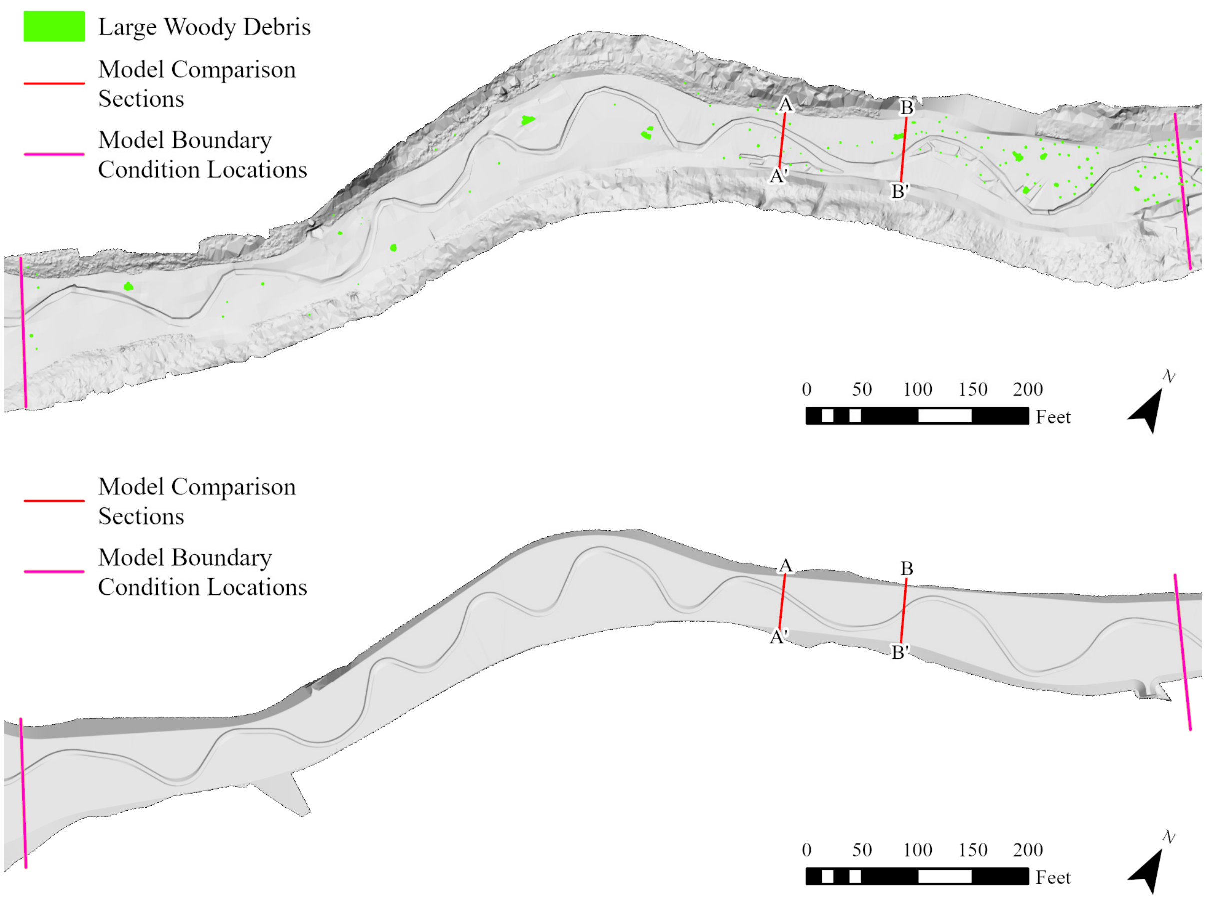


Figure A-1. Furnace Creek Model Testing Region. The post-restoration terrain is above, with the pre-restoration, proposed terrain below.

To determine the appropriate hydrodynamic model for research purposes both TUFLOW and HEC-RAS 2D were examined. Figure A-2 demonstrates the results of the comparison of these two models in the Furnace Creek testing region. Both the post-restoration terrain and a pre-restoration proposed terrain were examined. Model comparison sections are shown in Figure A-1.

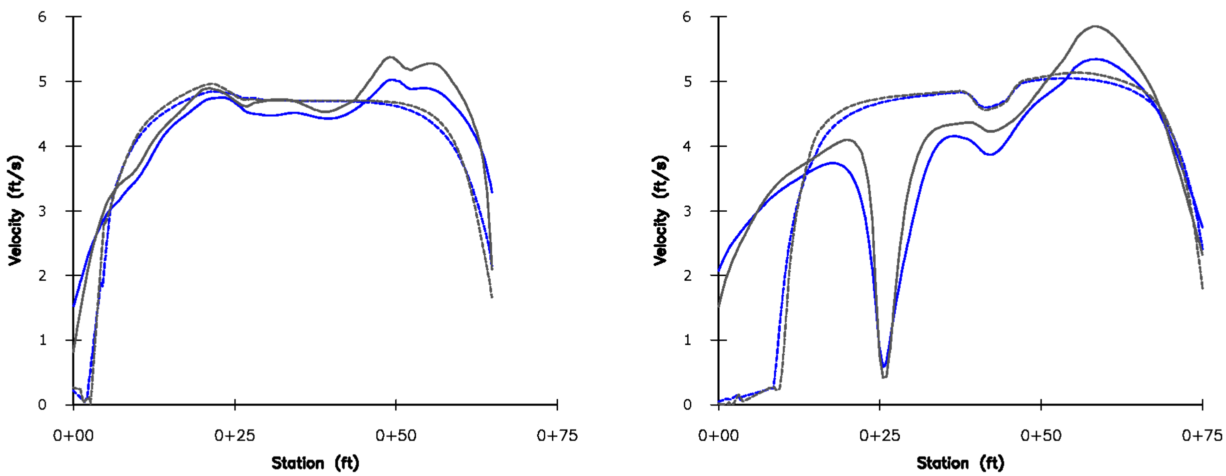


Figure A-2. 2D Model Velocities at Sections Using TUFLOW (grey) and HEC-RAS (blue). Dotted lines are results for the proposed condition. Solid lines are for the post-restoration condition. Section A-A’ is shown on the left. Section B-B’ is shown on the right.

To the extent possible the two software programs were identically configured. Both models were run at a uniform grid resolution of one foot, using a turbulence coefficient of 0.5. The parameterization of turbulence is discussed further in section A.2. Minor differences in the sub-grid model are present, including how obstacles within the flow domain are considered.

Modeling of the proposed terrain produced nearly identical results, with the location of peak velocities coincident and velocity maximums deviating by less than 0.2 feet per second. In the proposed terrain models, very minor velocity differences are evident in both sections at the boundary of the floodplain where velocities drop quickly. These minor differences are attributed to grid origin differences, numerical routines used in each software, and how the characteristic length in the turbulence model is defined in each software. TUFLOW uses the lower of water depth or distance to a dry boundary, whereas HEC-RAS 2D uses water depth.

For the post-restoration terrain there are several minor differences in the model results. At the edge of sections TUFLOW velocities drop more quickly than for HEC-RAS 2D, reducing the conveyance which occurs in this region. The obstacle at section B-B’ produces a larger effect in the TUFLOW model due to how the obstacle is represented in the turbulence model and sub-grid. The combination of the model representing a larger projected area for the obstacle and reduced conveyance at the boundary of the floodplain are attributed to the higher velocity peak predicted by TUFLOW in section B-B’.

Both HEC-RAS 2D and TUFLOW produced output which can be used to develop effective 2D models. The individual choices used in the sub-grids, turbulence models, ease of setup, budget available for commercial software licensing, and run time efficiencies can be considered in determining which model is appropriate. In this research TUFLOW was used for all simulations due to its superior run time efficiency and efficient model batch processing.

A.2 Turbulence Modeling and Grid Resolution

The turbulent diffusion (as eddy viscosity) applied to 2D models in this research is based on the product of the local shear velocity, lower of the water depth or distance to dry boundary, and the user specified turbulence coefficient. This method is a common approach to parameterizing turbulence in 2D models (G. Brunner, 2016; Froehlich, 1989). To evaluate the appropriate user specified turbulence model coefficient and grid resolution, supplemental analysis was conducted to identify limiting model behavior in an environment where detailed flow depth and velocity data are available. This analysis was conducted using results from the multifunctional flume system found at the Federal Highway Administration's Sterling Jones laboratory. Data provided by the Sterling Jones laboratory included velocity and water depth measurements from an experiment of flow past a skewed pier. The flume setup and dimensions can be seen in Figure A-3. 2D models were run at a grid of 0.16 feet (0.05 meters) to 0.08 feet (0.025 meters). The width of the pier projected into a cross section perpendicular to flow is 0.38 feet (0.11 meters), leading to three grid cells defining the pier at the 0.16-foot grid resolution, and five grid cells defining the pier at the 0.08-foot grid resolution. At the two grid resolutions, 2D models were run at user specified turbulence coefficients of 0.5, 1.0, 2.0, 4.0 and 8.0. The range of turbulence model coefficients are chosen to produce 2D model output that range from diffusion dominated (turbulence model has a significant impact on results) to advection dominated (turbulence model minimally impacts results).

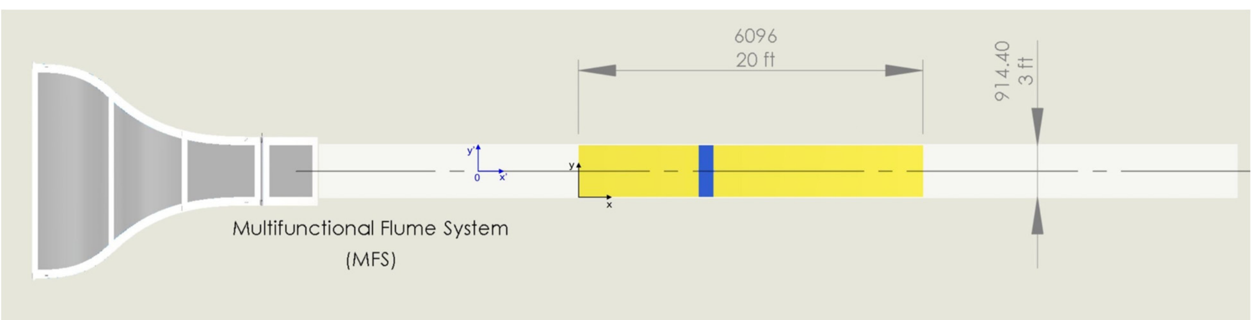


Figure A-3. Multifunctional Flume System Used for 2D Model Testing. The skewed pier is located within the blue rectangle.

Figure A-4 shows the observed and 2D Model predicted velocities surrounding the skewed pier at a grid resolution of 0.08 feet. The observed velocities are shown at the top of the figure in (a), with velocity measurements made at 60% of the water depth at each location. Simulation (b) shows the model output with a turbulence model coefficient of 0.5, where numerical instability is observed as a pattern of oscillation below the pier. Simulation (d) shows 2D model output with a turbulence model coefficient of 8.0, where significant turbulent diffusion reduces the extent of the wake zone below the obstacle that is visible in the observed velocity measurements, dampens peak velocities, and realigns the jet of water below the obstacle. Simulation (c) has a turbulence model coefficient of 2.0, which is sufficient to maintain model stability, prevent excess contraction of the wake region, and avoid dampening the high velocities which occur off the right edge of the pier.

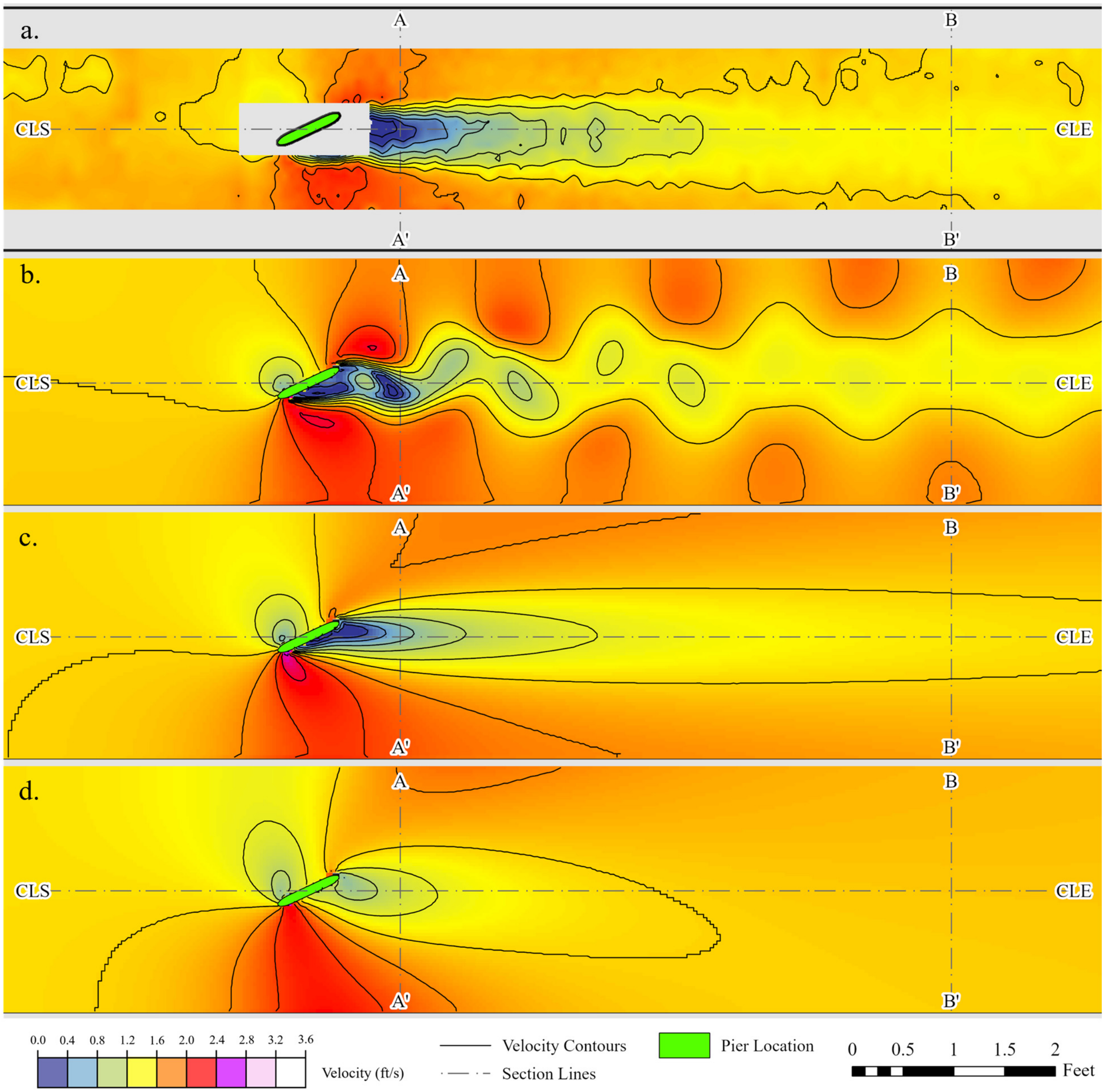


Figure A-4. Observed (a) and Predicted (b-d) Velocities Surrounding FHWA Skewed Pier.

Figures A-5 and A-6 provide further analysis of the use of turbulence coefficients which balance the need for numerical stability in the model without dampening model effectiveness.

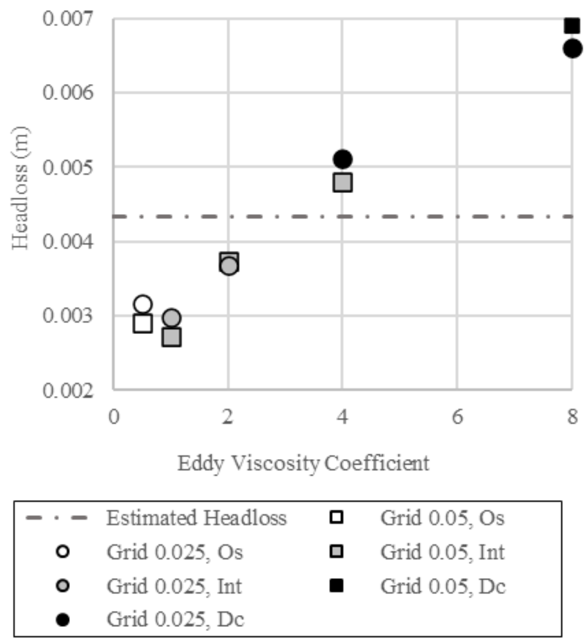


Figure A-5. 2D Model Predicted Headloss Surrounding the Skewed Pier.

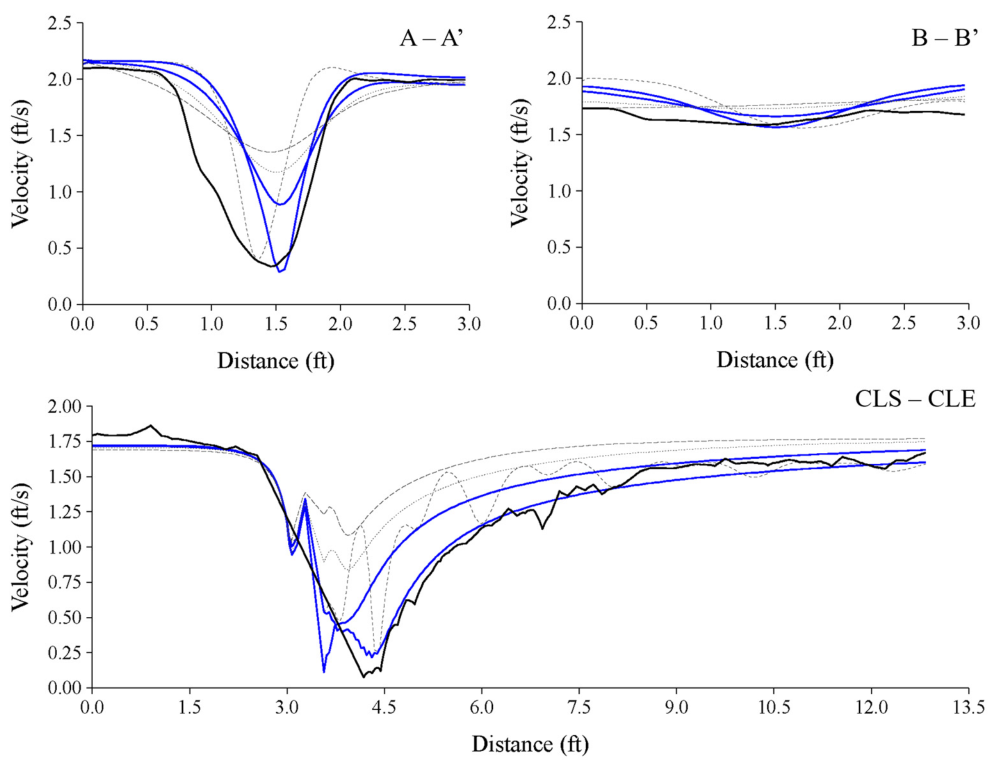


Figure A-6. Observed (black) and Predicted Velocities at Sections and Flume Centerline for a model grid of 0.08 feet. The unstable simulation (insufficiently diffusive) is shown in grey with wavy pattern. Diffusive simulations are shown in grey.

Figure A-5 compares headloss attributed to the pier for all simulations and along with the estimated headloss determined from observed velocities and water depths. Figure A-6 contains model velocities along the centerline CLS-CLE and two sections, A-A' and B-B' which are identified in Figure A-4. The excessively diffusive and oscillating simulations are the end members in the headloss analysis, with the intermediate simulations closer to the empirical headloss estimate. By considering the velocity distribution at sections and along the centerline, it is evident that both the excessively diffusive and oscillatory simulation do not effectively capture the observed velocity distributions.

Some general conclusions can be reached from this turbulence and grid sensitivity analysis:

- For evaluating flood vulnerability, it is necessary to refine the model to the physical scale of the features which are determining the vulnerability. The smallest features of interest in this study are the obstacles found in Furnace Creek. The flume results show that similar headloss and velocity maximums (not shown) are achieved with the coarser grid, where three grid cells define the pier in the model. A similar level of refinement was applied in 2D models used in this study but scaled to the size of the larger obstacles in the study, which are typically greater than two feet wide, and can be resolved with a one-foot model grid.
- At more refined grids, advective dominated simulations produce unsteadiness in the output which is observed as oscillations below obstacles. These simulations are unreliable; the oscillations are due to numerical instability in the model which superficially resemble the shedding of vortices which occur downstream of obstacles. Areas of oscillations lead to large flow separations below obstacles which are not effectively closed by diffusion of turbulent momentum.
- The choice of turbulence model coefficient impacts the headloss and maximum velocities predicted. Larger turbulence coefficients will produce greater turbulent diffusion in the model, increasing headloss and dampening high velocities.
- The impact of turbulence model coefficient on 2D model output is dependent on the grid resolution. A coefficient that produces numerically unstable behavior (including oscillations) at one grid resolution may be diffusive at a more refined grid.
- To reduce the dampening effect of turbulence models on 2D model outputs, the lowest turbulence coefficient which produces a stable simulation is used. This reduces the potential for underestimation of high velocities and boundary shear stress in vulnerable areas and prevents excessive prediction of water surface rise. In the five sites used in this study, a turbulent coefficient of 0.5 was found to produce numerically stable simulations without excessive numerical diffusion.

APPENDIX B. FIGURES FOR READERS WITH COLOR VISION DEFICIENCY

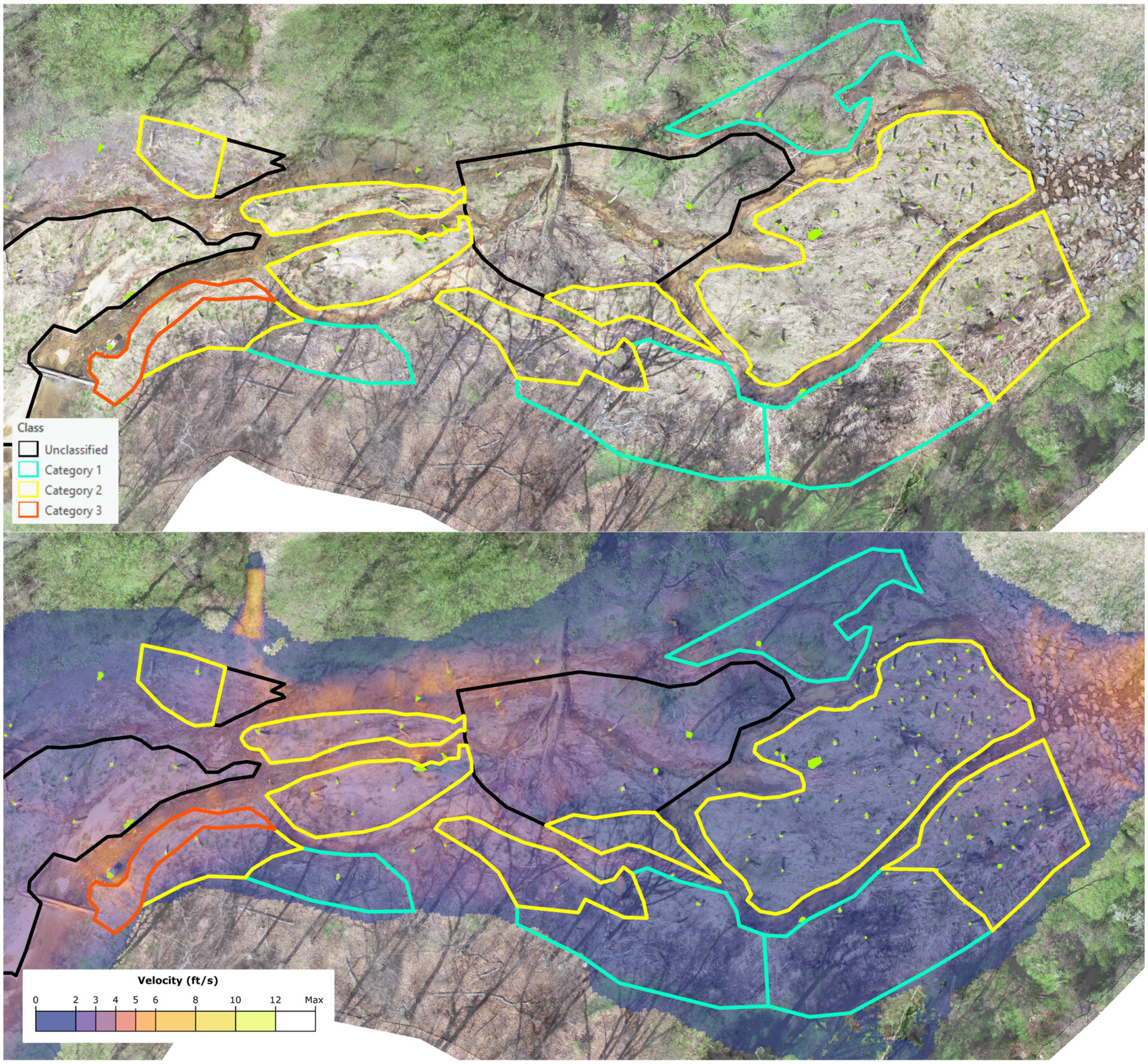


Figure 6. Classification of Floodplain Areas

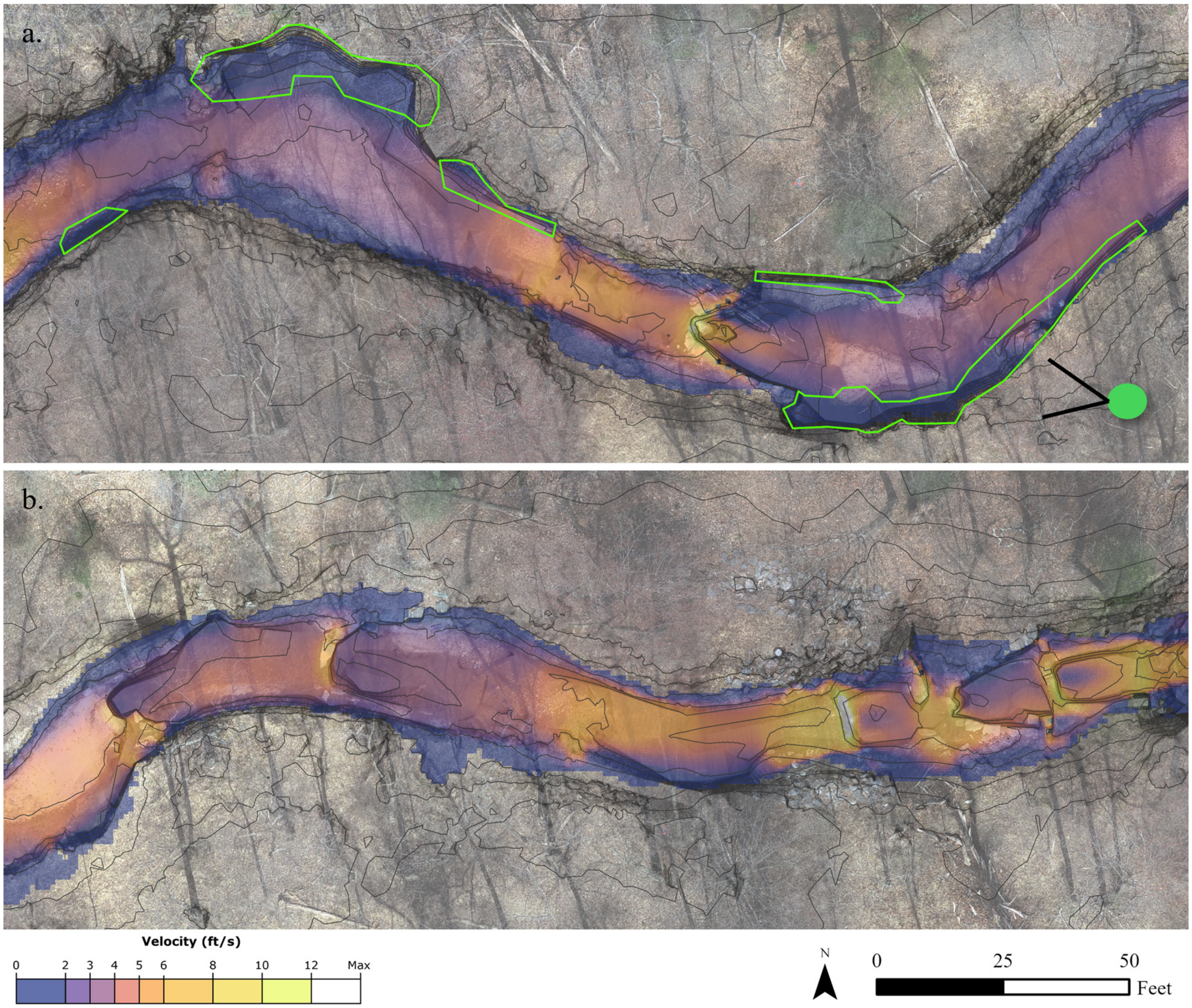


Figure 9. Largest Event at Bear Branch during Study

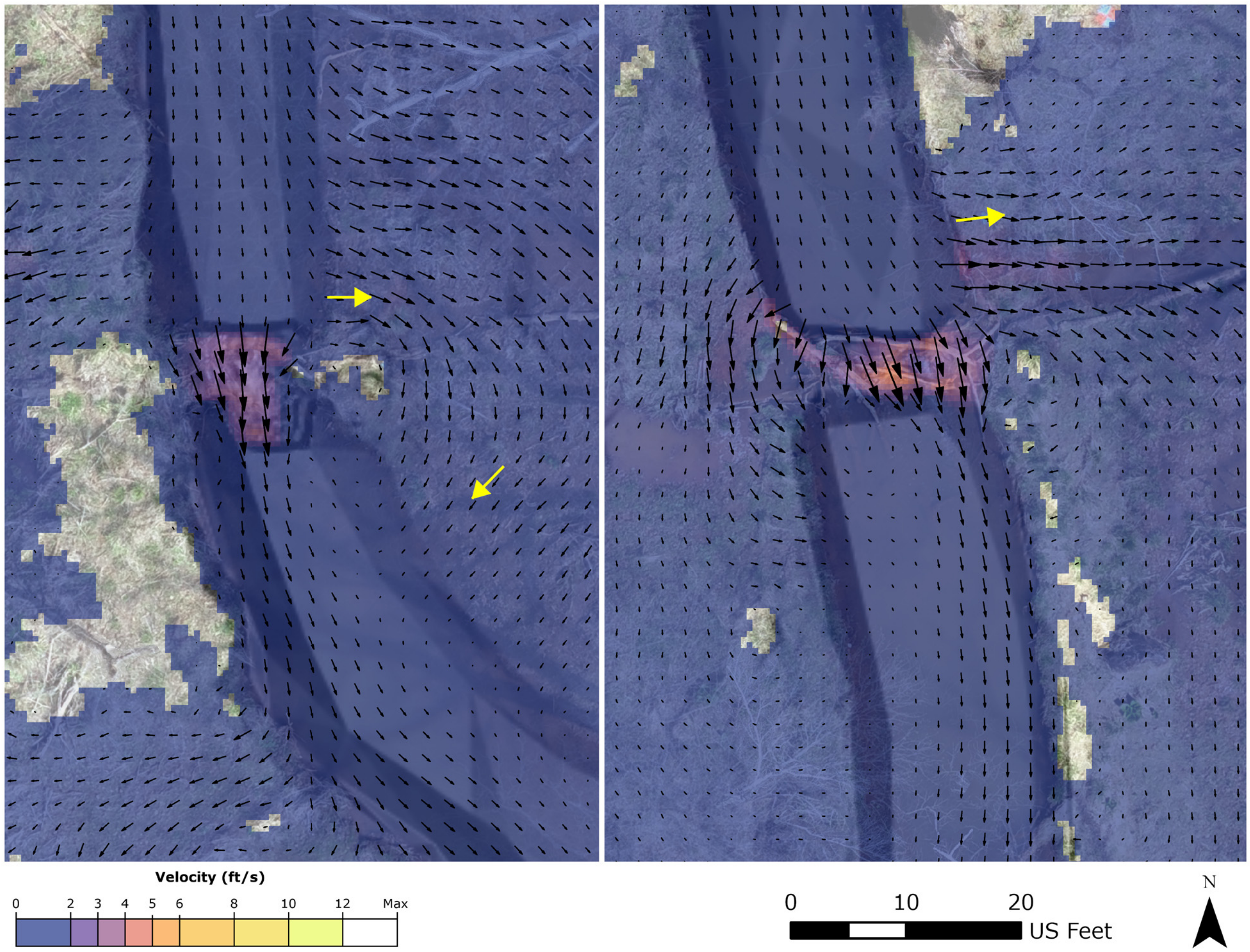


Figure 11. Planview of Flow Direction at Bacon Ridge Structures

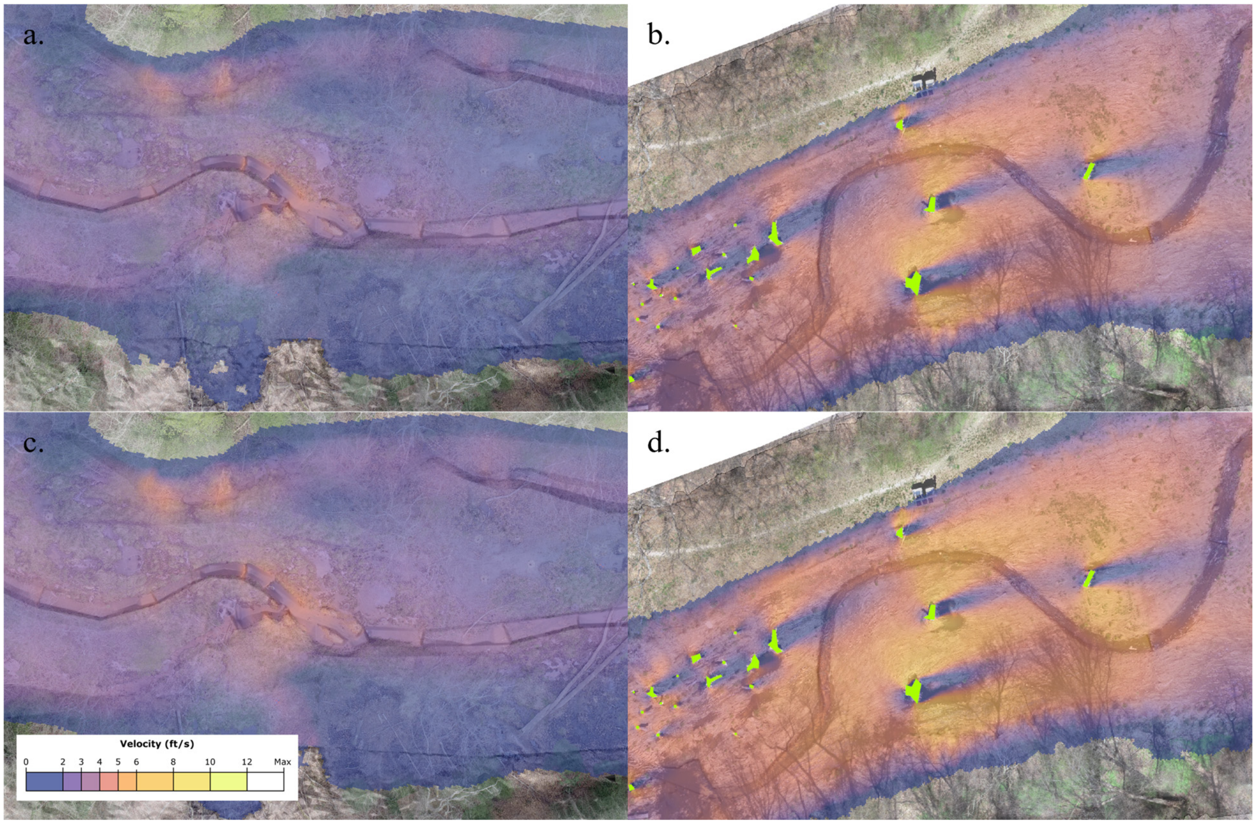
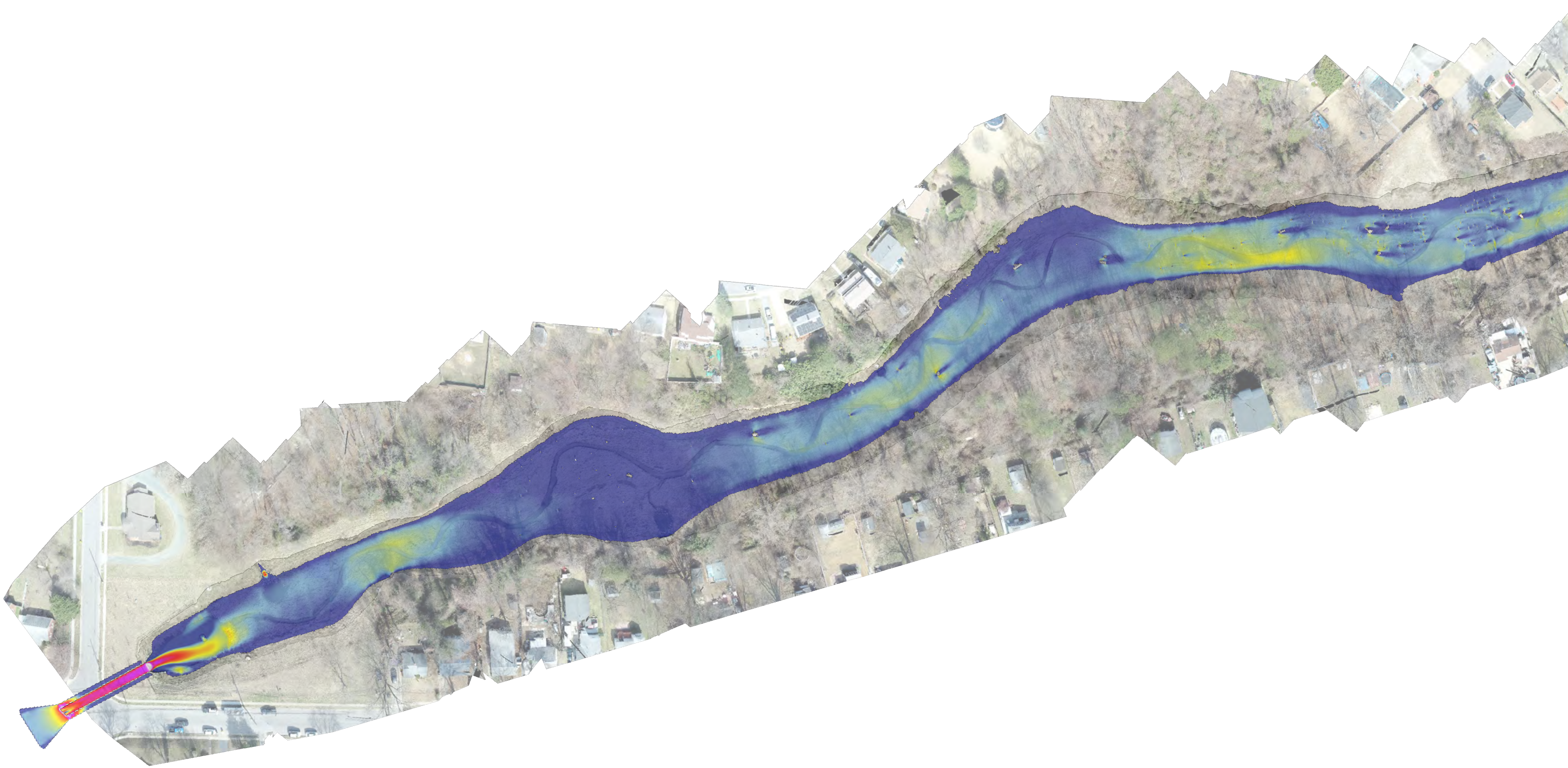


Figure 16. Velocities in Vulnerable Areas at the 100-year and CC Scenario Flows. Plots include the 100-year at Cat Branch (a) and Furnace Creek (b) and the CC Scenario at Cat Branch (c) and Furnace Creek (d).

APPENDIX C. 2D MODEL VELOCITIES FOR ALL FLOW EVENTS



Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 50 100 150 200 Feet

N

Two Dimensional Hydrodynamic Model Results: Furnace Creek (Upper)

Largest Event During Study

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Two Dimensional Hydrodynamic Model Results:
Furnace Creek (Upper)

2-yr Event Predicted Flood Velocities

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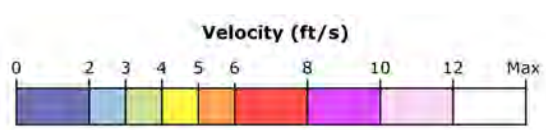

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 50 100 150 200 Feet

N

Two Dimensional Hydrodynamic Model Results:
Furnace Creek (Upper)

10-yr Event Predicted Flood Velocities

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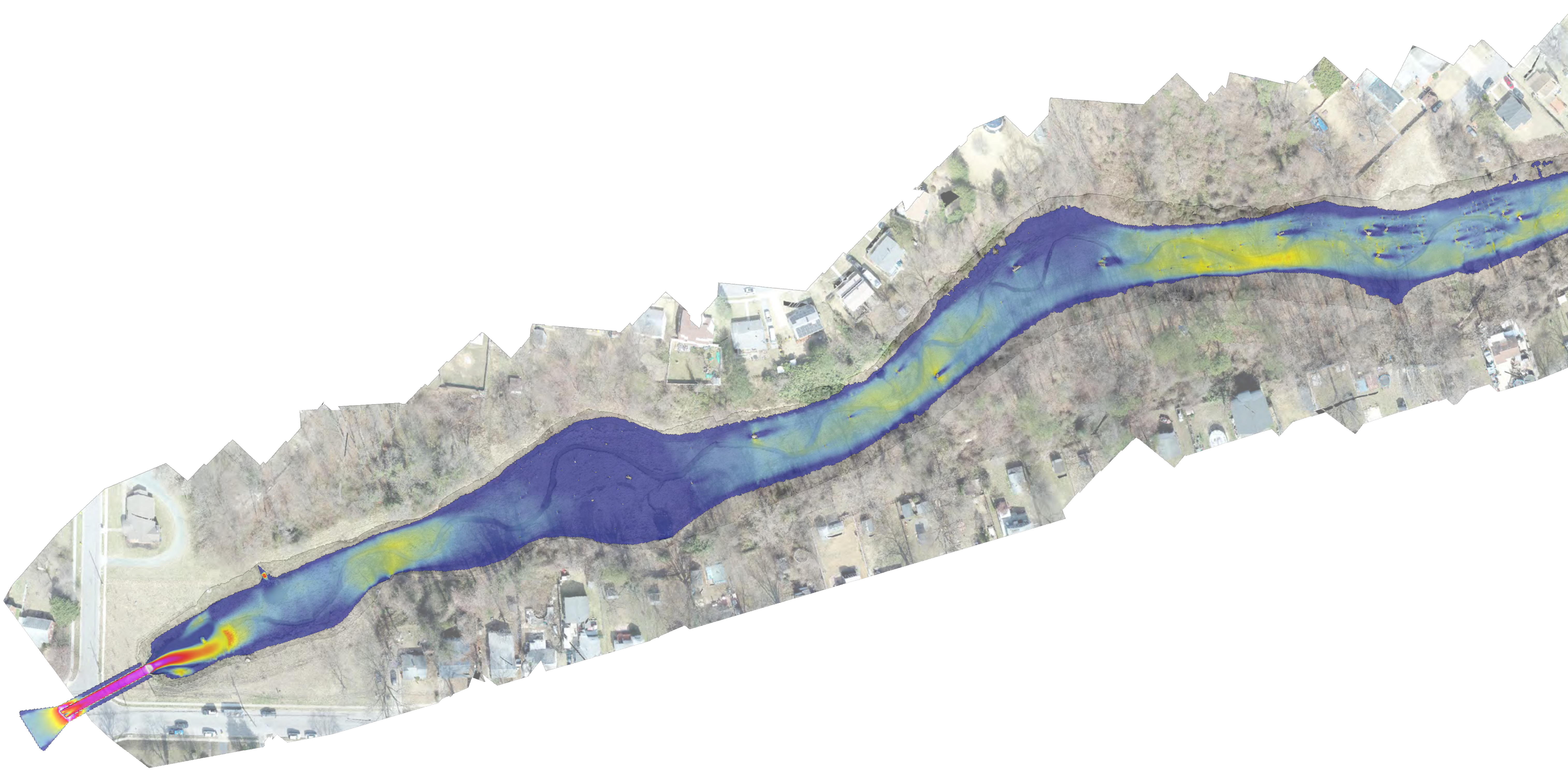

Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

UNIVERSITY OF LOUISVILLE
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 50 100 150 200 Feet

N

Two Dimensional Hydrodynamic Model Results: Furnace Creek (Upper)

50-yr Event Predicted Flood Velocities

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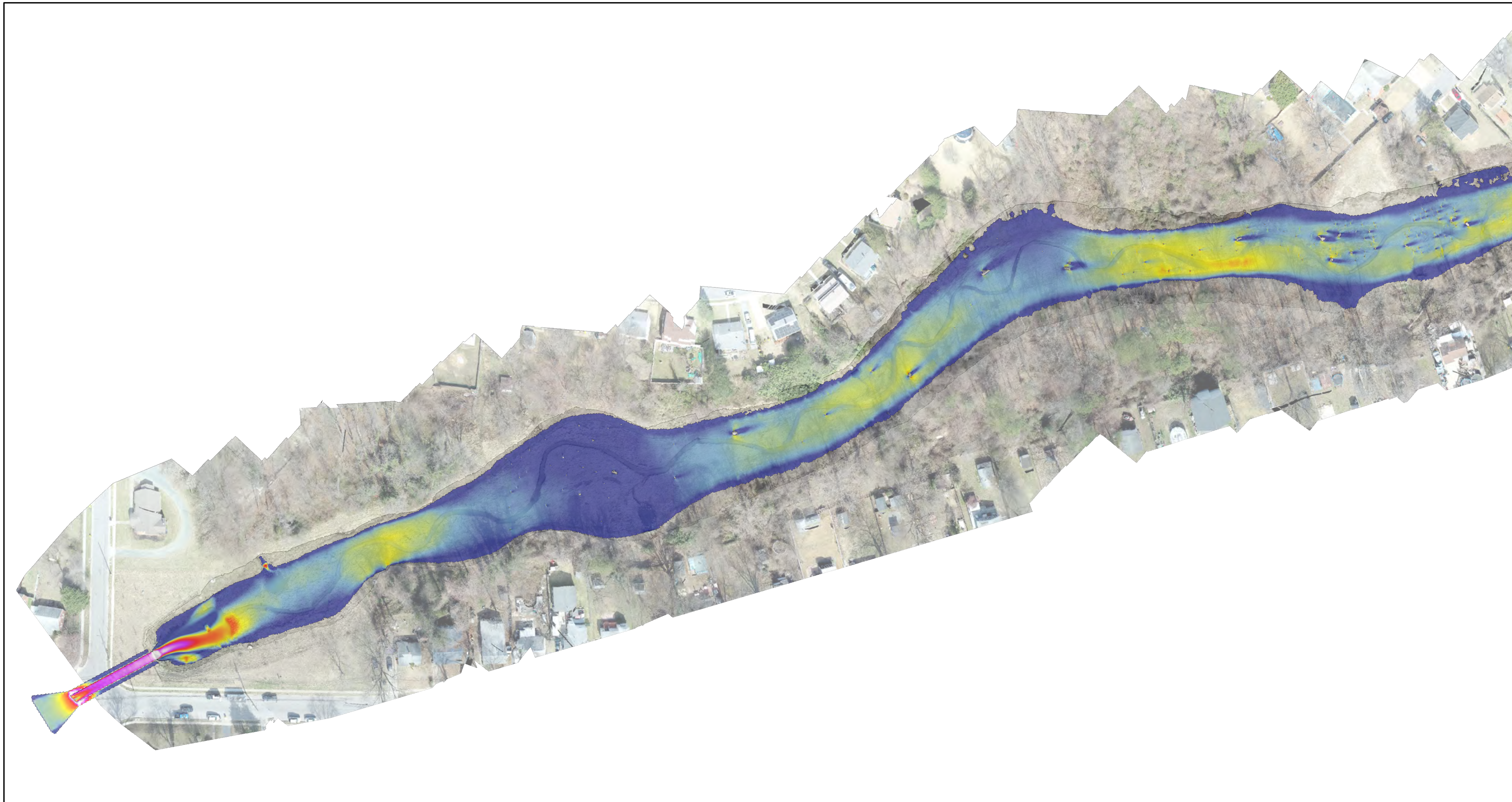

Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 50 100 150 200 Feet

N

Two Dimensional Hydrodynamic Model Results:
Furnace Creek (Upper)

100-yr Event Predicted Flood Velocities

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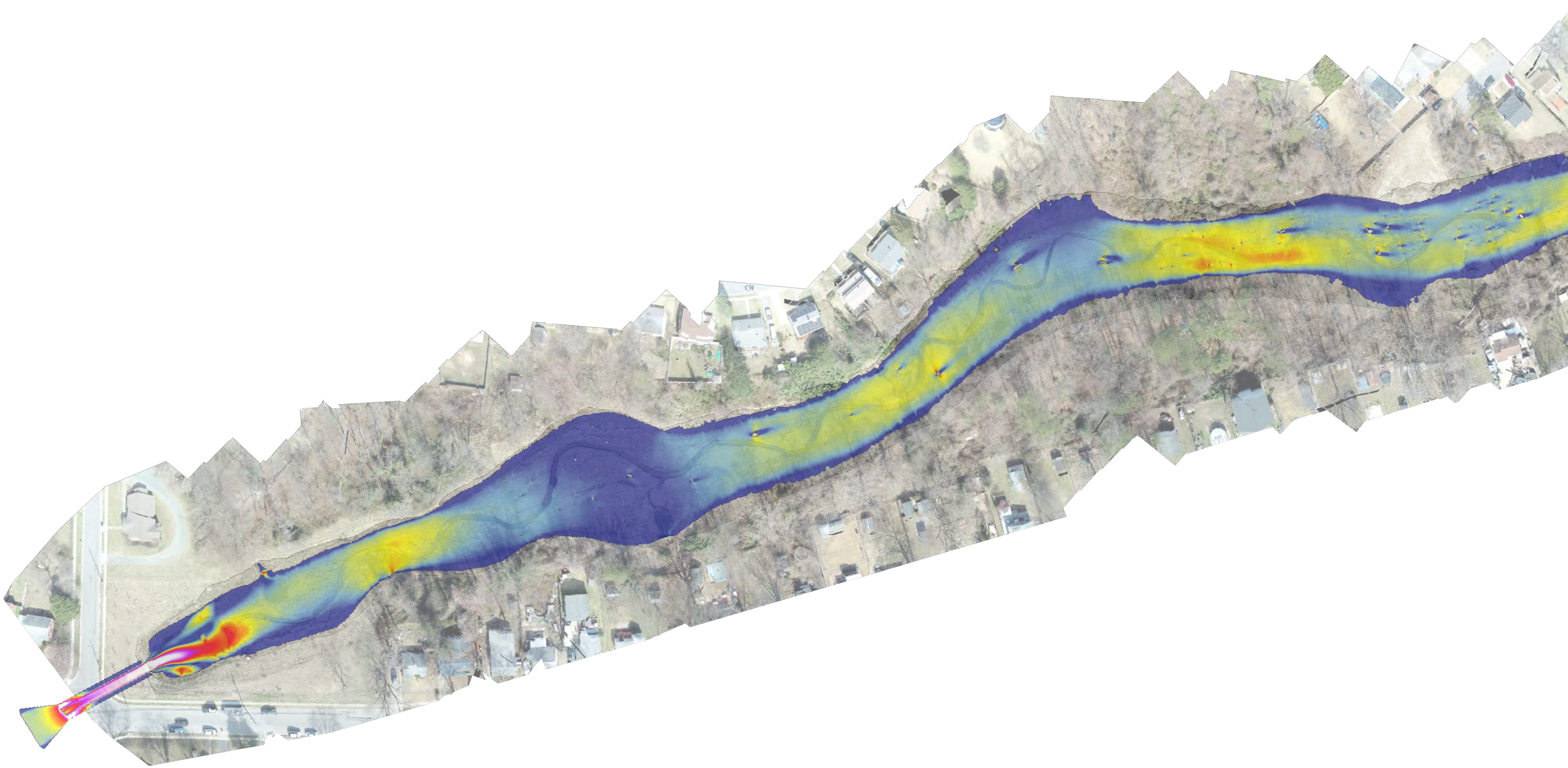

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 50 100 150 200 Feet

N

Two Dimensional Hydrodynamic Model Results:
Furnace Creek (Upper)

Climate Change Scenario (100-yr + 33%)

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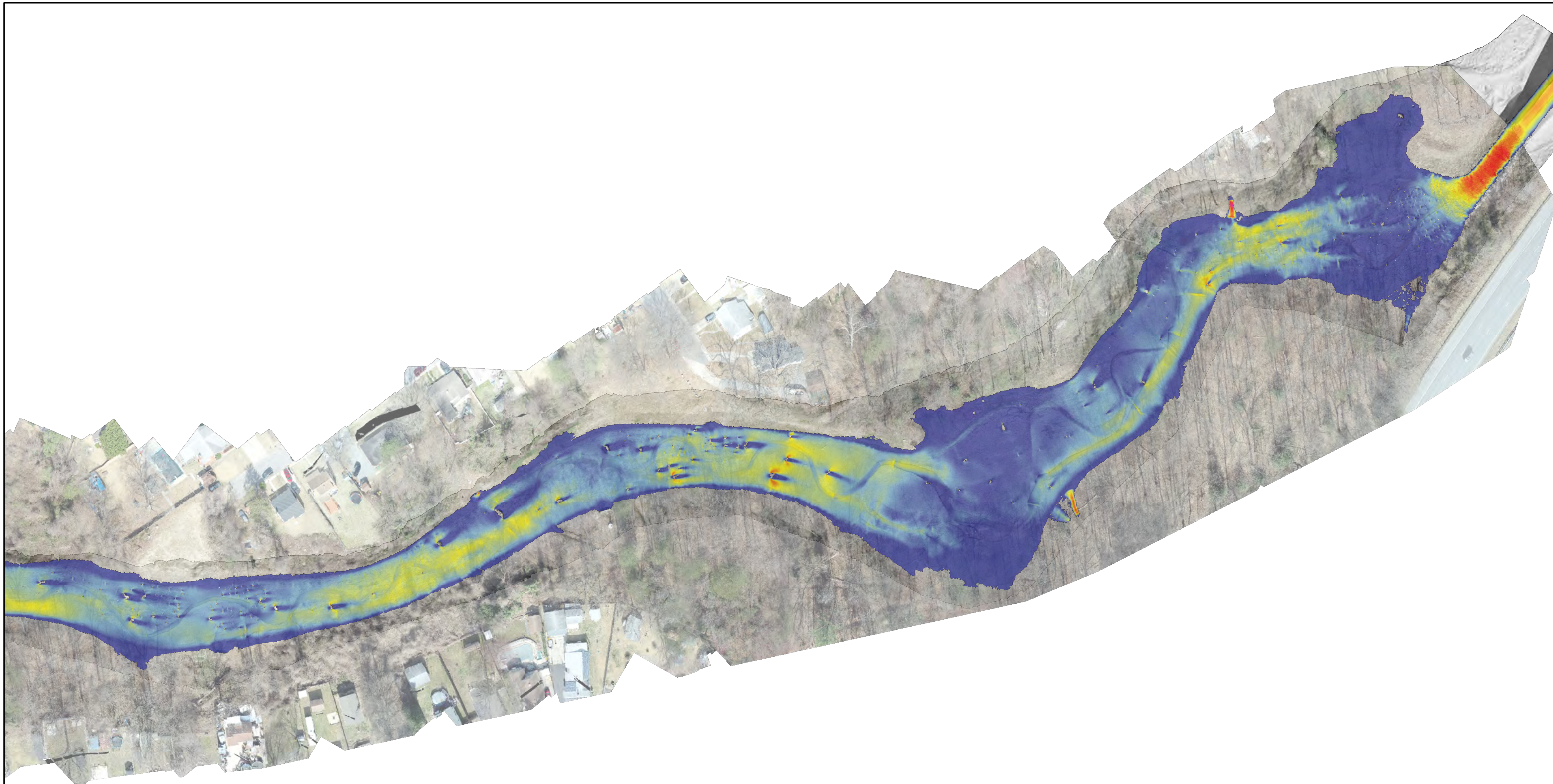

Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 50 100 150 200 Feet

N

Two Dimensional Hydrodynamic Model Results: Furnace Creek (Lower)

Largest Event During Study

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Restoration Research Award Program Funding Partners:

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 50 100 150 200 Feet

N

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Two Dimensional Hydrodynamic Model Results:
Furnace Creek (Lower)

2-yr Event Predicted Flood Velocities

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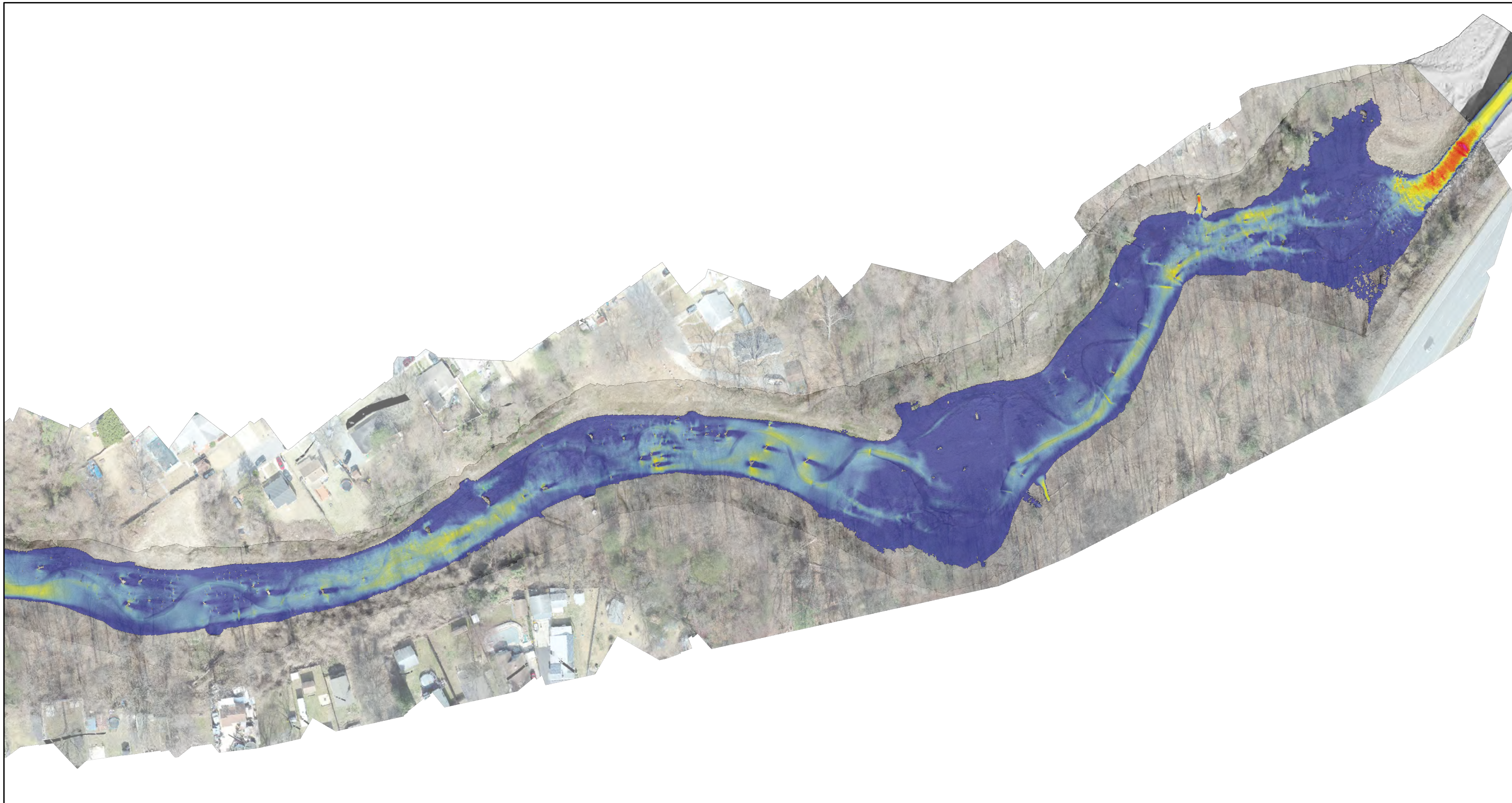

Velocity (ft/s)

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UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 50 100 150 200 Feet

N

Two Dimensional Hydrodynamic Model Results: Furnace Creek (Lower)

10-yr Event Predicted Flood Velocities

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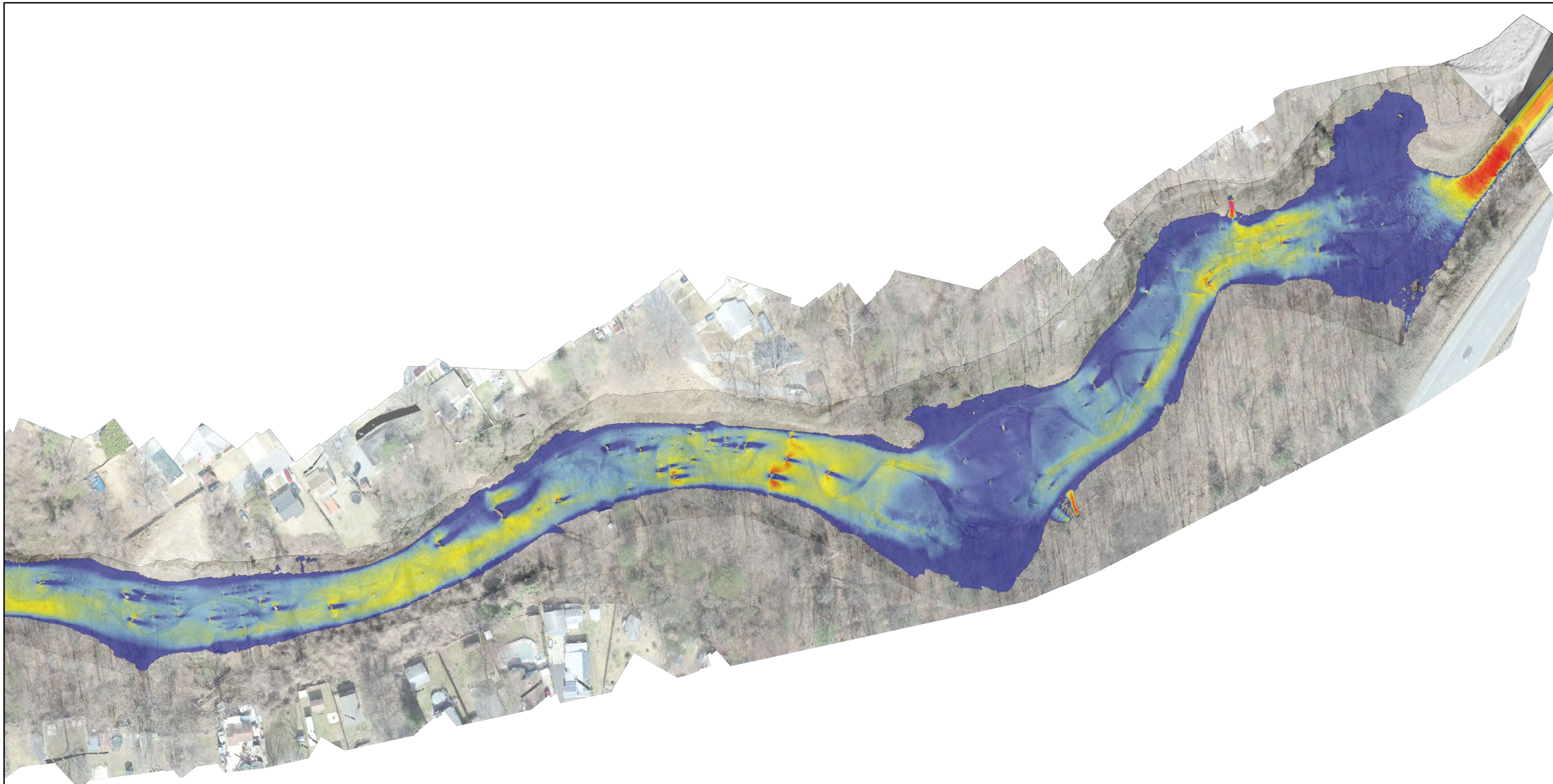

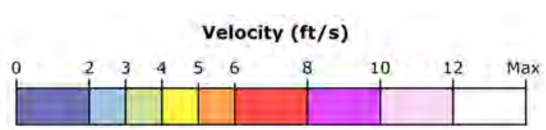

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 50 100 150 200 Feet

N

Two Dimensional Hydrodynamic Model Results: Furnace Creek (Lower)

50-yr Event Predicted Flood Velocities

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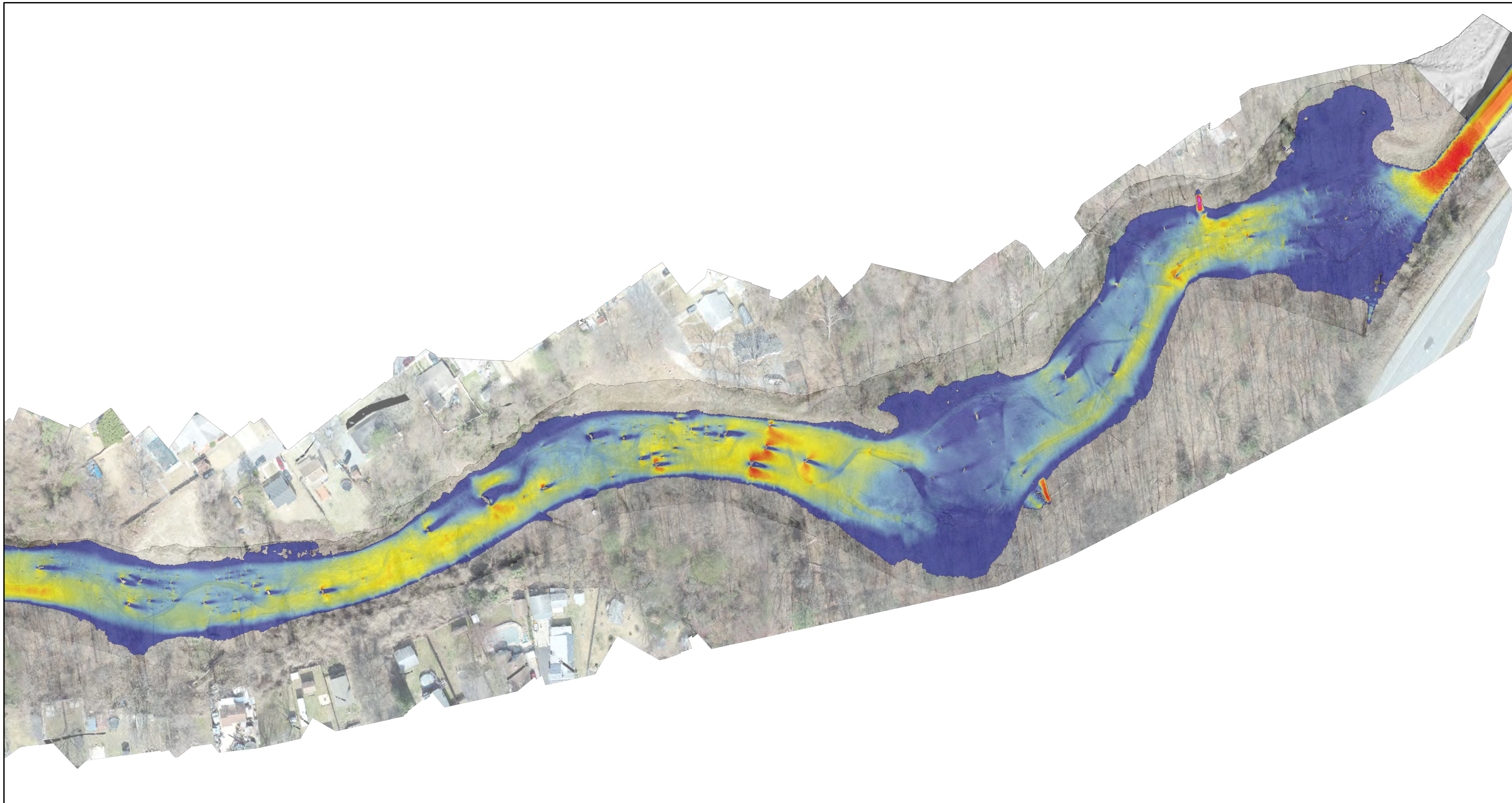

Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 50 100 150 200 Feet

N

Two Dimensional Hydrodynamic Model Results: Furnace Creek (Lower)

100-yr Event Predicted Flood Velocities

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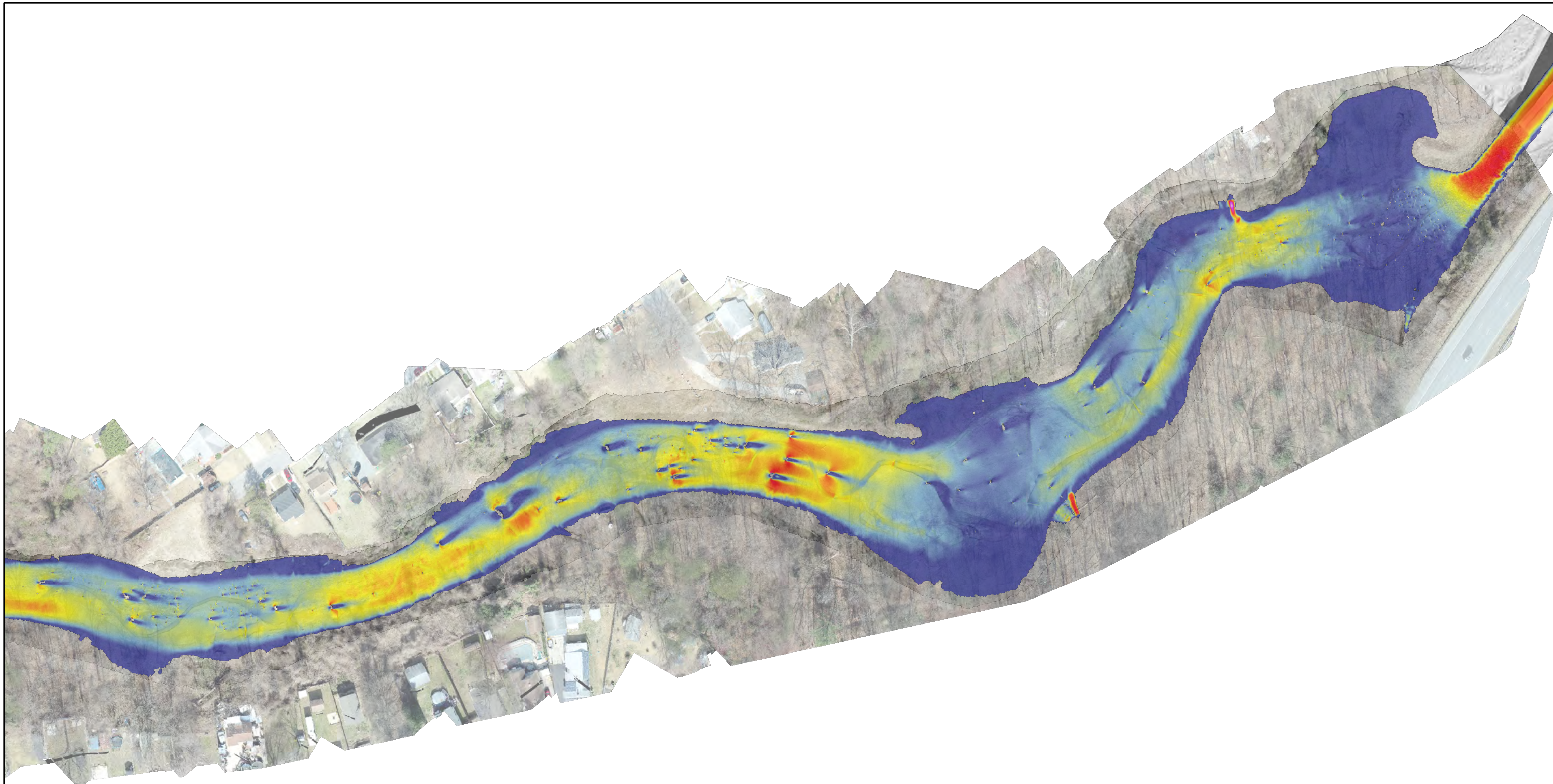

Velocity (ft/s)

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UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 50 100 150 200 Feet

N

Two Dimensional Hydrodynamic Model Results: Furnace Creek (Lower)

Climate Change Scenario (100-yr + 33%)

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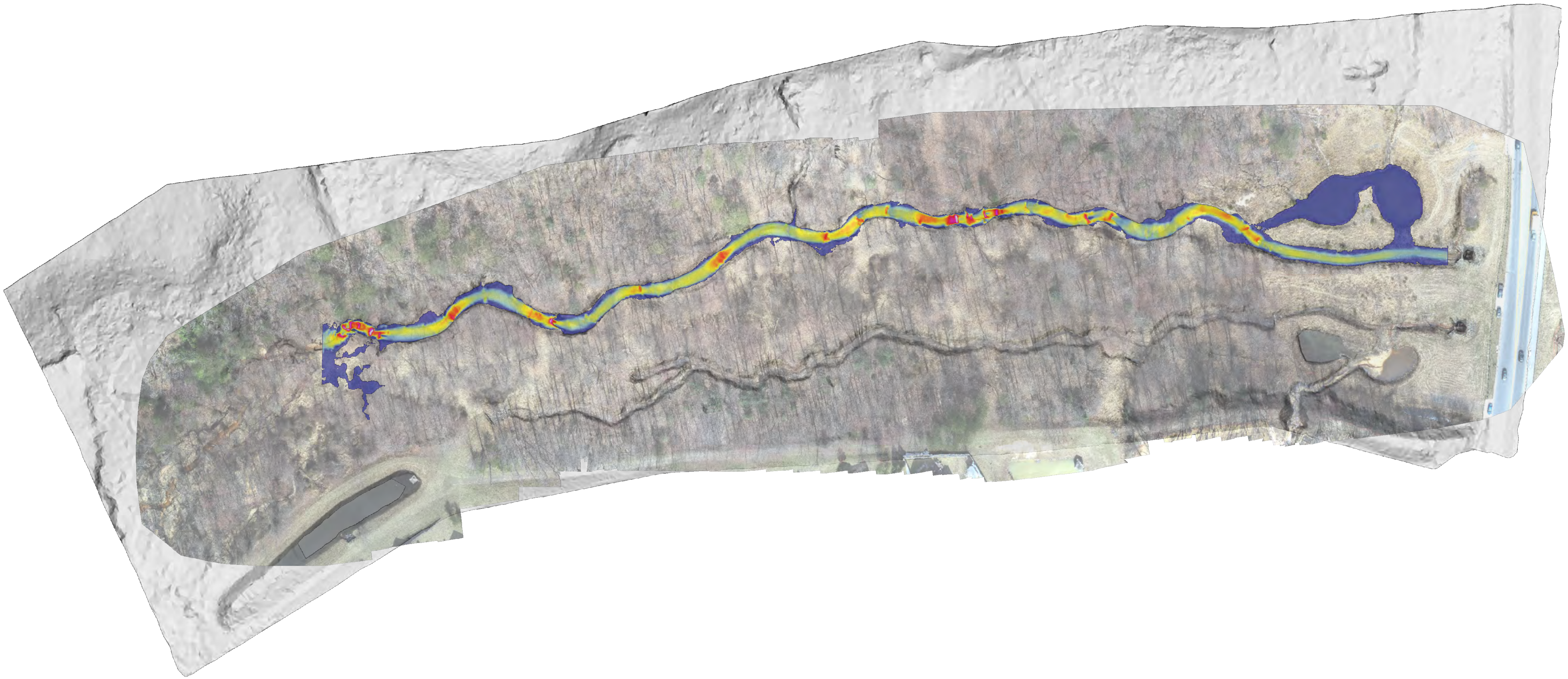

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 Feet

N

Two Dimensional Hydrodynamic Model Results: Bear Branch

Largest Event During Study

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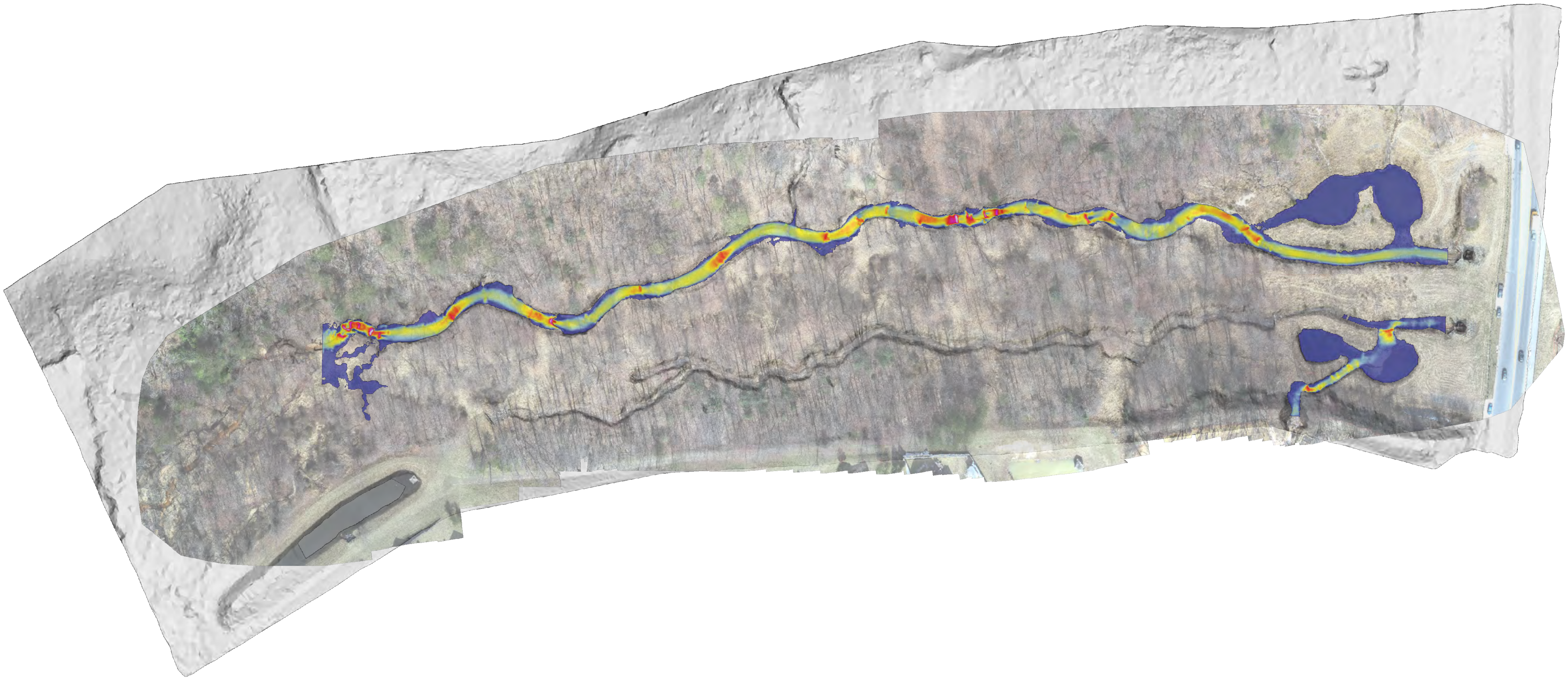

Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 Feet

N

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Two Dimensional Hydrodynamic Model Results: Bear Branch

2-yr Event Predicted Flood Velocities

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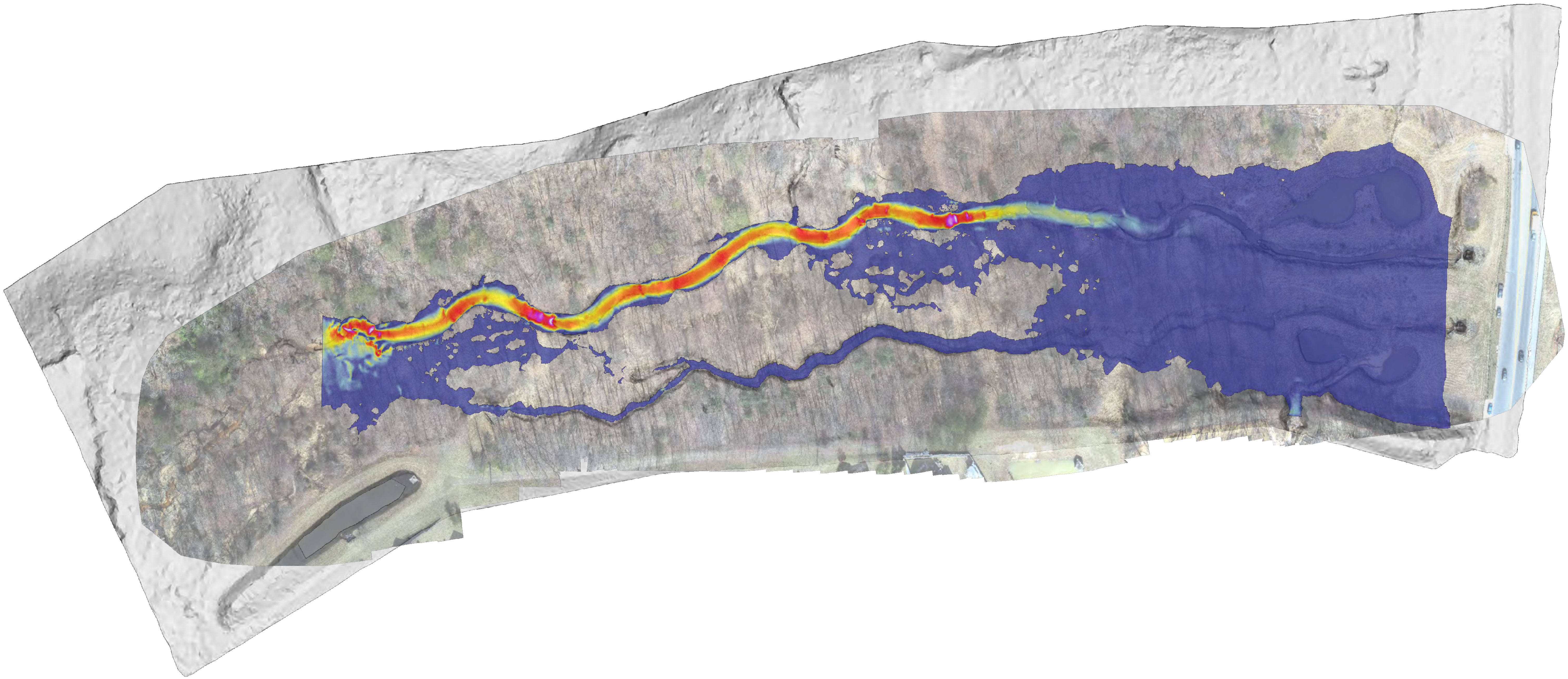

Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 Feet

N

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Two Dimensional Hydrodynamic Model Results: Bear Branch

10-yr Event Predicted Flood Velocities

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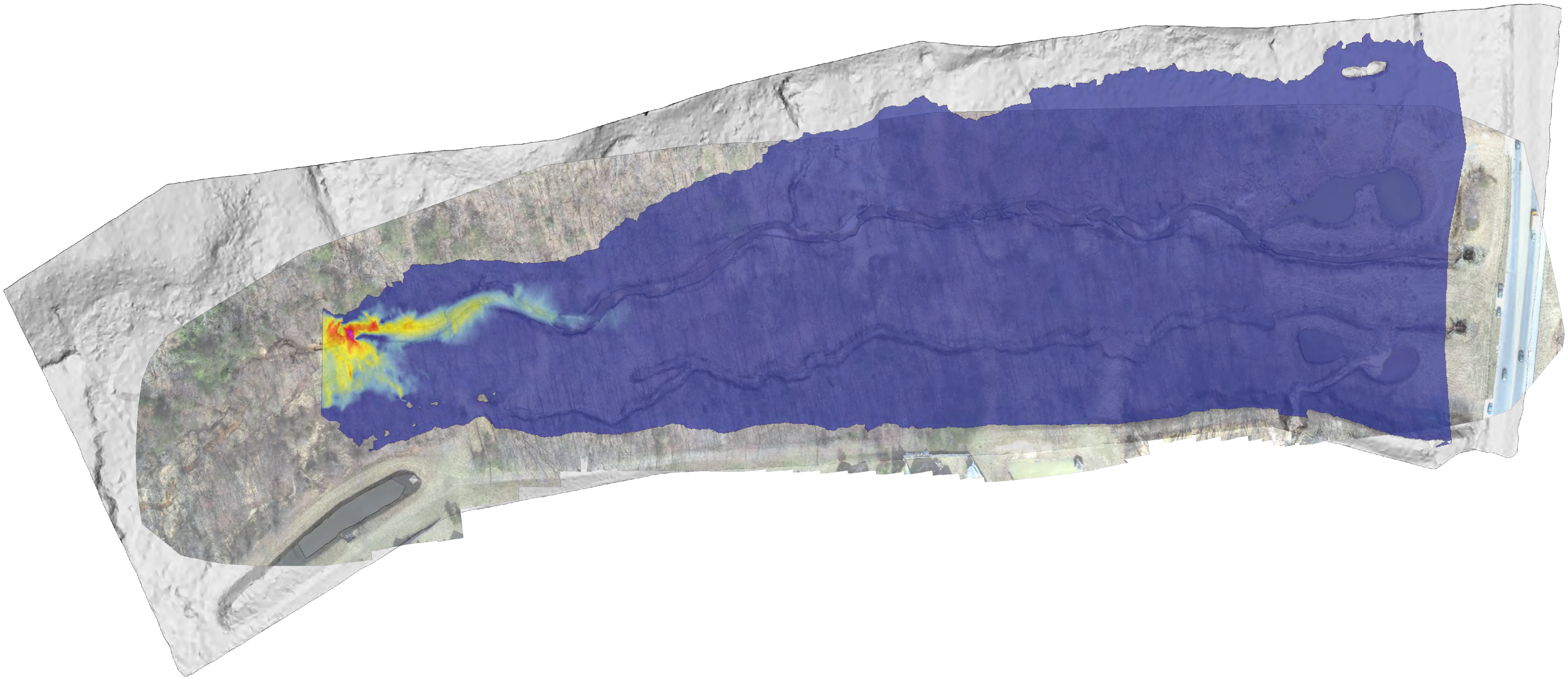

Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

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Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 Feet

N

Two Dimensional Hydrodynamic Model Results: Bear Branch

50-yr Event Predicted Flood Velocities

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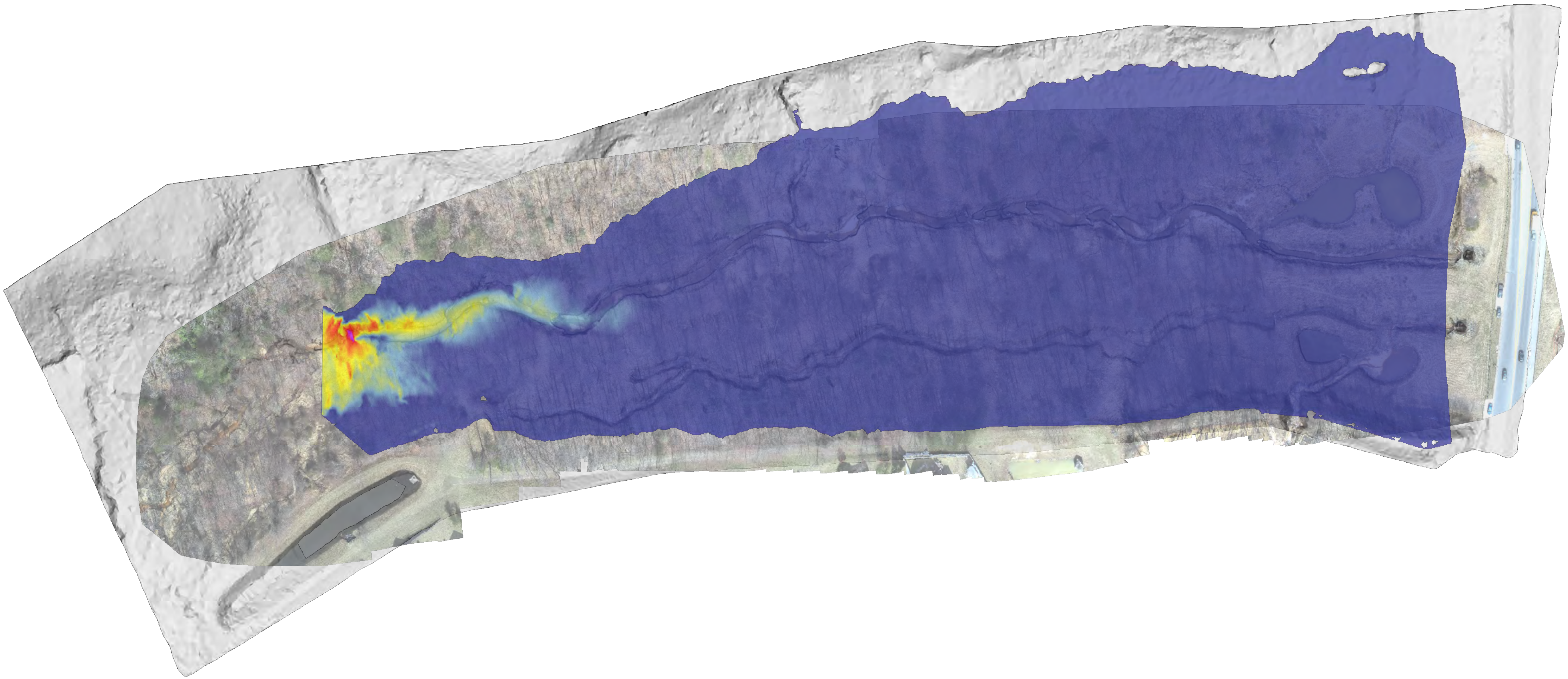

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

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STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 Feet

N

Two Dimensional Hydrodynamic Model Results: Bear Branch

100-yr Event Predicted Flood Velocities

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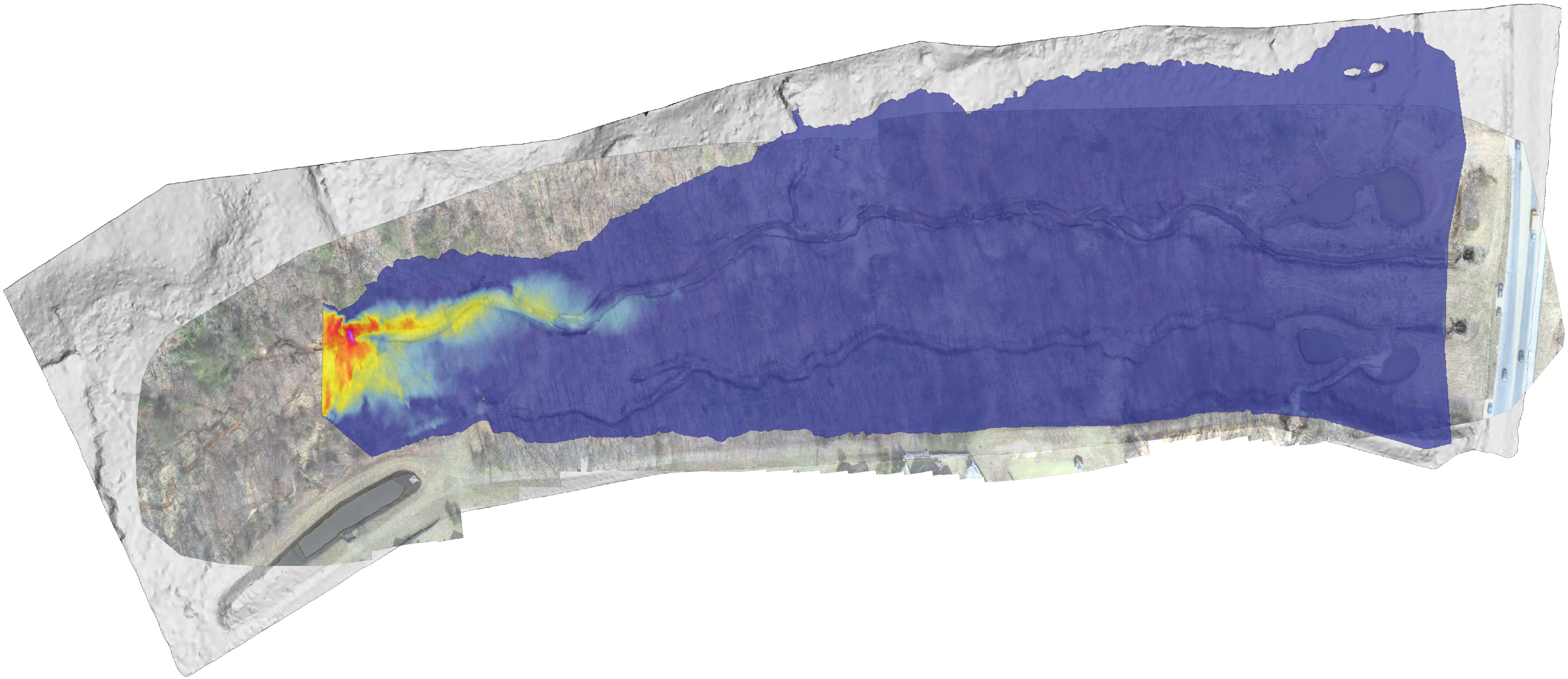

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 Feet

N

Two Dimensional Hydrodynamic Model Results: Bear Branch

Climate Change Scenario (100-yr + 33%)

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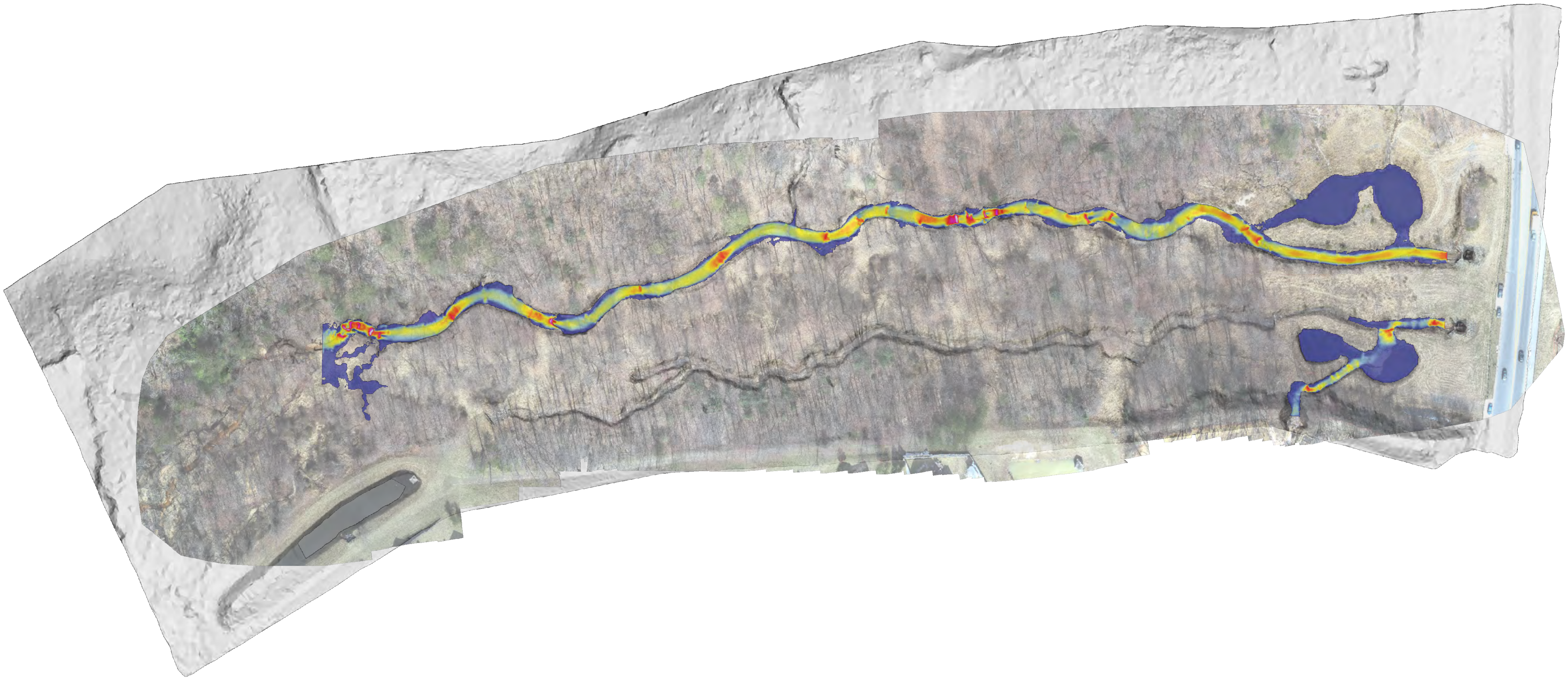

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 Feet

N

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STREAM INSTITUTE

Two Dimensional Hydrodynamic Model Results:
Bear Branch
No Backwater From Culvert

2-yr Event Predicted Flood Velocities

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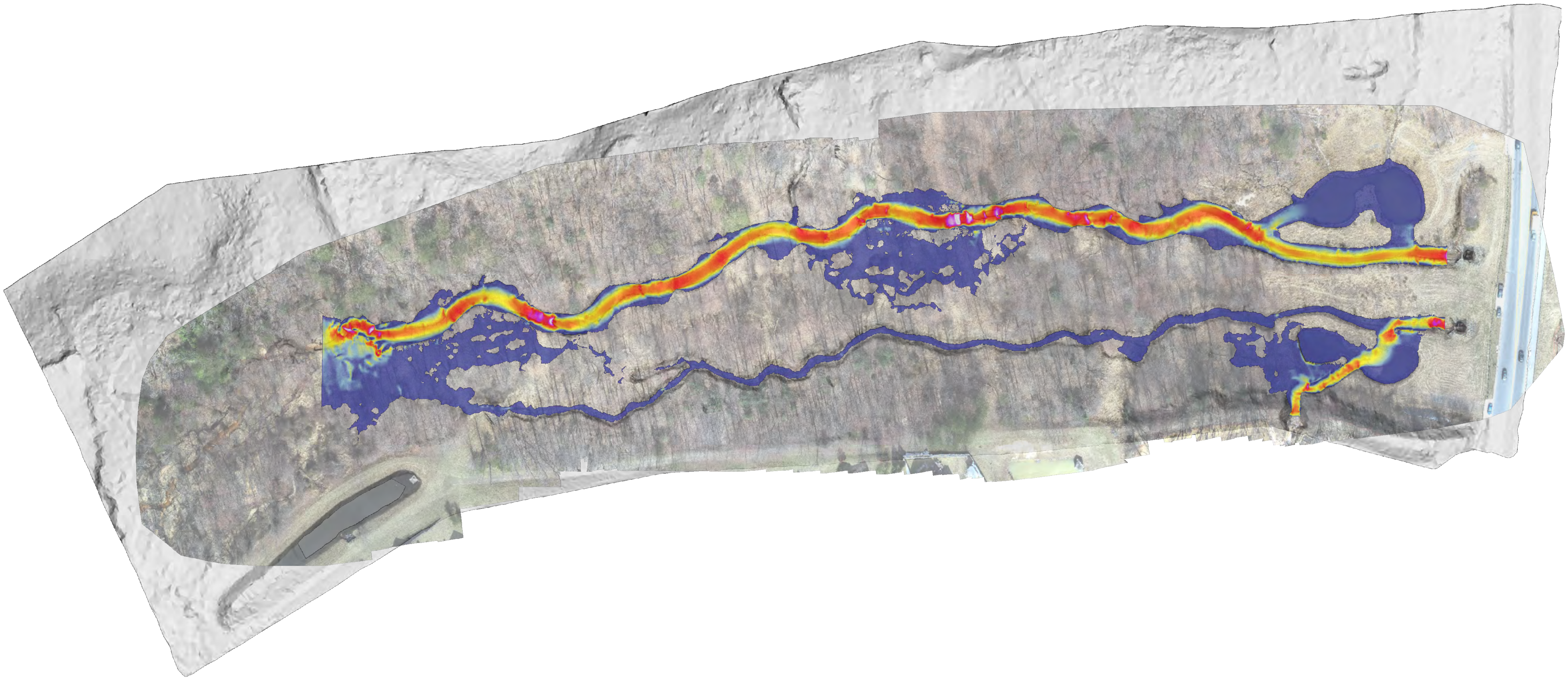
Program Funding Partners:



Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 Feet

N

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Two Dimensional Hydrodynamic Model Results: Bear Branch No Backwater From Culvert

10-yr Event Predicted Flood Velocities

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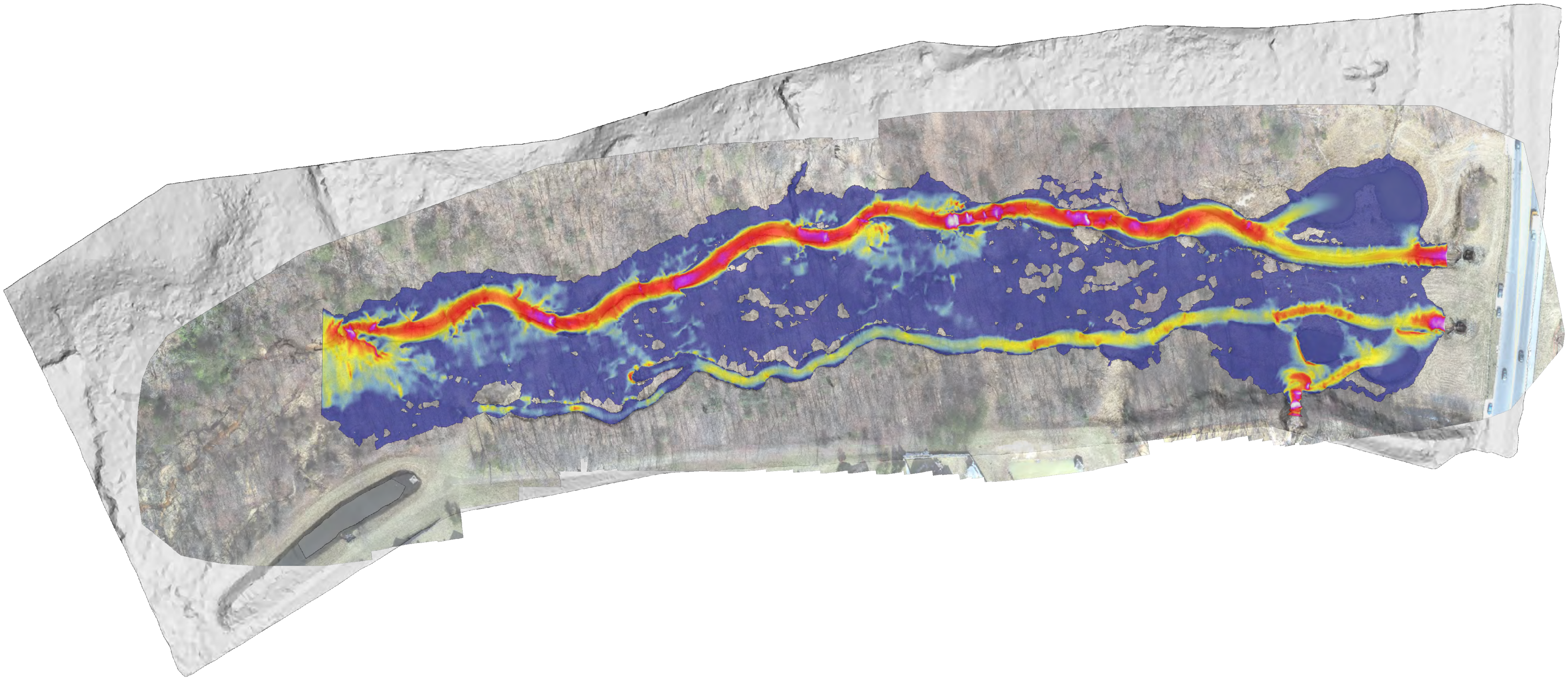

Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 Feet

N

Two Dimensional Hydrodynamic Model Results: Bear Branch No Backwater From Culvert

50-yr Event Predicted Flood Velocities

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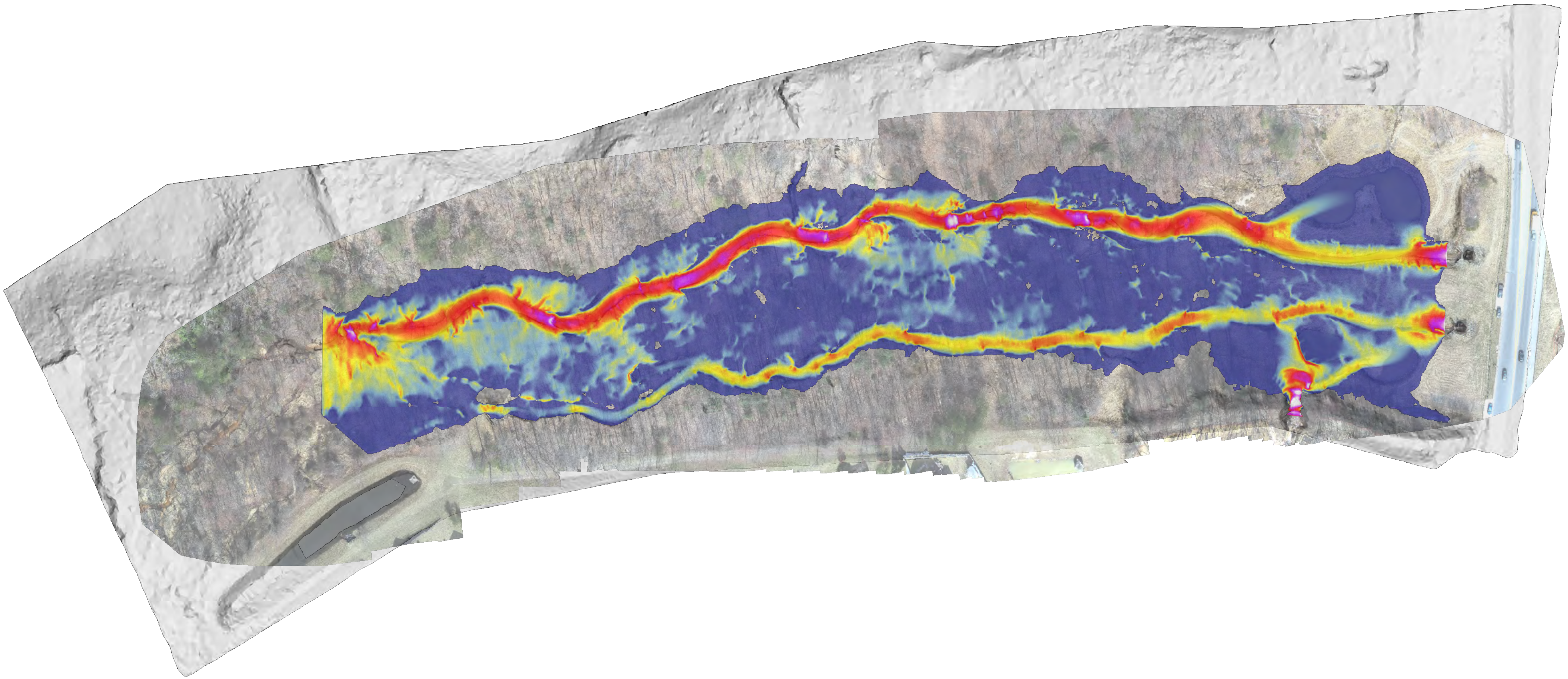

Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 Feet

N

Two Dimensional Hydrodynamic Model Results:
Bear Branch
No Backwater From Culvert

100-yr Event Predicted Flood Velocities

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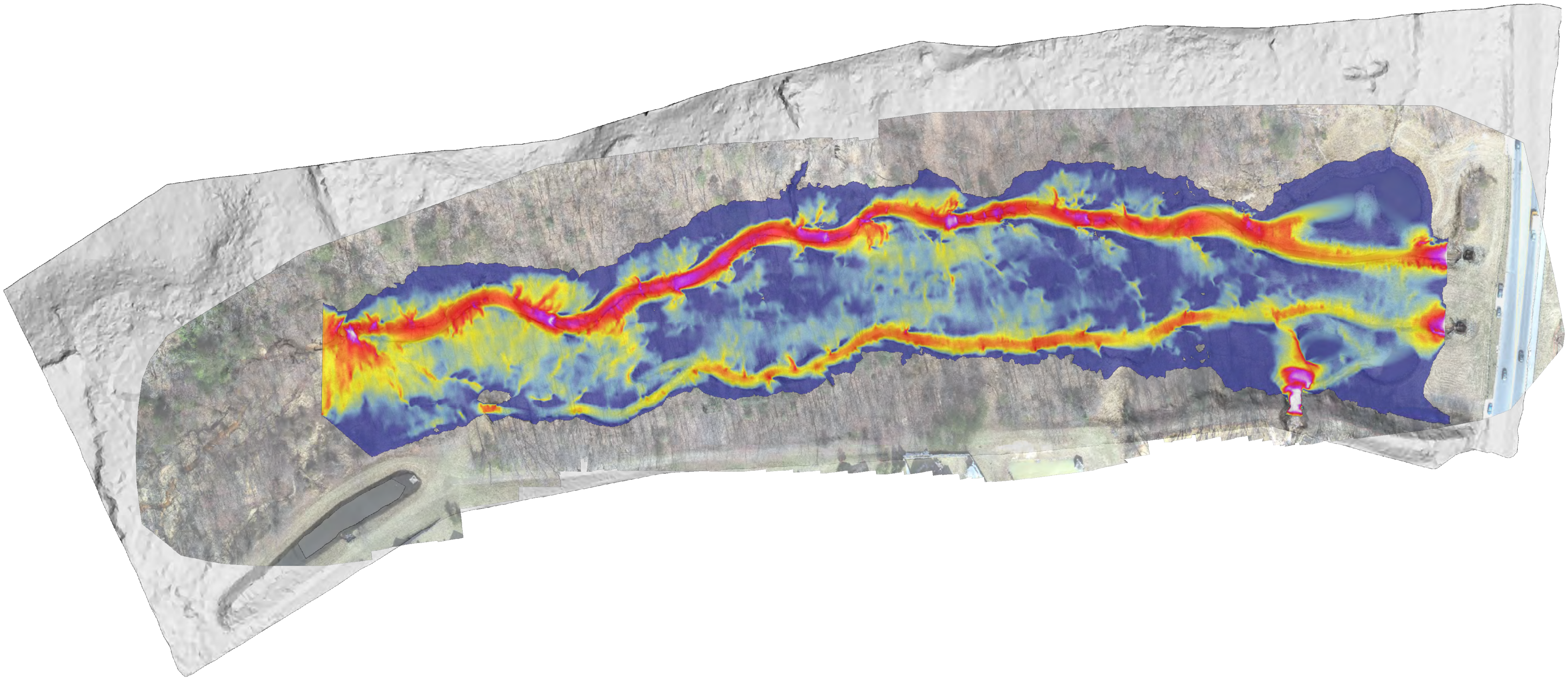

Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

UNIVERSITY OF LOUISVILLE.
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0 80 160 240 Feet

N

Two Dimensional Hydrodynamic Model Results:
Bear Branch
No Backwater From Culvert

Climate Change Scenario (100-yr + 33%)

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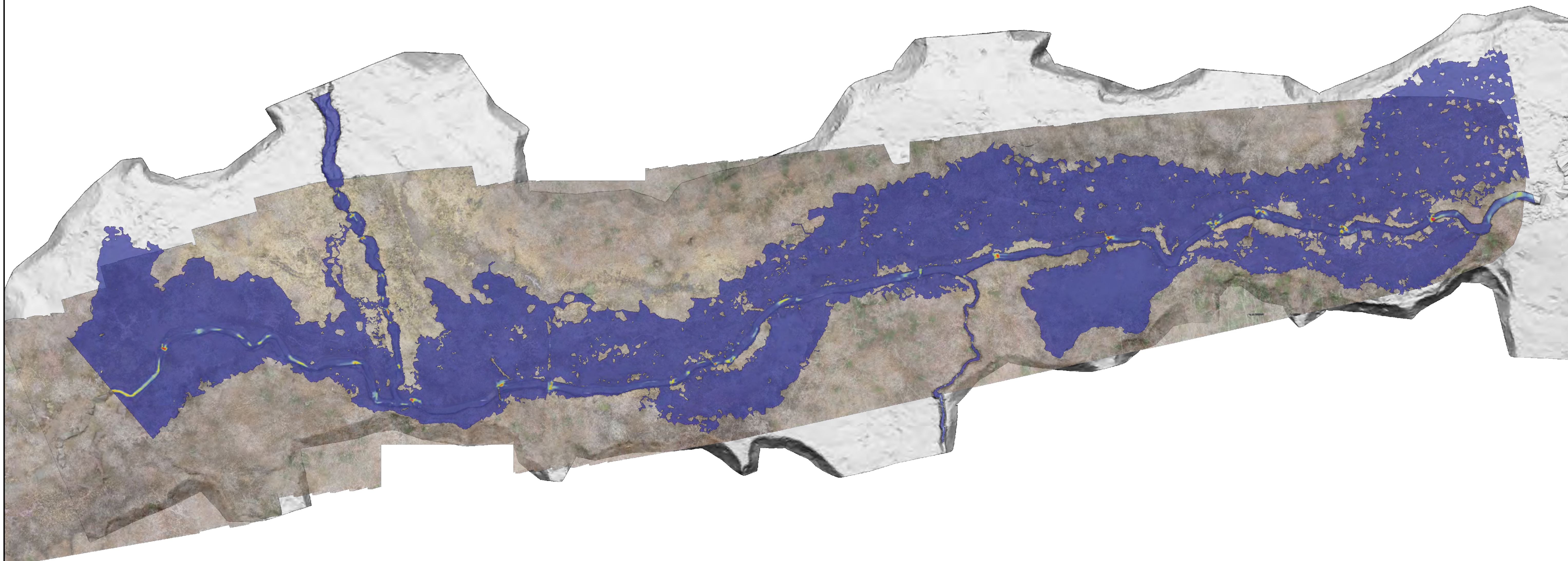
Restoration Research Award
Program Funding Partners:



Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 320 Feet

N

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Two Dimensional Hydrodynamic Model Results: Bacon Ridge

Largest Event During Study

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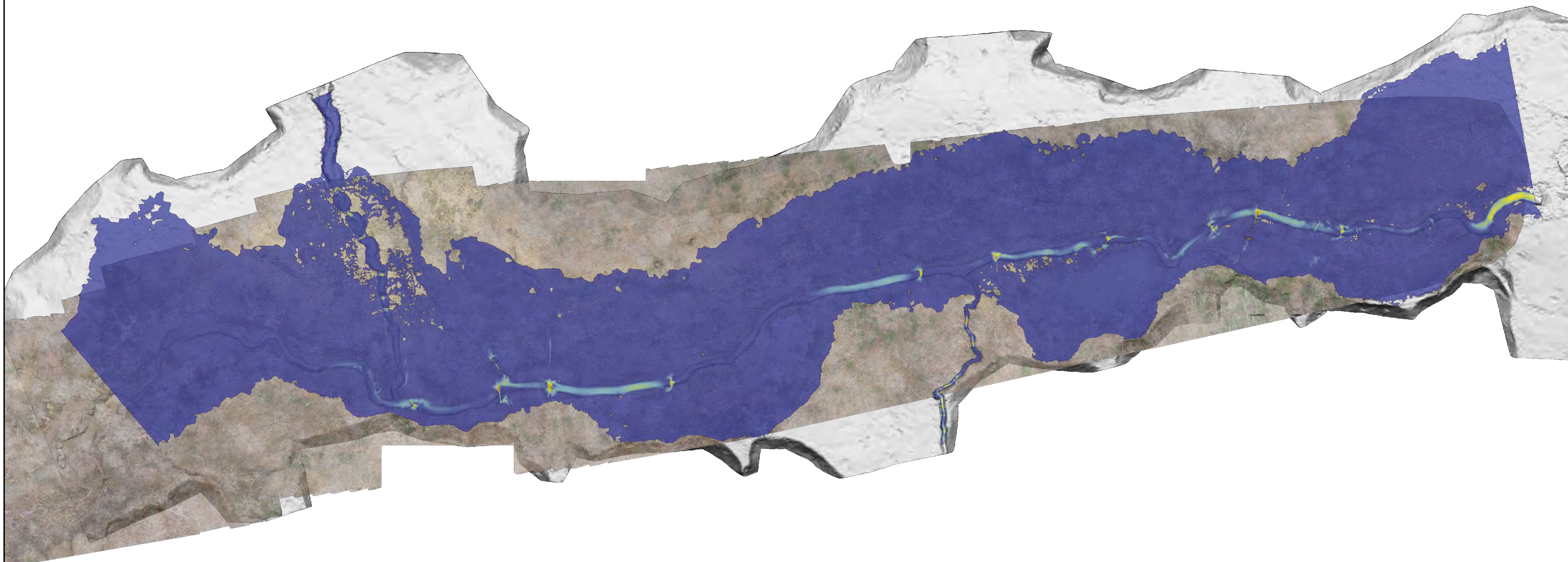

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 320 Feet

N

Two Dimensional Hydrodynamic Model Results: Bacon Ridge

2-yr Event Predicted Flood Velocities

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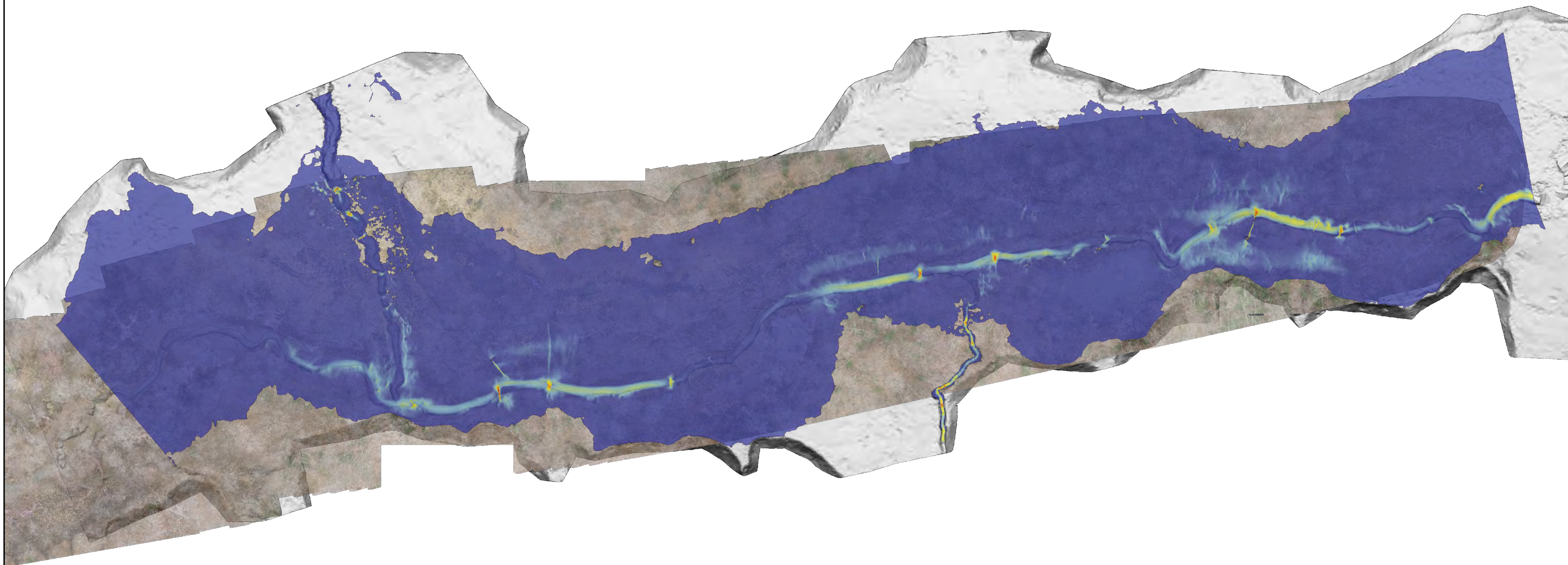
Restoration Research Award Program Funding Partners:



Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 320 Feet

N

Two Dimensional Hydrodynamic Model Results:
Bacon Ridge

10-yr Event Predicted Flood Velocities

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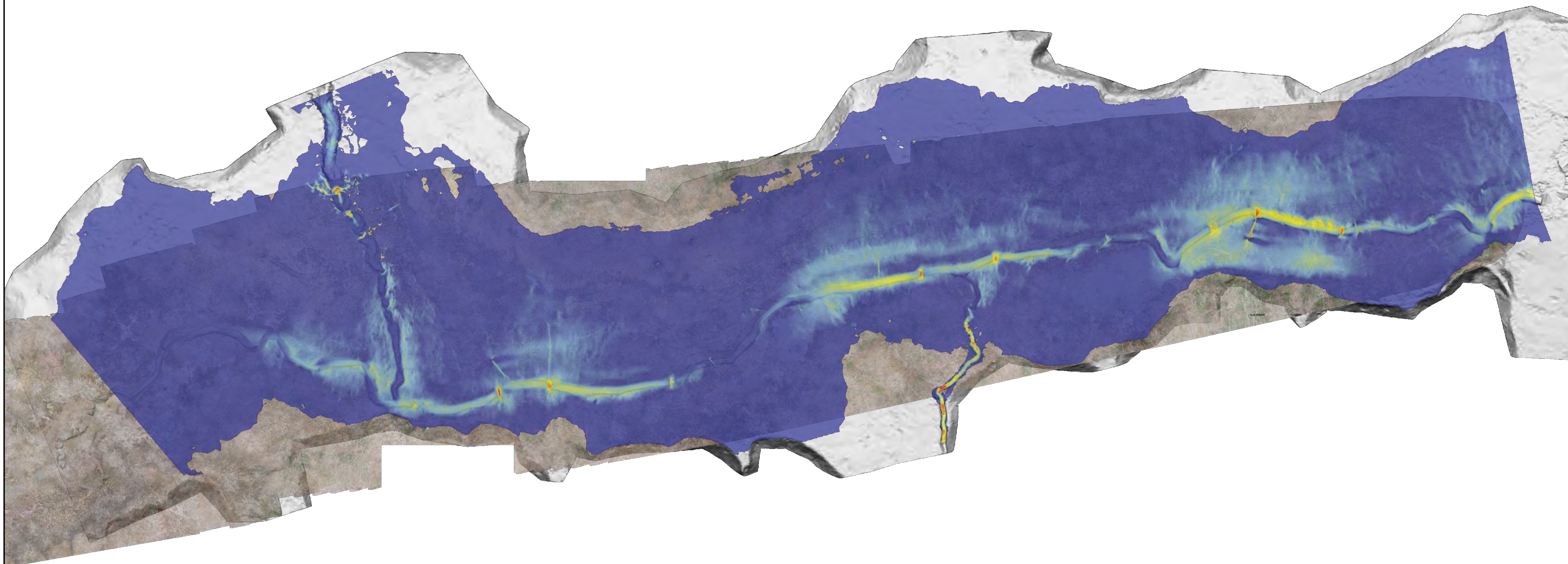

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 320 Feet

N

Two Dimensional Hydrodynamic Model Results: Bacon Ridge

50-yr Event Predicted Flood Velocities

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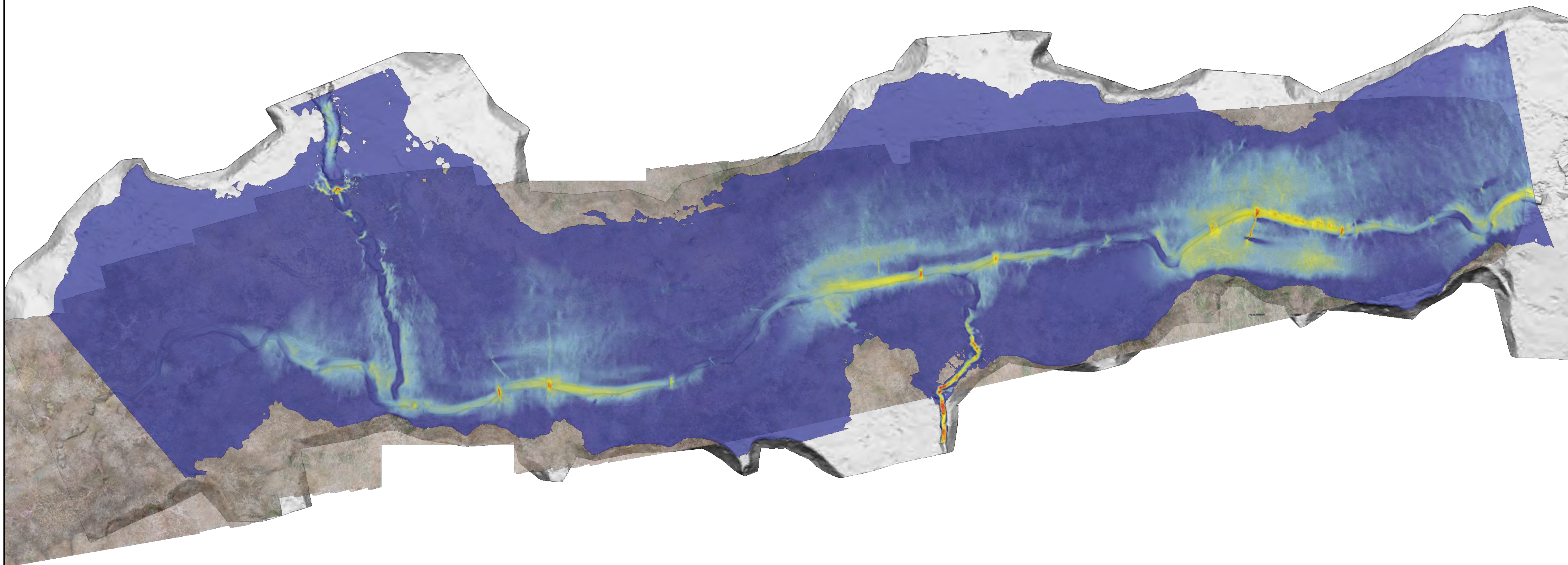
Restoration Research Award
Program Funding Partners:



Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 320 Feet

N

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Two Dimensional Hydrodynamic Model Results:
Bacon Ridge

100-yr Event Predicted Flood Velocities

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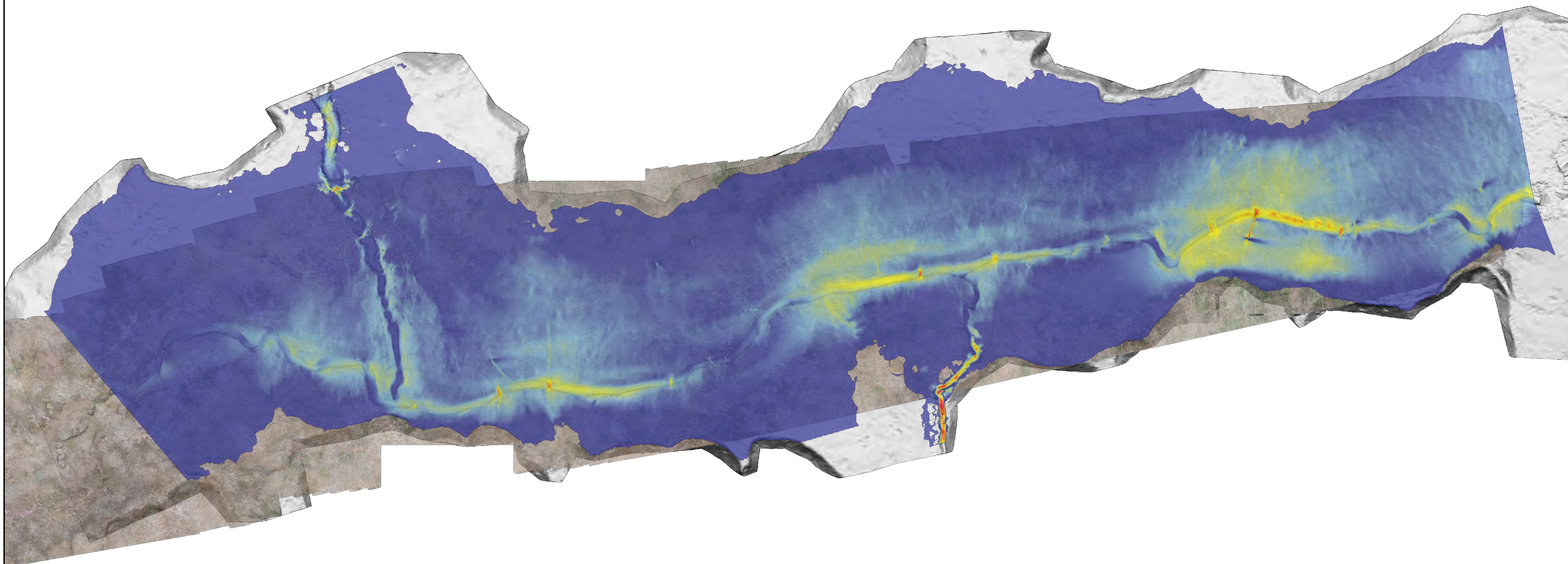

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 320 Feet

N

Two Dimensional Hydrodynamic Model Results:
Bacon Ridge

Climate Change Scenario (100-yr + 33%)

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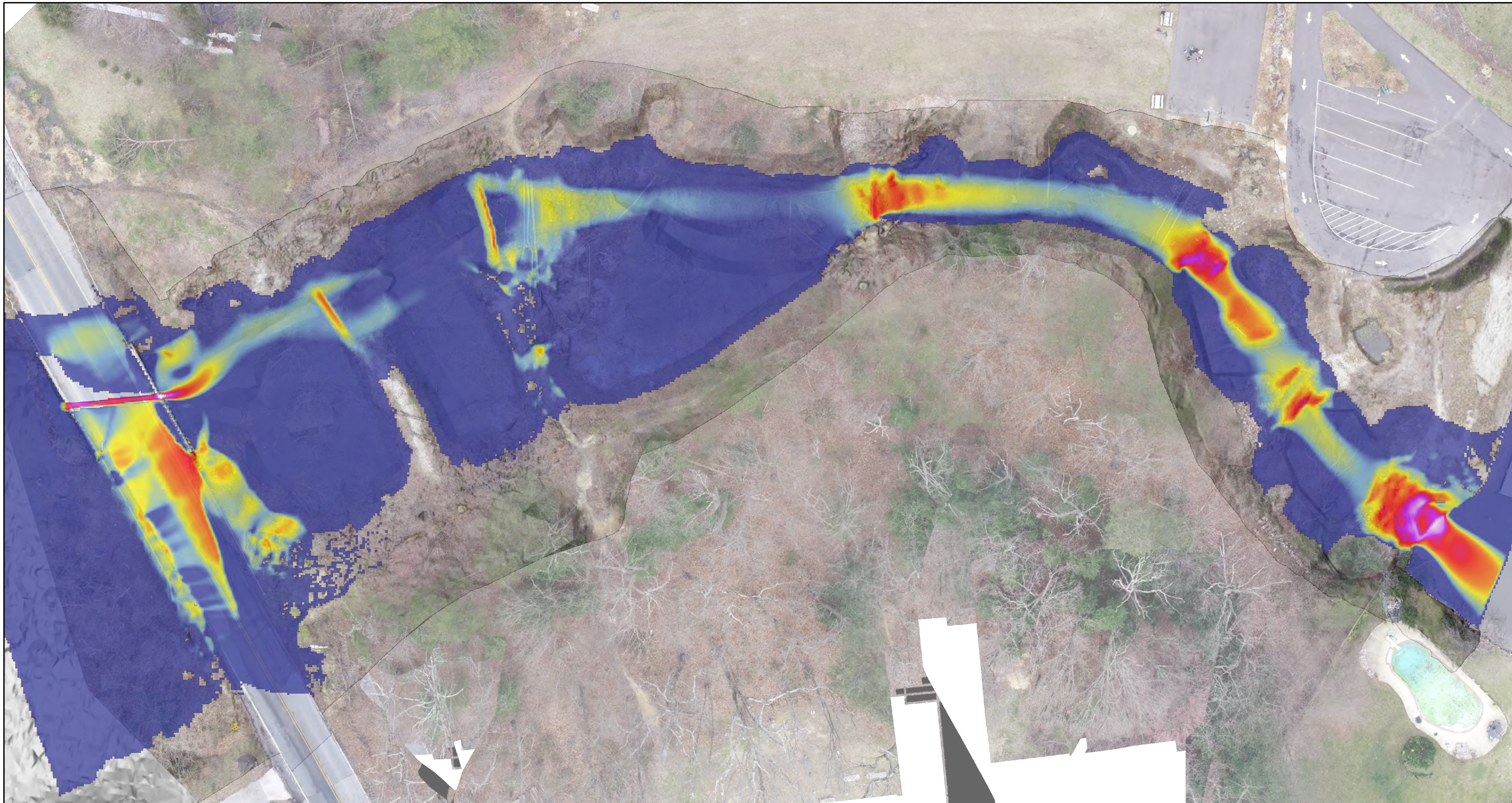
Program Funding Partners:



Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

UNIVERSITY OF LOUISVILLE
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 20 40 60 Feet

N

Two Dimensional Hydrodynamic Model Results:
Cattail Creek (Berrywood)

Largest Event During Study

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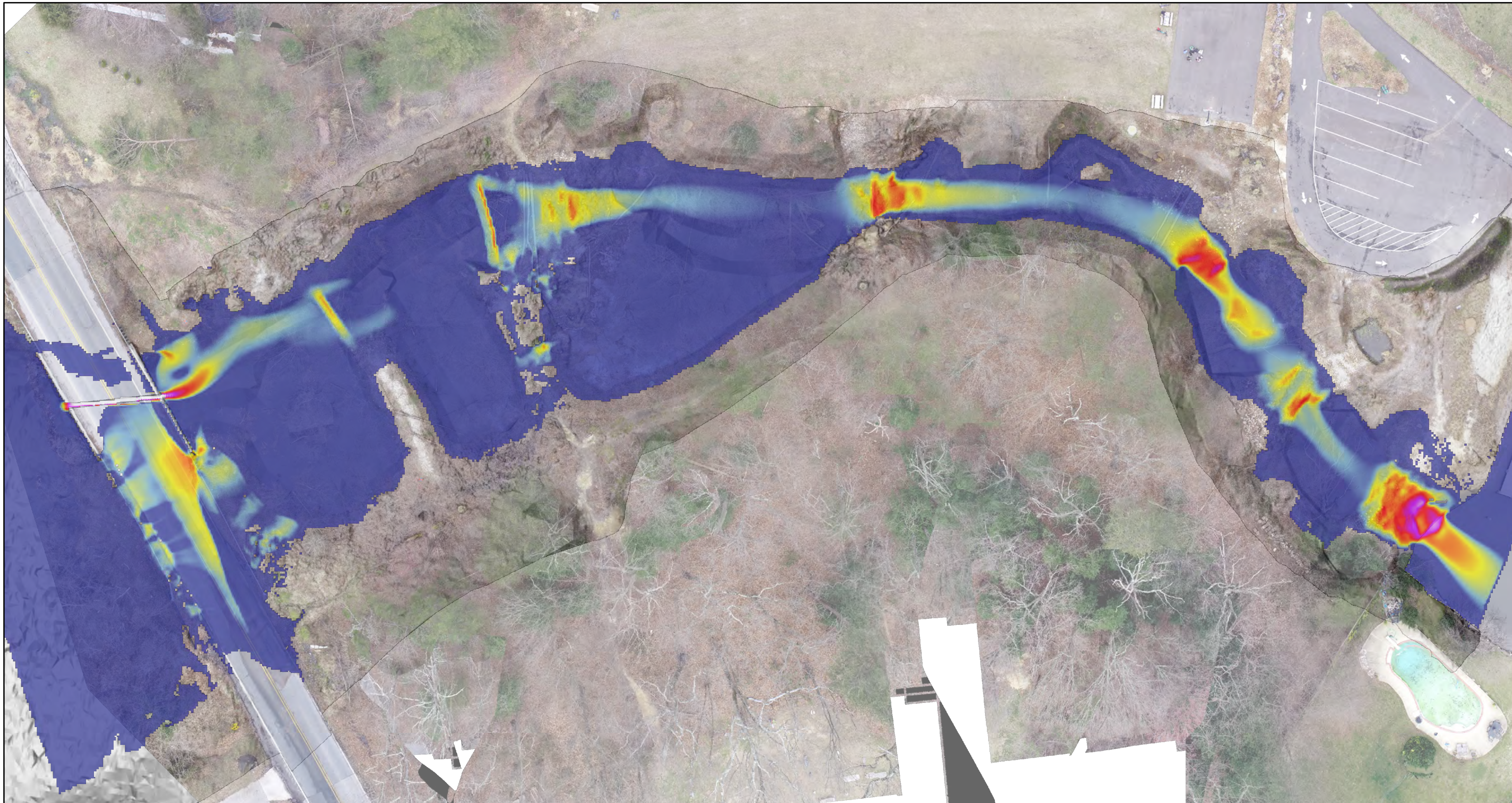
Restoration Research Award
Program Funding Partners:



Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 | 20 | 40 | 60 Feet

N

Two Dimensional Hydrodynamic Model Results: Cattail Creek (Berrywood)

2-yr Event Predicted Flood Velocities

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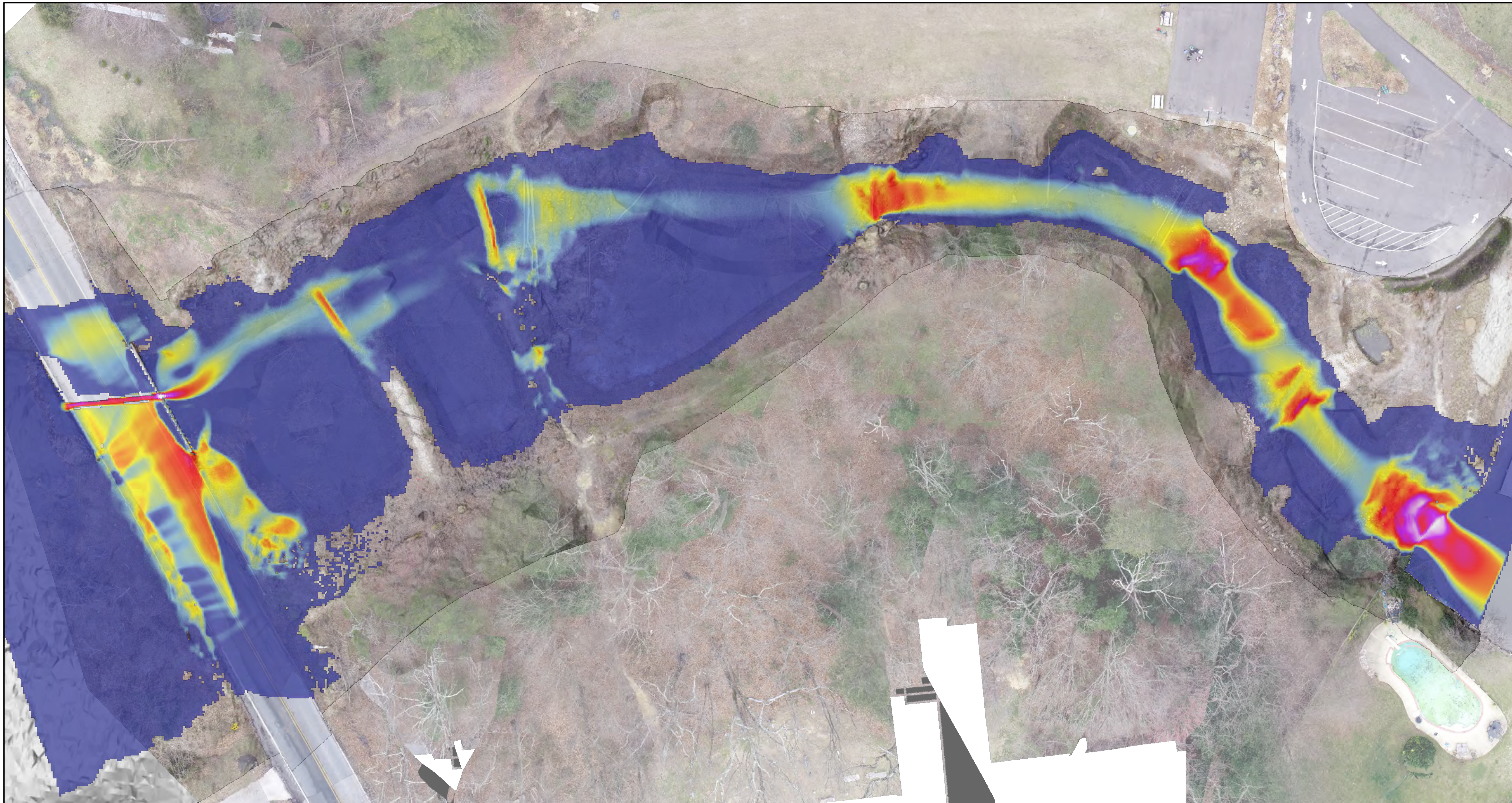

Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 20 40 60 Feet

N

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Two Dimensional Hydrodynamic Model Results: Cattail Creek (Berrywood)

10-yr Event Predicted Flood Velocities

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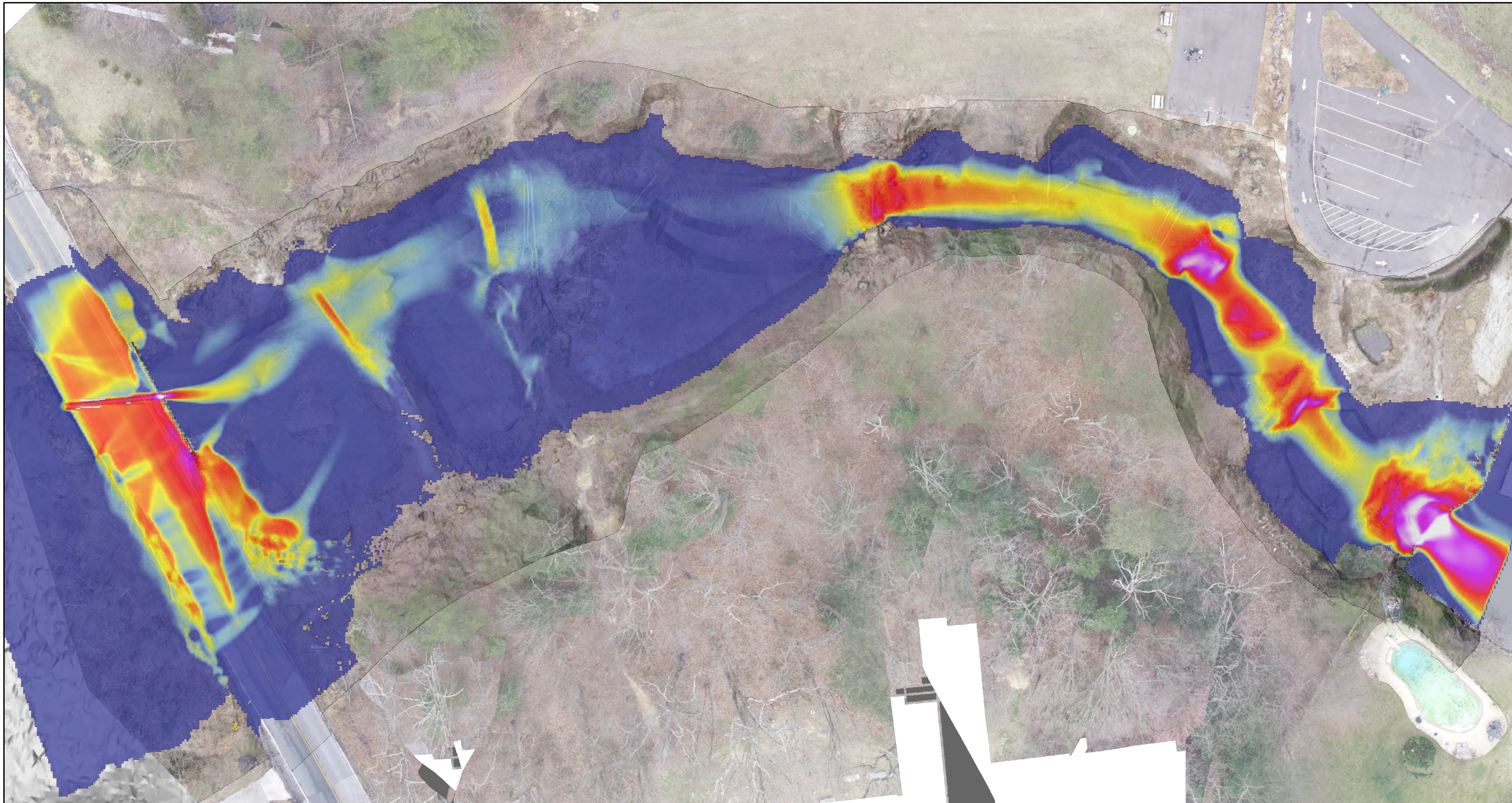
Restoration Research Award Program Funding Partners:



Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 | 20 | 40 | 60 Feet

N

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Two Dimensional Hydrodynamic Model Results:
Cattail Creek (Berrywood)

50-yr Event Predicted Flood Velocities

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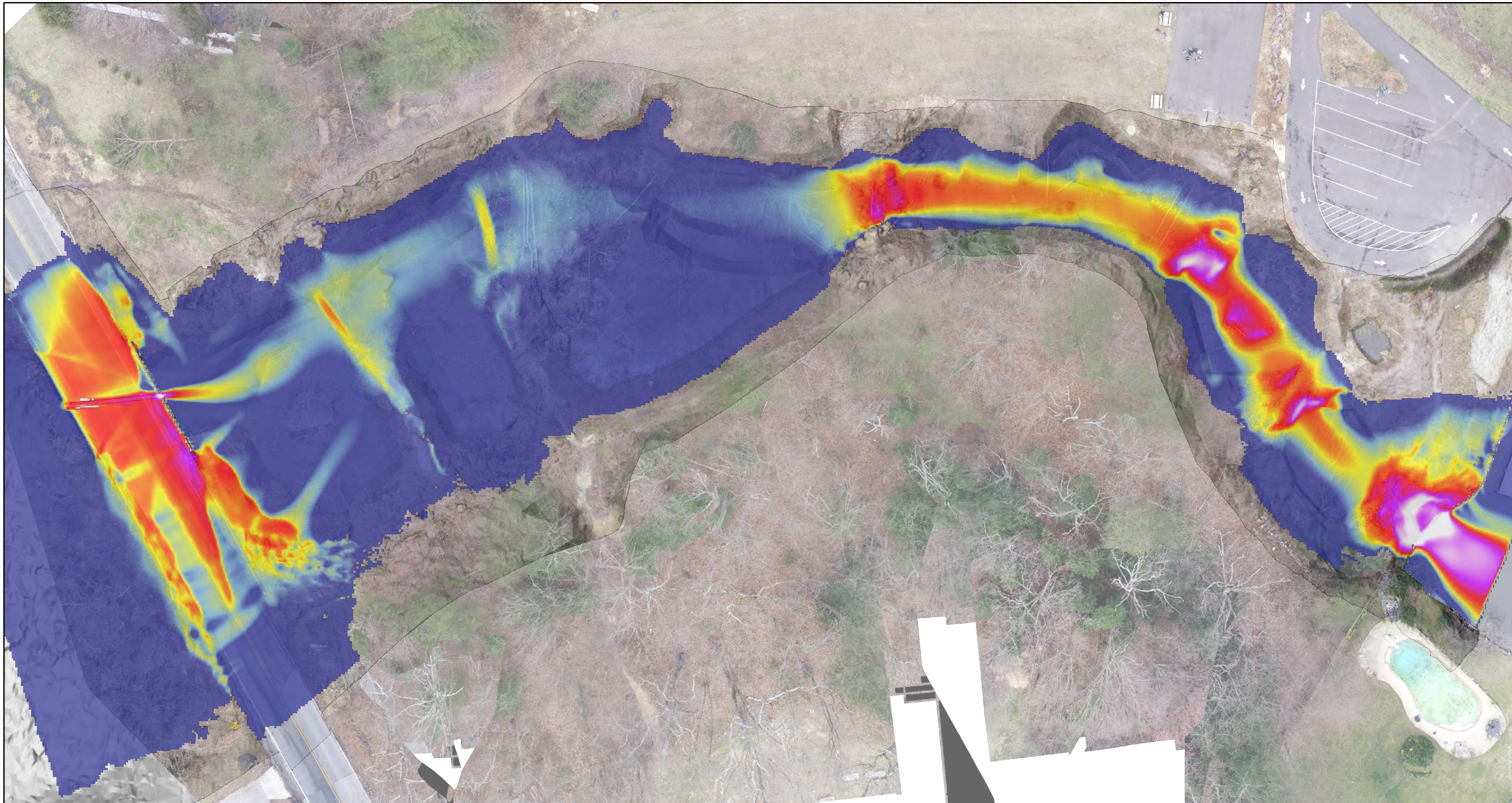
Restoration Research Award
Program Funding Partners:



Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 20 40 60 Feet

N

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Two Dimensional Hydrodynamic Model Results: Cattail Creek (Berrywood)

100-yr Event Predicted Flood Velocities

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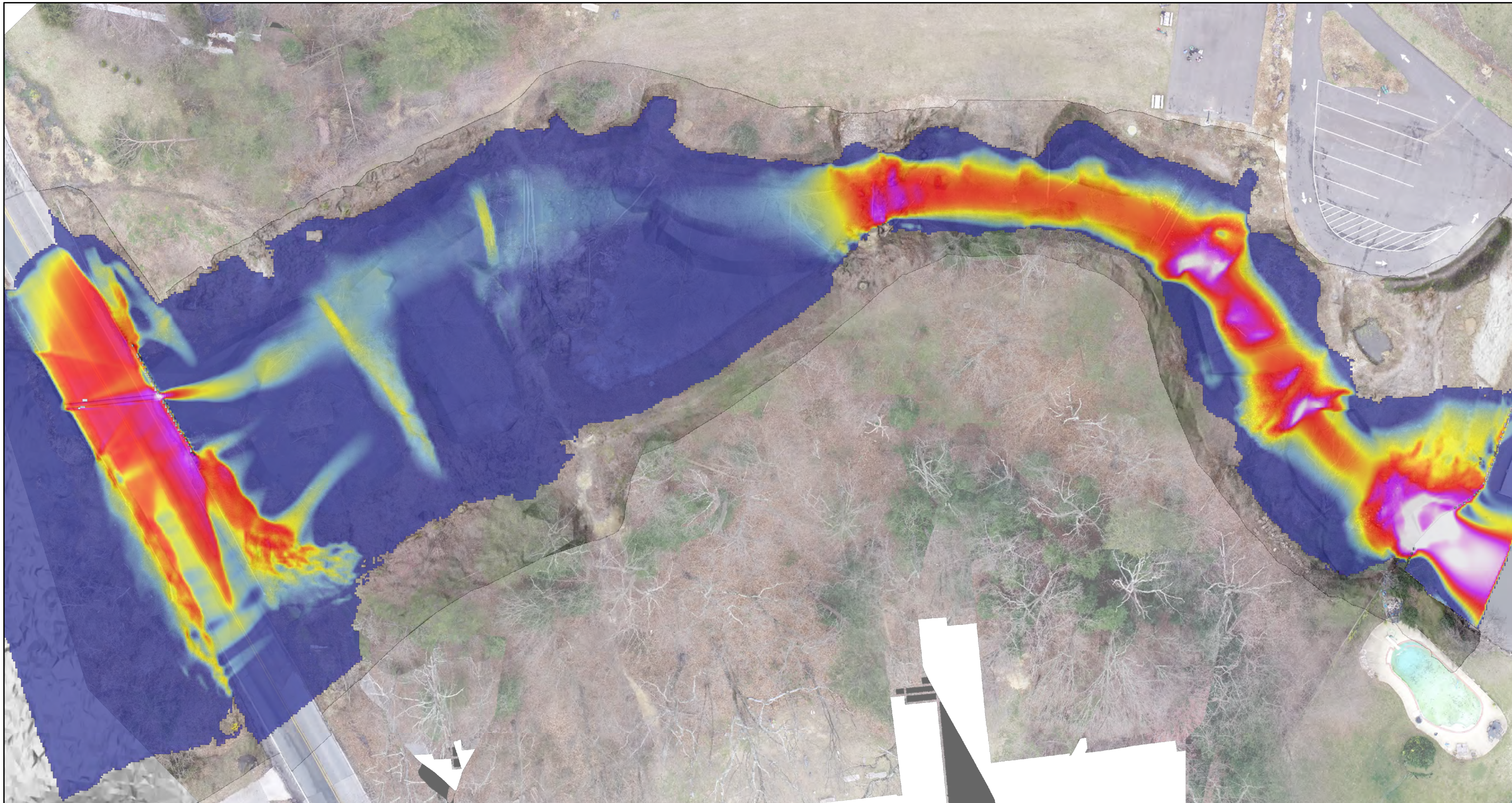
Restoration Research Award Program Funding Partners:



Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 20 40 60 Feet

N

Two Dimensional Hydrodynamic Model Results:
Cattail Creek (Berrywood)

Climate Change Scenario (100-yr + 33%)

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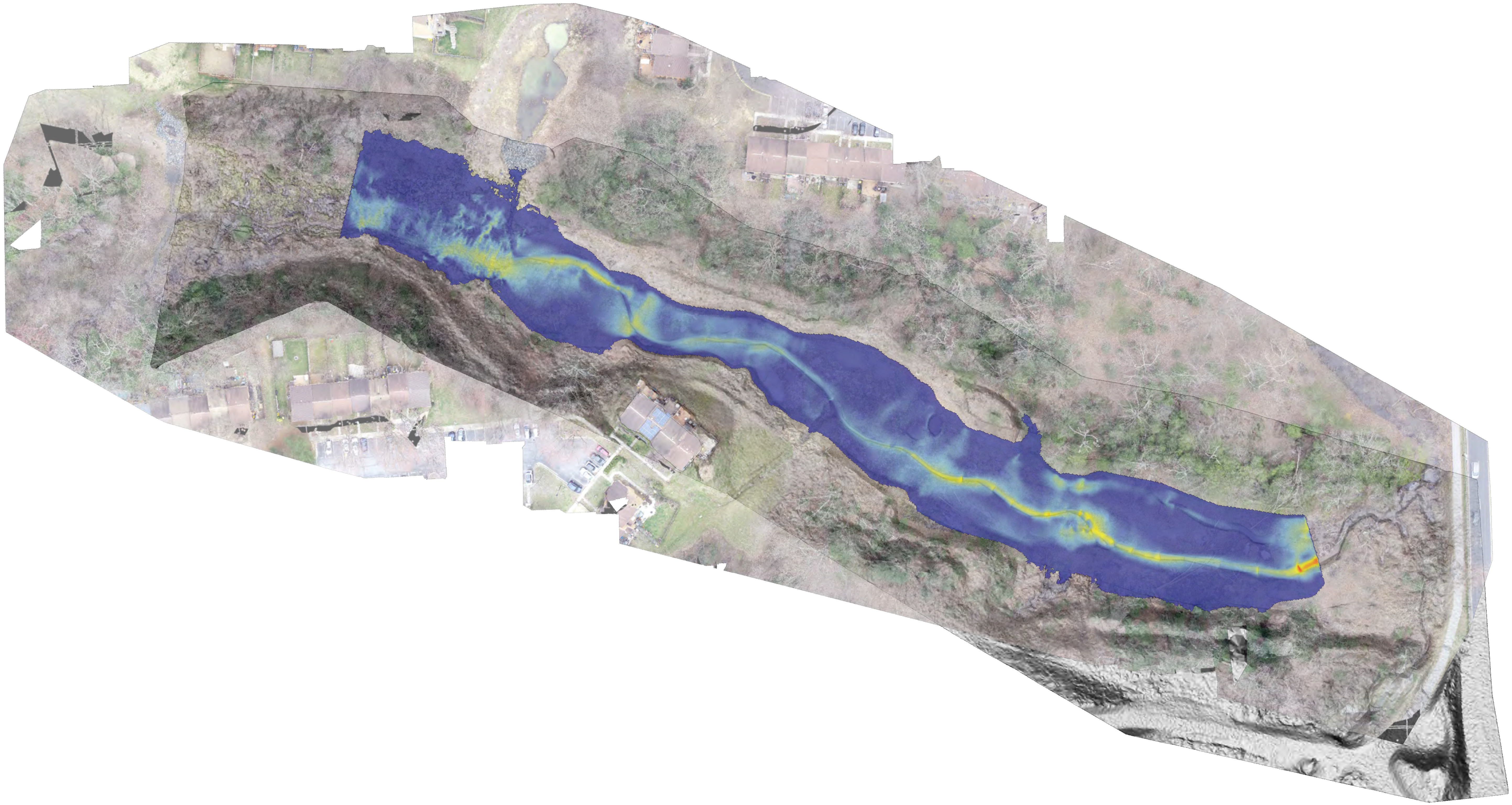
Restoration Research Award
Program Funding Partners:



Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 | 40 | 80 | 120 | 160 Feet

N

Two Dimensional Hydrodynamic Model Results:
Cat Branch

Largest Event During Study

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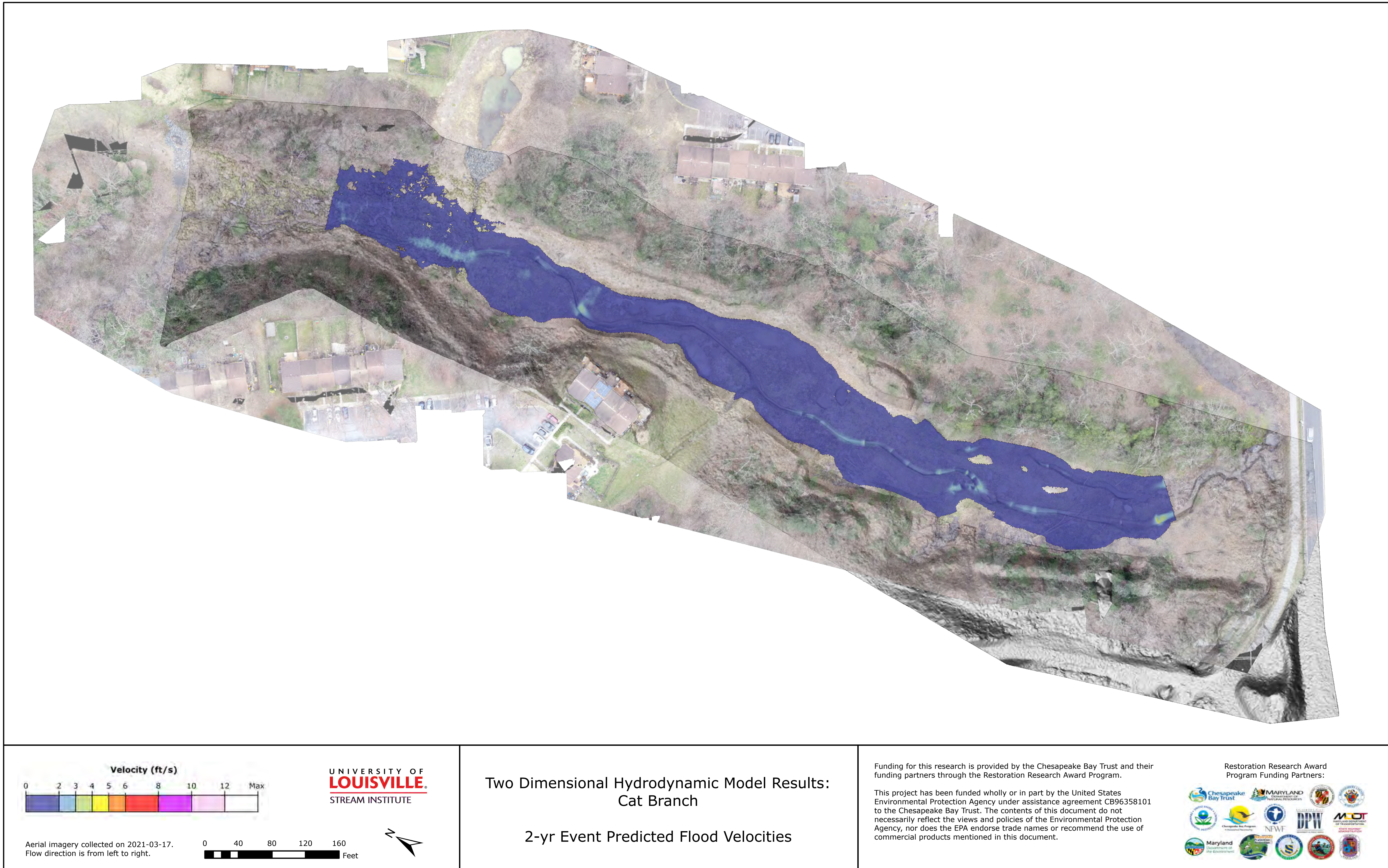
Program Funding Partners:



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Two Dimensional Hydrodynamic Model Results: Cat Branch

2-yr Event Predicted Flood Velocities

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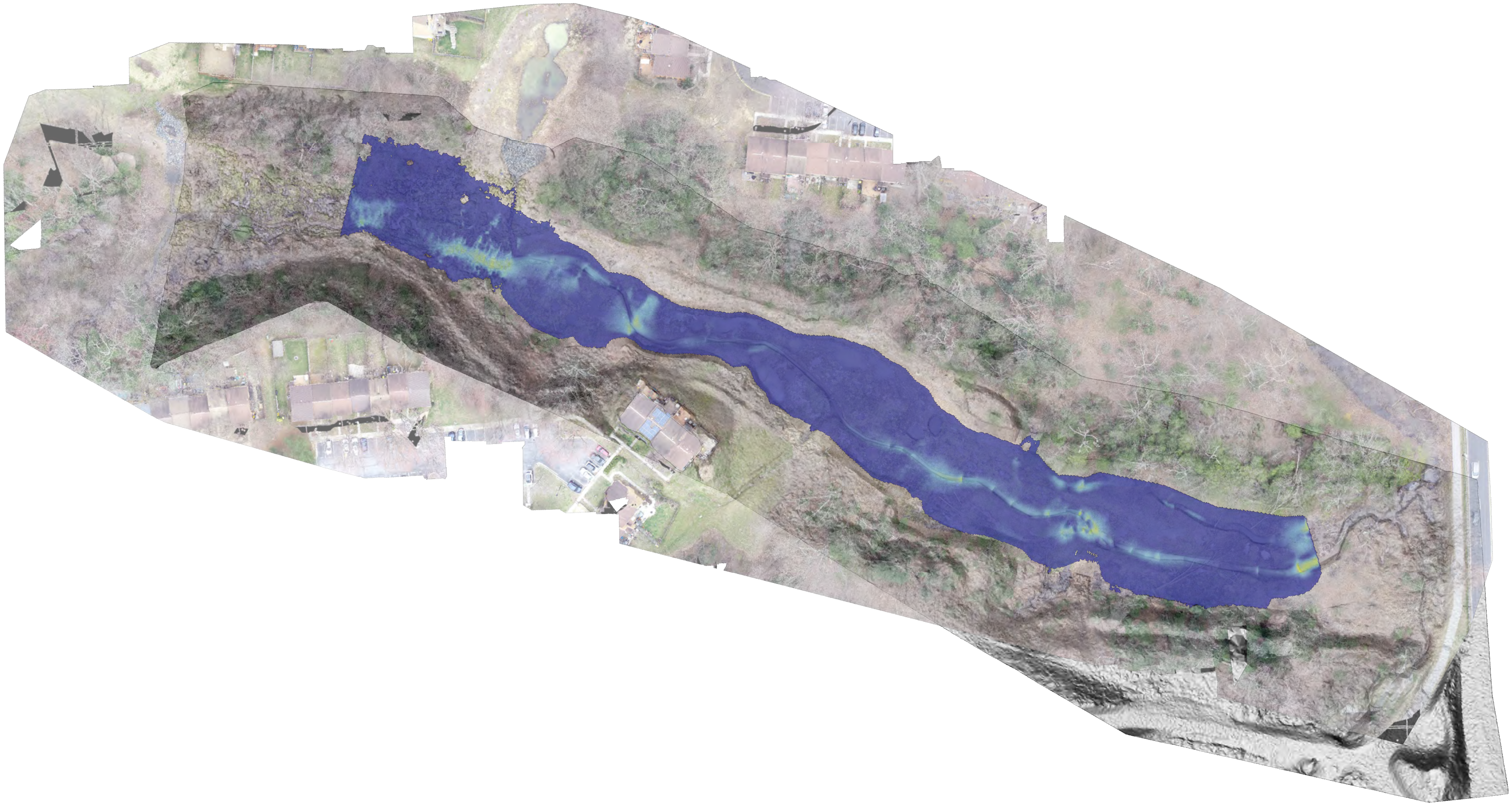

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 40 80 120 160 Feet

Two Dimensional Hydrodynamic Model Results:
Cat Branch

10-yr Event Predicted Flood Velocities

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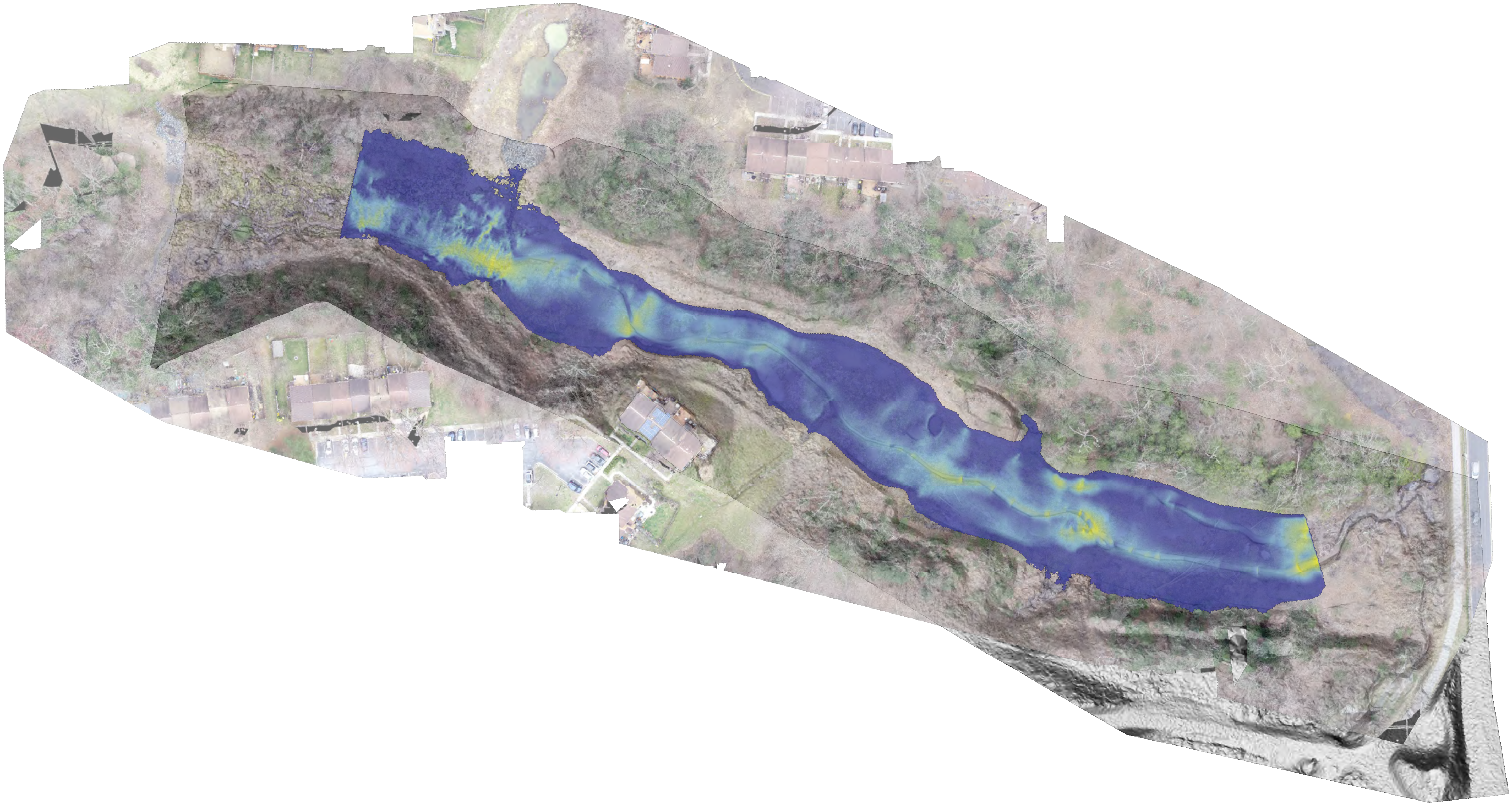

Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 40 80 120 160 Feet

N

Two Dimensional Hydrodynamic Model Results:
Cat Branch

50-yr Event Predicted Flood Velocities

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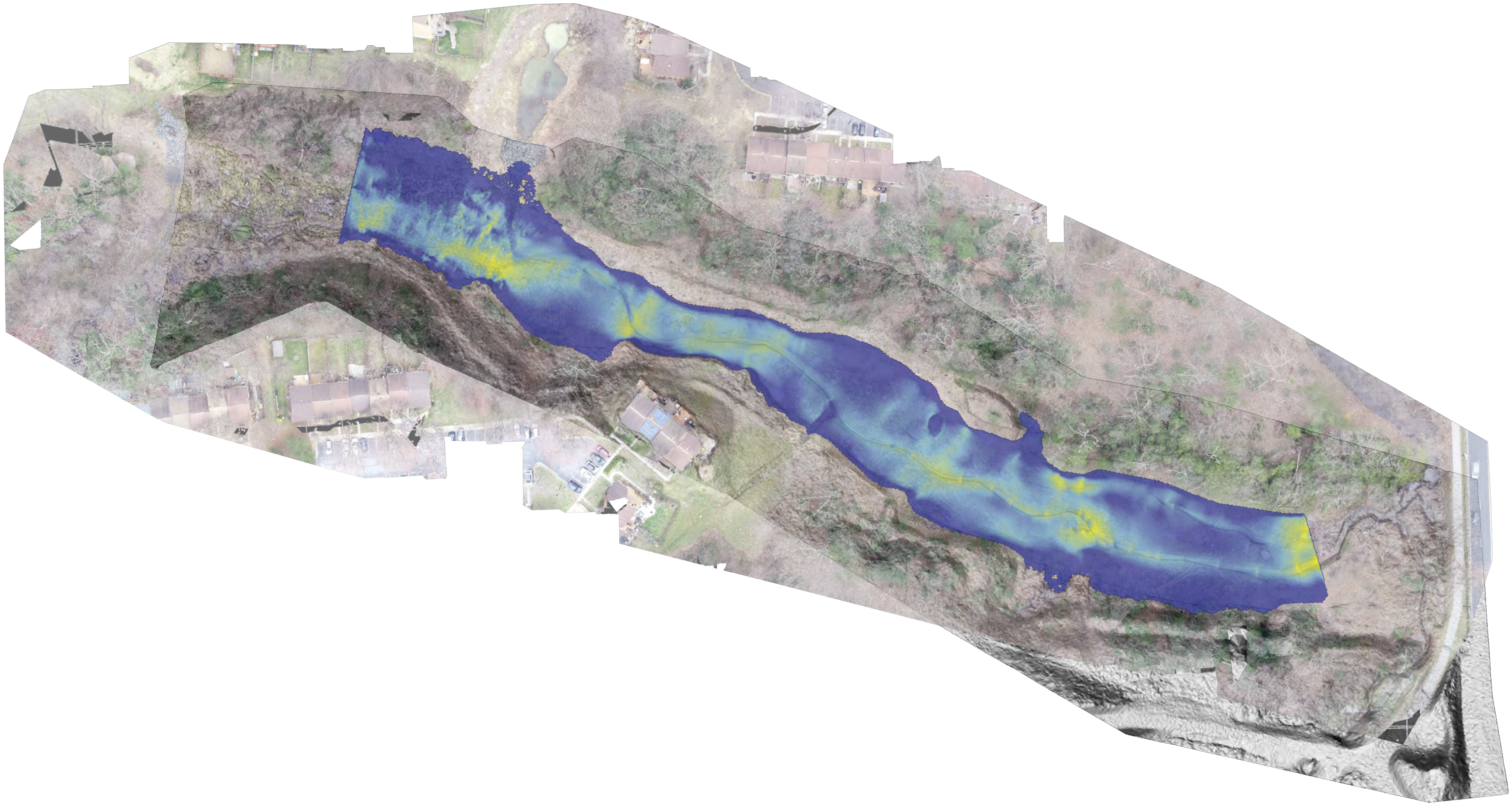

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 40 80 120 160 Feet

Two Dimensional Hydrodynamic Model Results: Cat Branch

100-yr Event Predicted Flood Velocities

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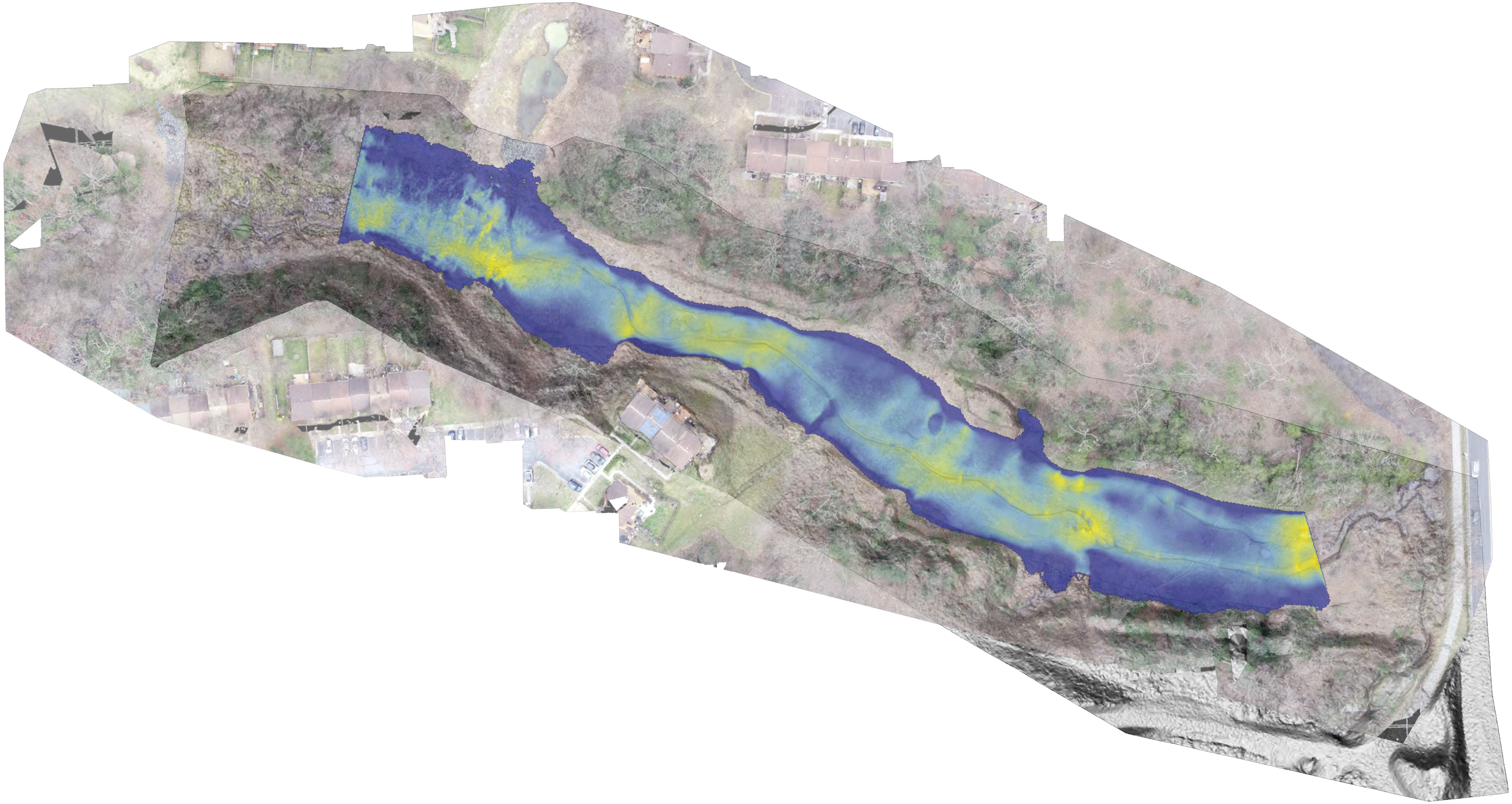

Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

UNIVERSITY OF LOUISVILLE
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 40 80 120 160 Feet

N

Two Dimensional Hydrodynamic Model Results: Cat Branch

Climate Change Scenario (100-yr + 33%)

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Restoration Research Award Program Funding Partners:

APPENDIX D. 2D MODEL VELOCITIES FOR READERS WITH COLOR VISION DEFICIENCY

The results of all modeling completed in this study are reproduced with a color ramp suited to users with color vision deficiency. An alternative color ramp for color vision deficiency is provided below, which uses sharp cut-offs between categories related to stability thresholds.

Velocity (ft/s)	Color Hex	Color
0 – 2 .0	#c0ffff	
2.1 – 3.0	#7d9ec0	
3.1 – 4.0	#0000ff	
4.1 – 4.7	#ffffe0	
4.8 – 5.3	#ffff00	
5.4 – 6.0	#ffd700	
6.1 – 6.7	#fE7f9c	
6.8 – 7.3	#ff0000	
7.4 – 8.0	#8b0000	
8.1 – 10.0	#d9d9d9	
10.1 – 12.0	#bfbfbf	
>12.1	#808080	

Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 50 100 150 200 Feet

N

Two Dimensional Hydrodynamic Model Results: Furnace Creek (Upper)

Largest Event During Study

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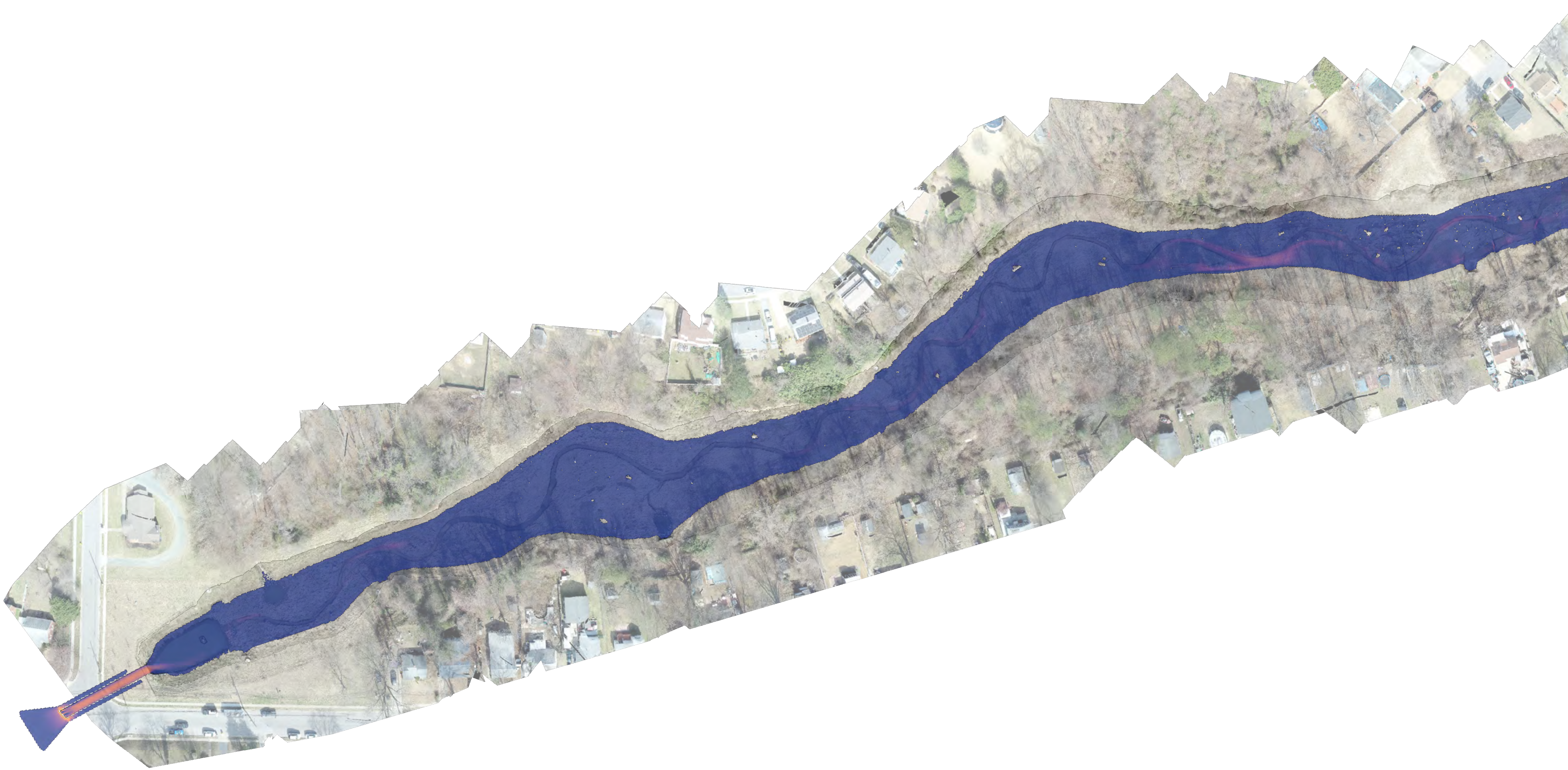

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 50 100 150 200 Feet

N

Two Dimensional Hydrodynamic Model Results:
Furnace Creek (Upper)

2-yr Event Predicted Flood Velocities

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Restoration Research Award
Program Funding Partners:

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 50 100 150 200 Feet

N

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Two Dimensional Hydrodynamic Model Results:
Furnace Creek (Upper)

10-yr Event Predicted Flood Velocities

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Restoration Research Award
Program Funding Partners:

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 50 100 150 200 Feet

N

Two Dimensional Hydrodynamic Model Results:
Furnace Creek (Upper)

50-yr Event Predicted Flood Velocities

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Restoration Research Award
Program Funding Partners:

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 50 100 150 200 Feet

N

Two Dimensional Hydrodynamic Model Results:
Furnace Creek (Upper)

100-yr Event Predicted Flood Velocities

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Restoration Research Award
Program Funding Partners:

Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 50 100 150 200 Feet

N

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Two Dimensional Hydrodynamic Model Results:
Furnace Creek (Upper)

Climate Change Scenario (100-yr + 33%)

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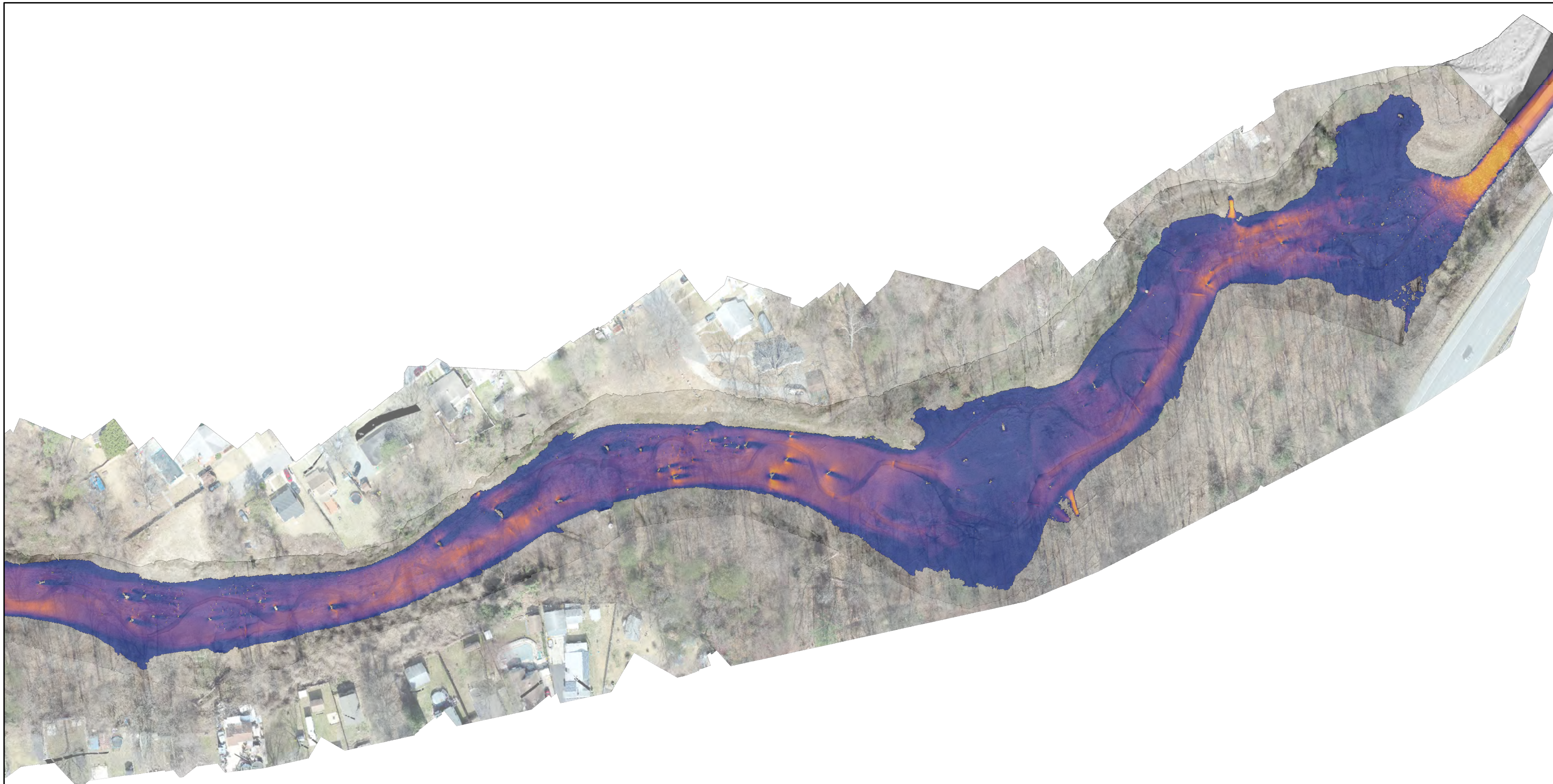
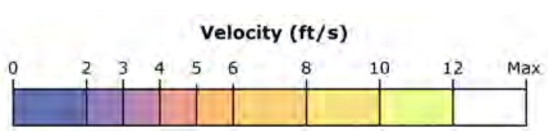
Restoration Research Award
Program Funding Partners:





UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

Two Dimensional Hydrodynamic Model Results: Furnace Creek (Lower)

Largest Event During Study

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Restoration Research Award Program Funding Partners:

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 50 100 150 200 Feet

N

Two Dimensional Hydrodynamic Model Results:
Furnace Creek (Lower)

2-yr Event Predicted Flood Velocities

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Restoration Research Award Program Funding Partners:

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 50 100 150 200 Feet

N

Two Dimensional Hydrodynamic Model Results: Furnace Creek (Lower)

10-yr Event Predicted Flood Velocities

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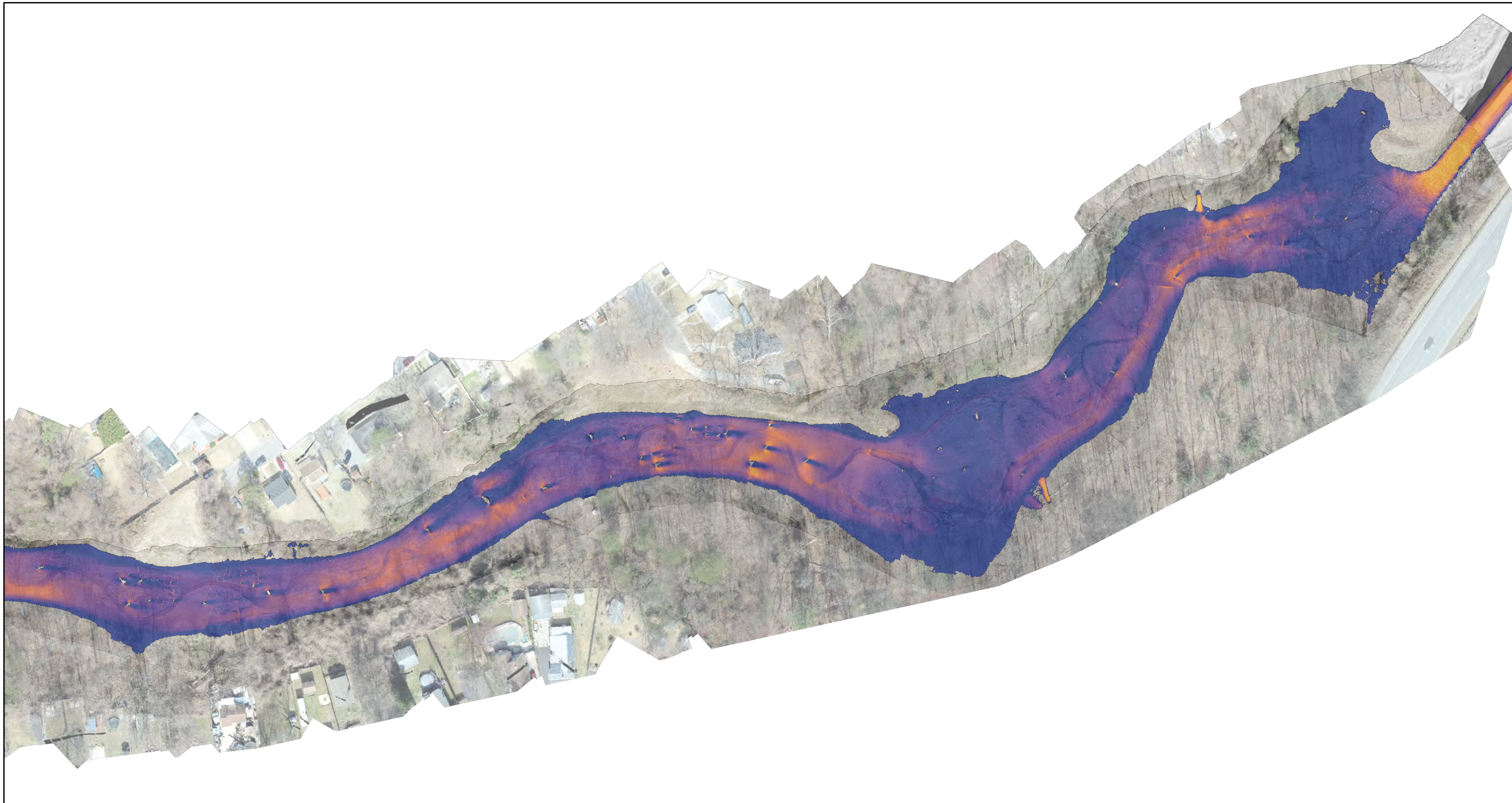

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 50 100 150 200 Feet

N

Two Dimensional Hydrodynamic Model Results: Furnace Creek (Lower)

50-yr Event Predicted Flood Velocities

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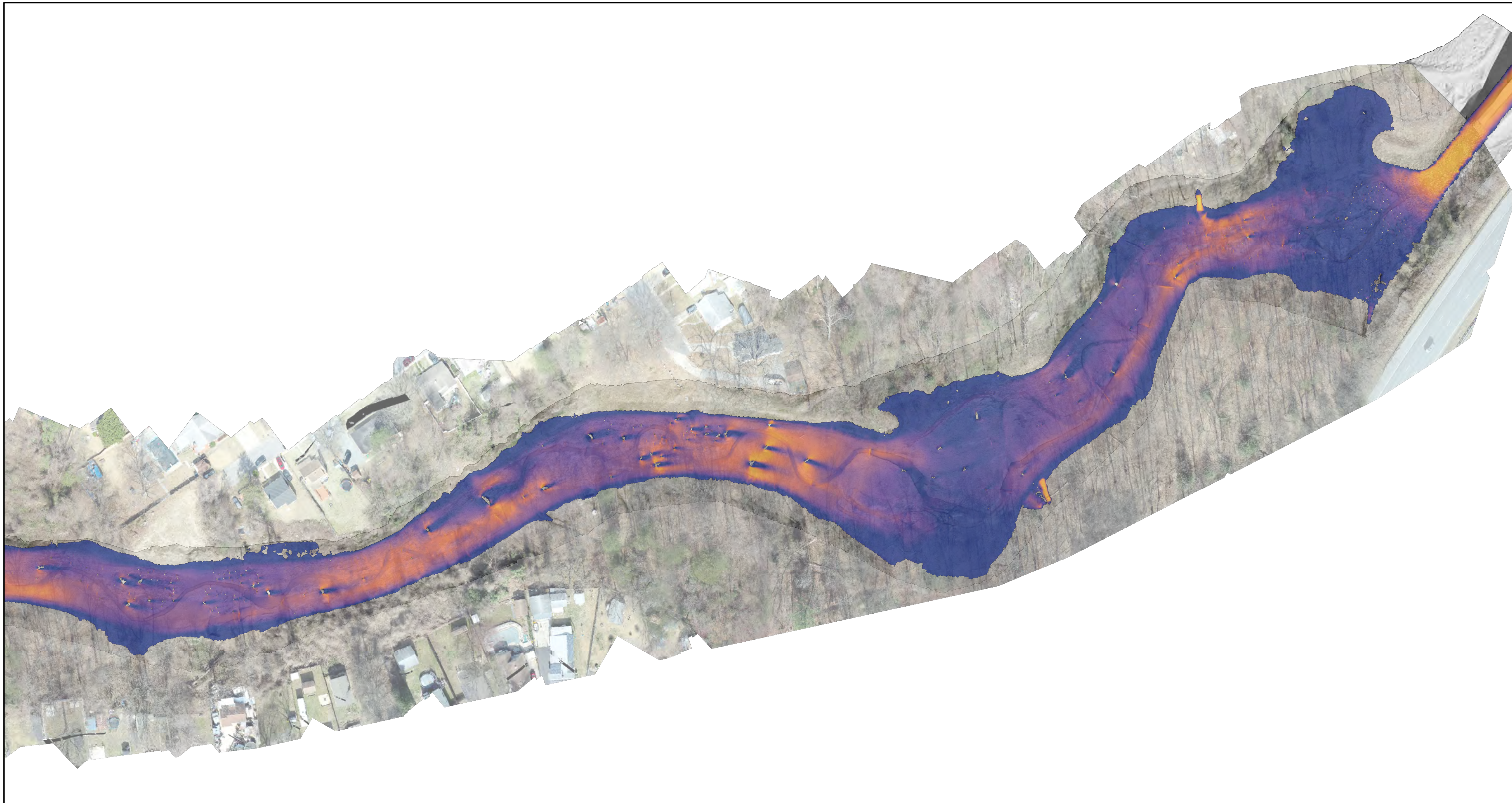

Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 50 100 150 200 Feet

N

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Two Dimensional Hydrodynamic Model Results: Furnace Creek (Lower)

100-yr Event Predicted Flood Velocities

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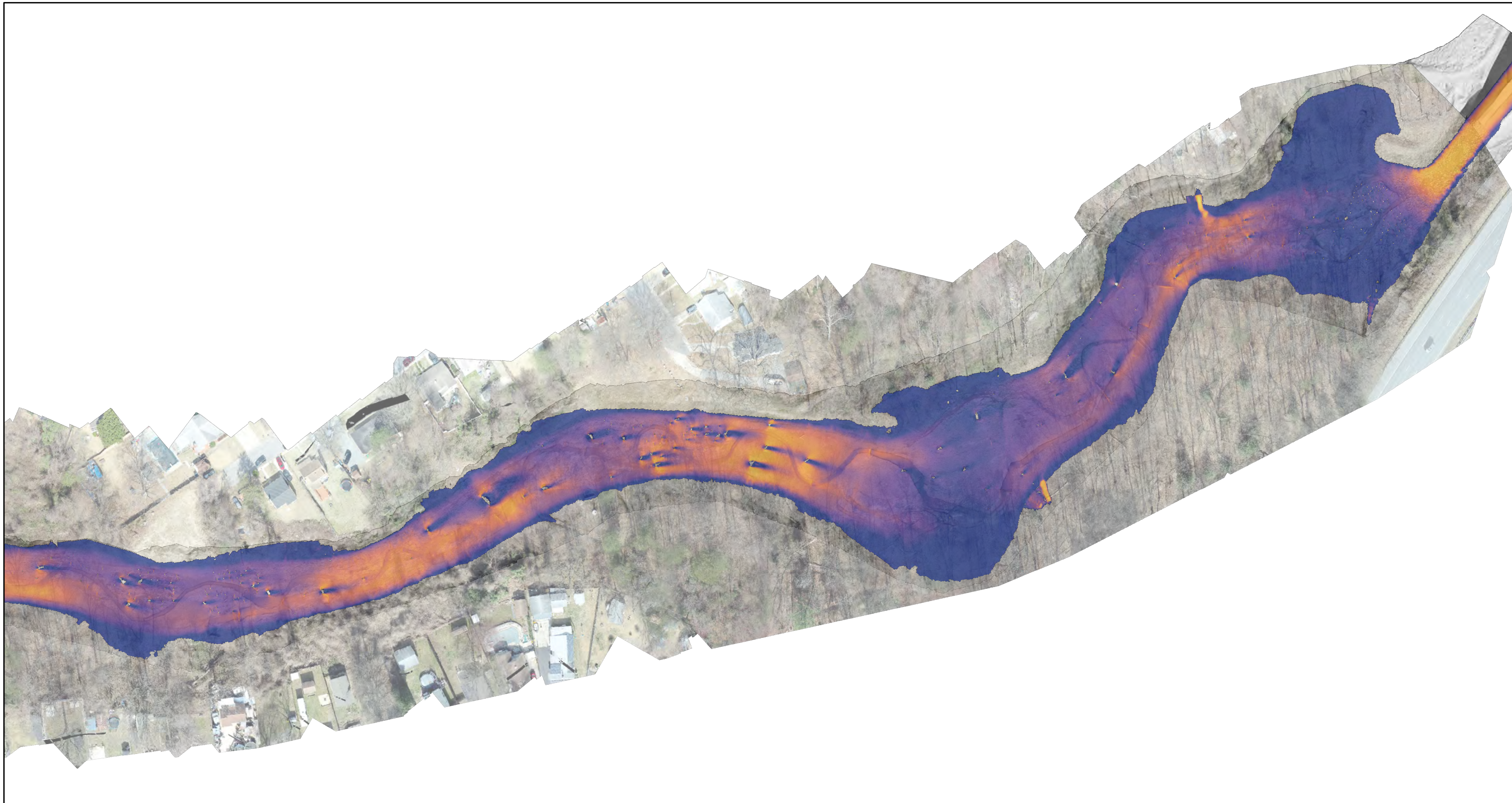

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 50 100 150 200
Feet

N

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Two Dimensional Hydrodynamic Model Results:
Furnace Creek (Lower)

Climate Change Scenario (100-yr + 33%)

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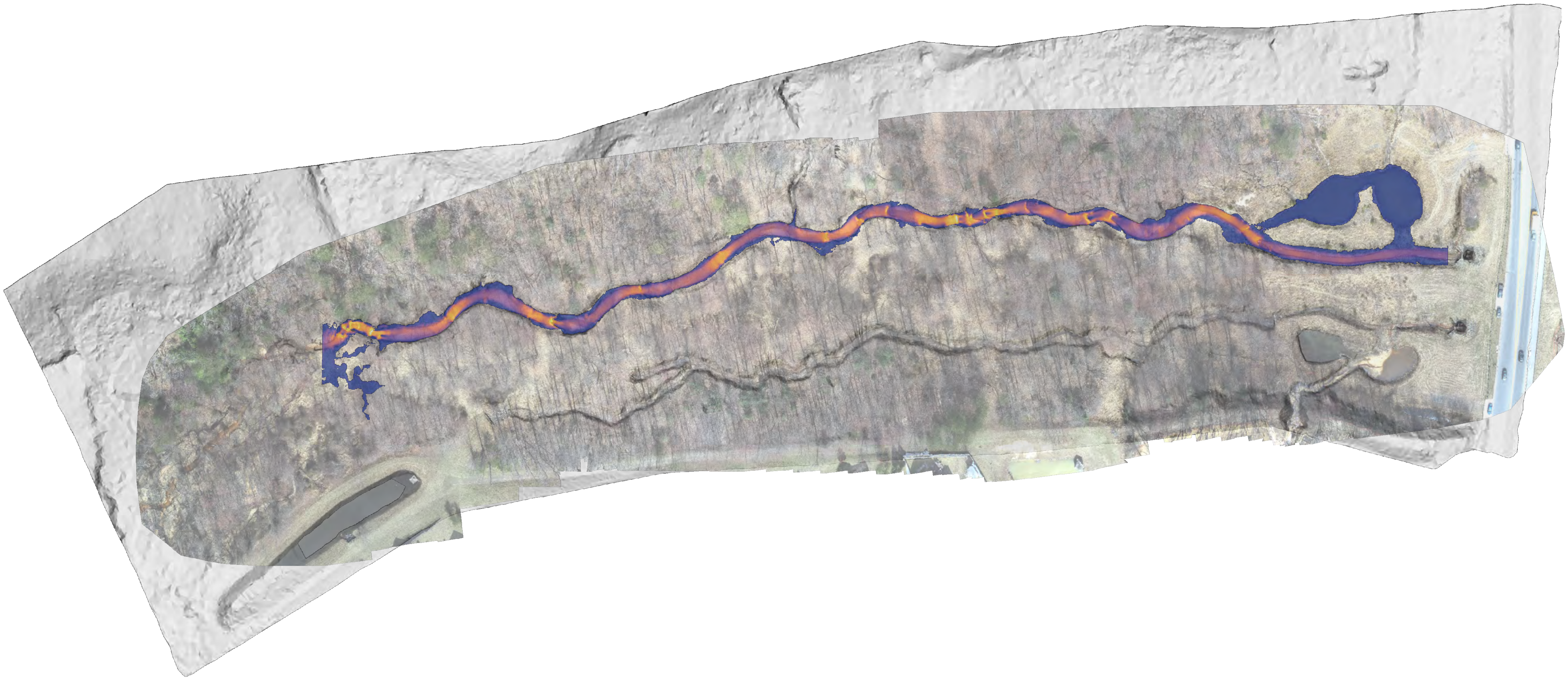

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 Feet

N

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Two Dimensional Hydrodynamic Model Results: Bear Branch

Largest Event During Study

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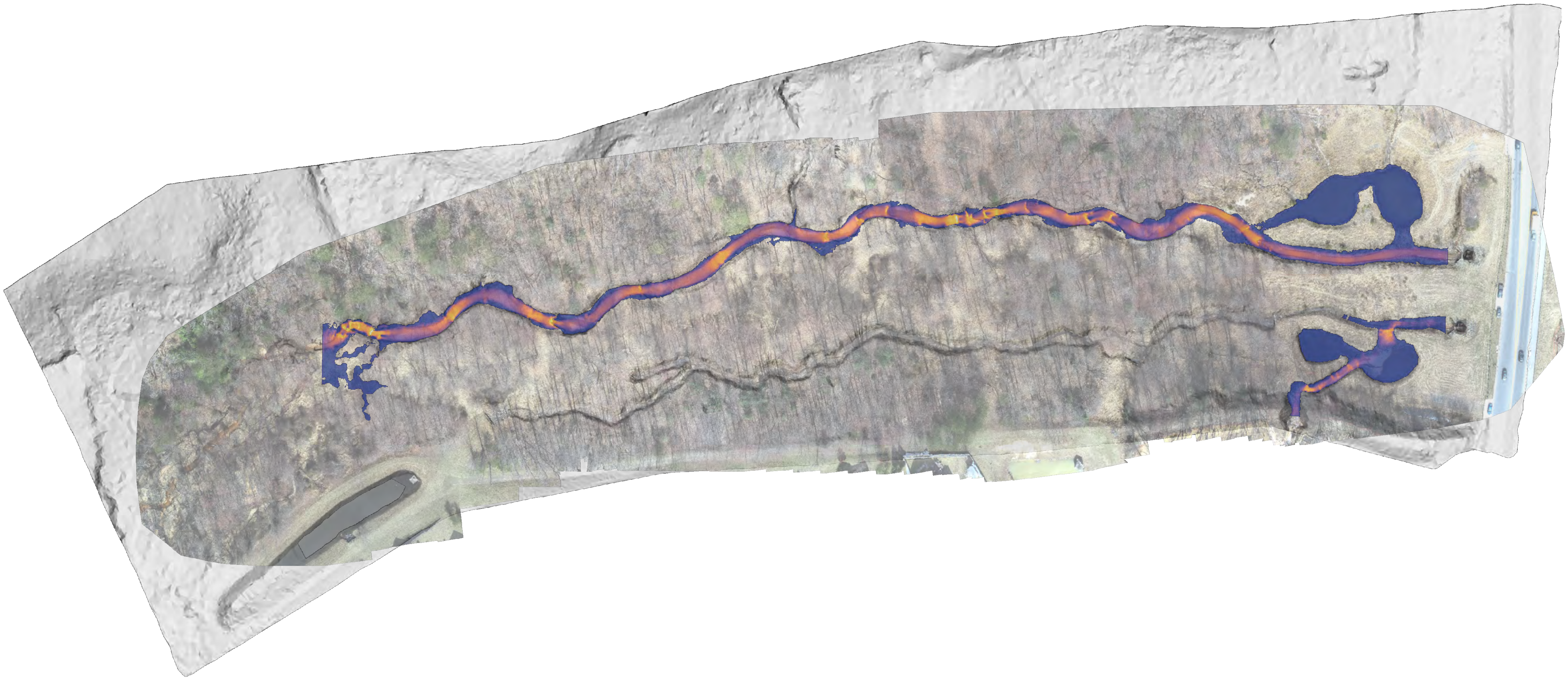

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 Feet

N

Two Dimensional Hydrodynamic Model Results:
Bear Branch

2-yr Event Predicted Flood Velocities

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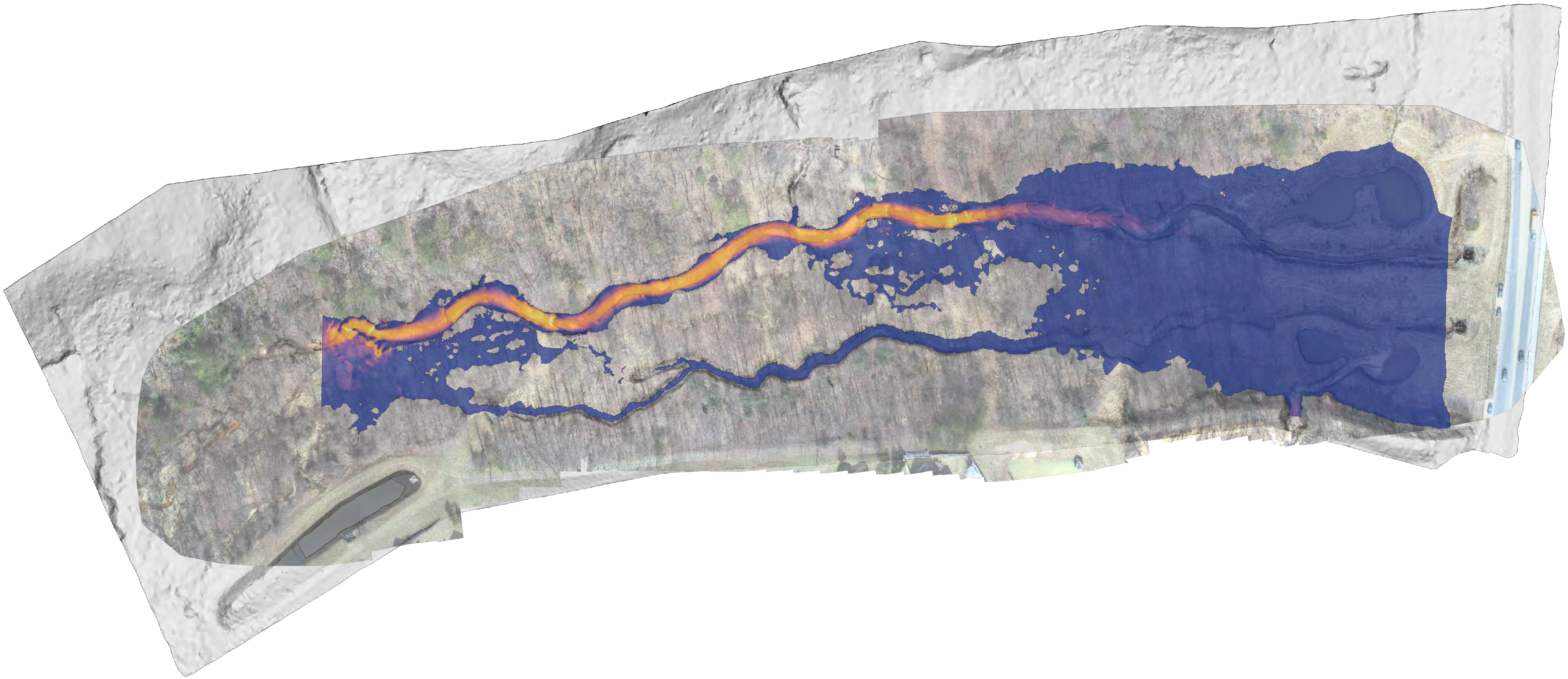

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240
Feet

N

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Two Dimensional Hydrodynamic Model Results: Bear Branch

10-yr Event Predicted Flood Velocities

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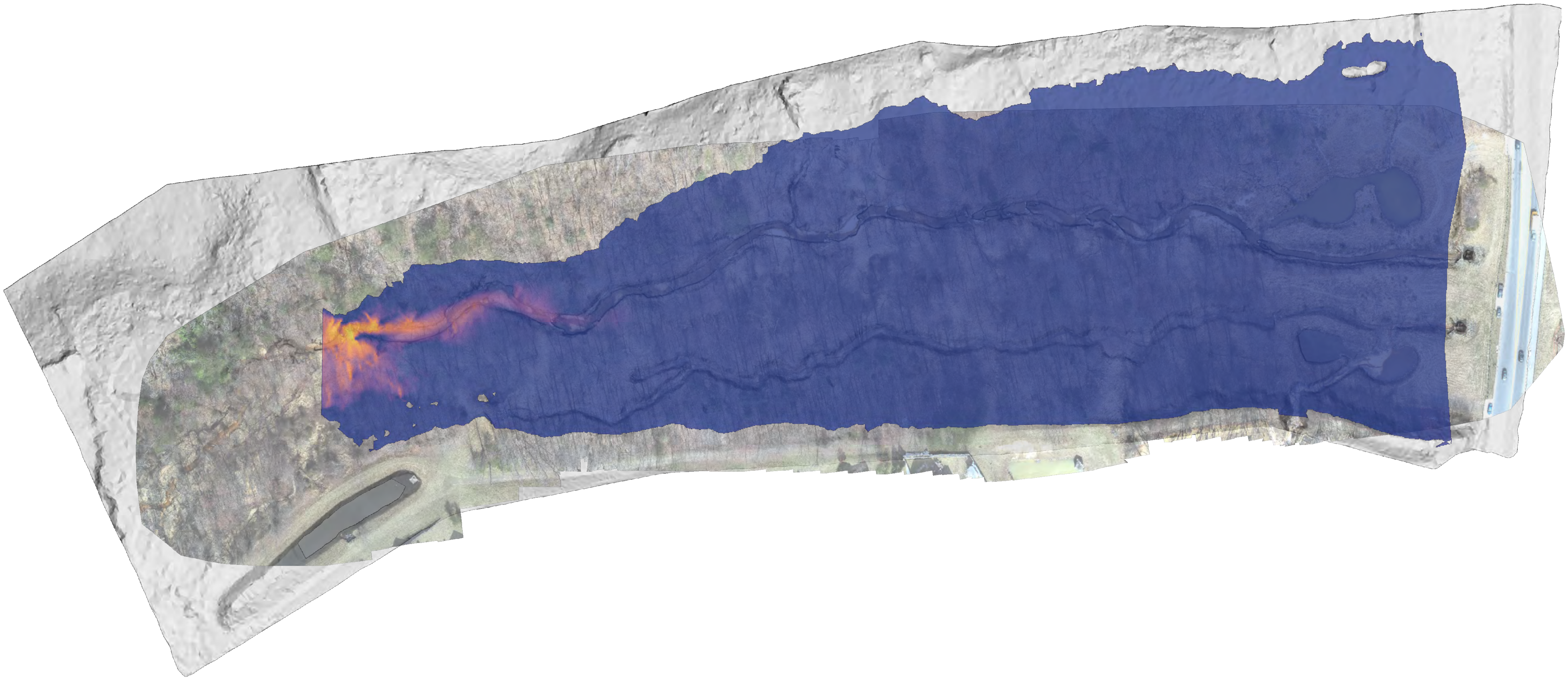
Restoration Research Award
Program Funding Partners:



Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 Feet

N

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Two Dimensional Hydrodynamic Model Results: Bear Branch

50-yr Event Predicted Flood Velocities

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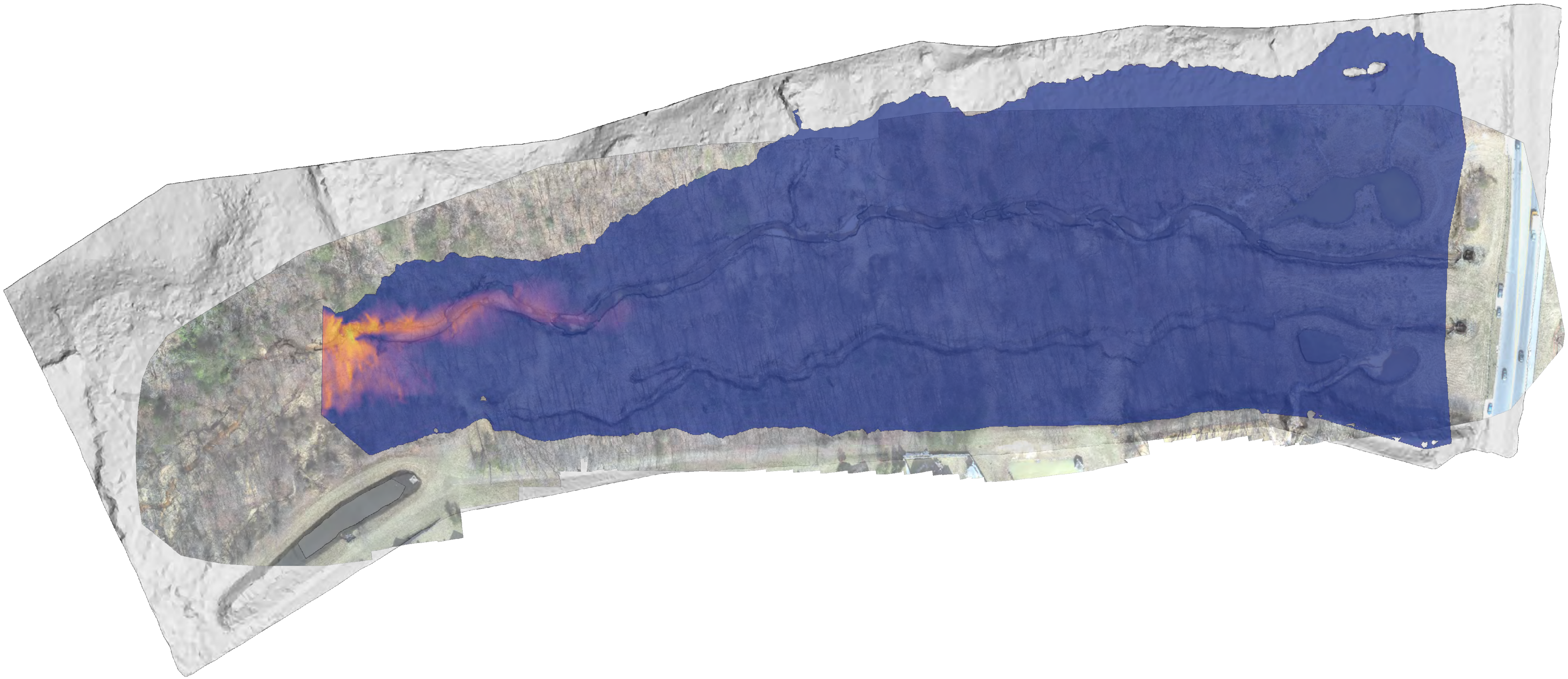

Two Dimensional Hydrodynamic Model Results: Bear Branch

100-yr Event Predicted Flood Velocities

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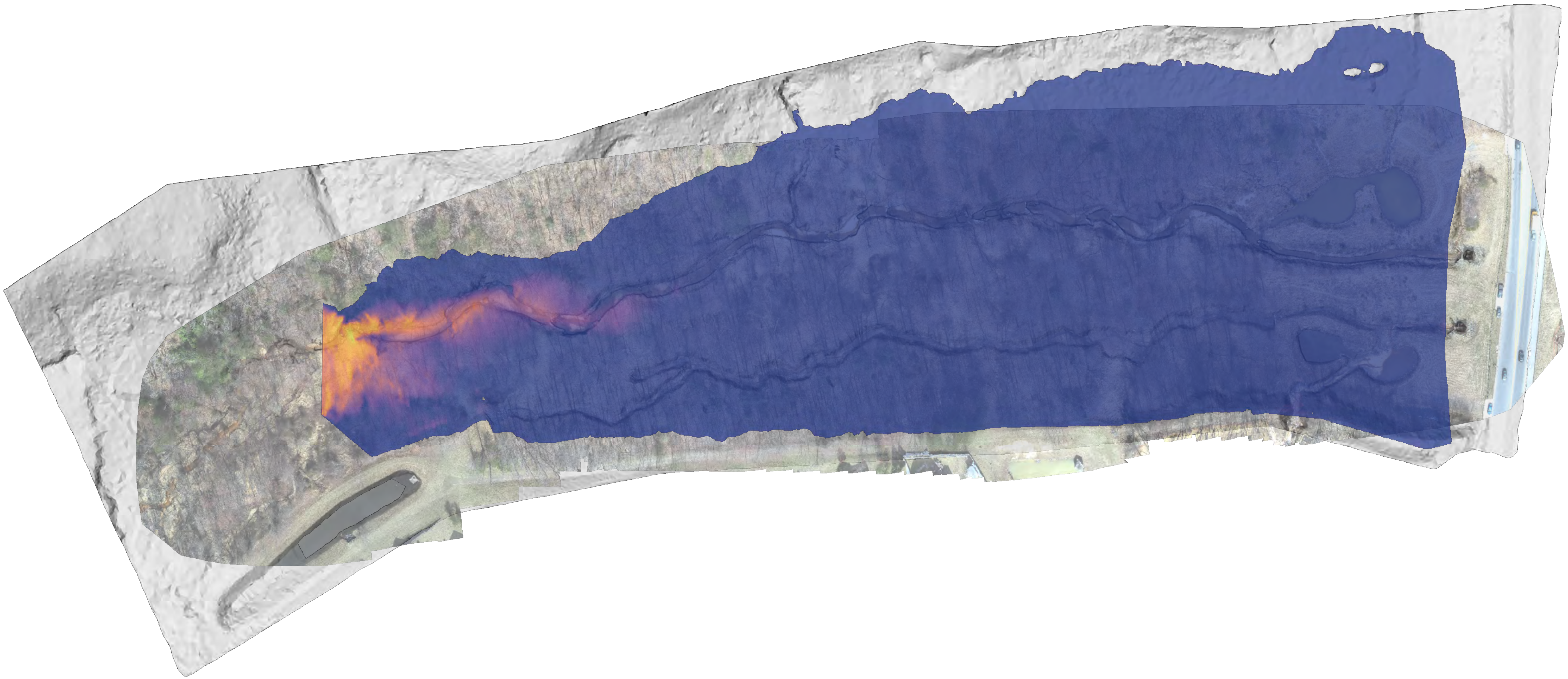

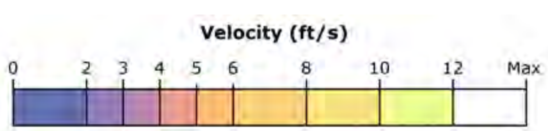

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 Feet

N

Two Dimensional Hydrodynamic Model Results: Bear Branch

Climate Change Scenario (100-yr + 33%)

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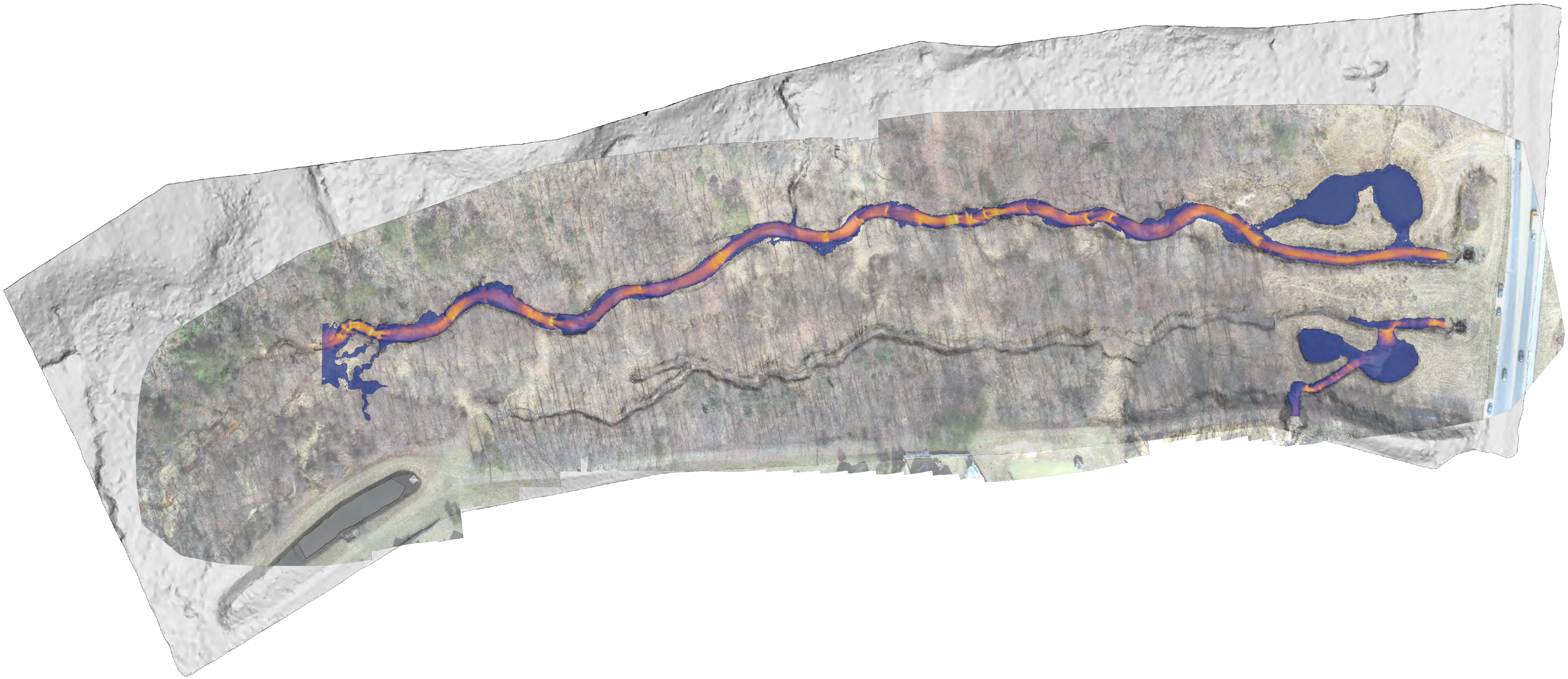

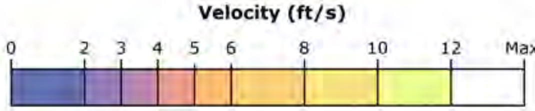

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 Feet

N

Two Dimensional Hydrodynamic Model Results: Bear Branch No Backwater From Culvert

2-yr Event Predicted Flood Velocities

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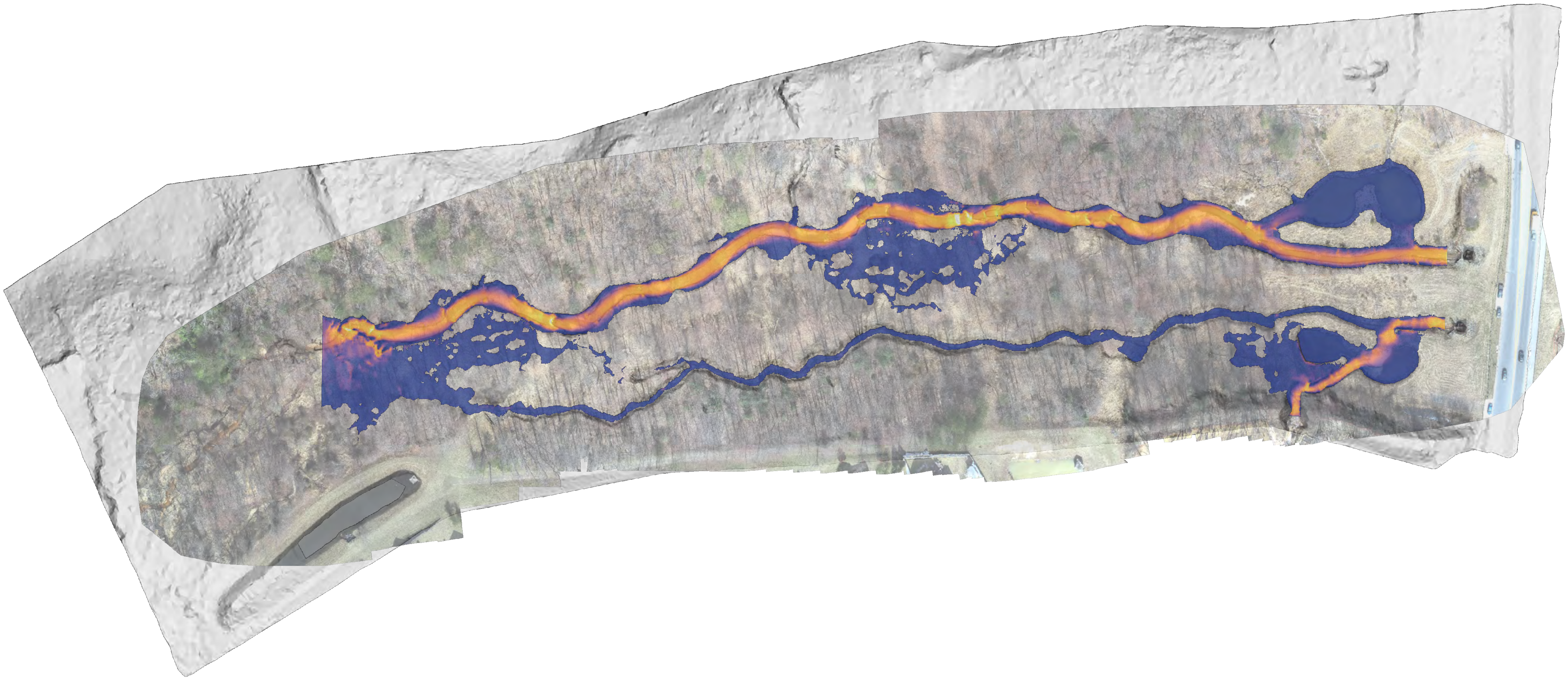

UNIVERSITY OF LOUISVILLE
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 Feet

N

Two Dimensional Hydrodynamic Model Results: Bear Branch No Backwater From Culvert

10-yr Event Predicted Flood Velocities

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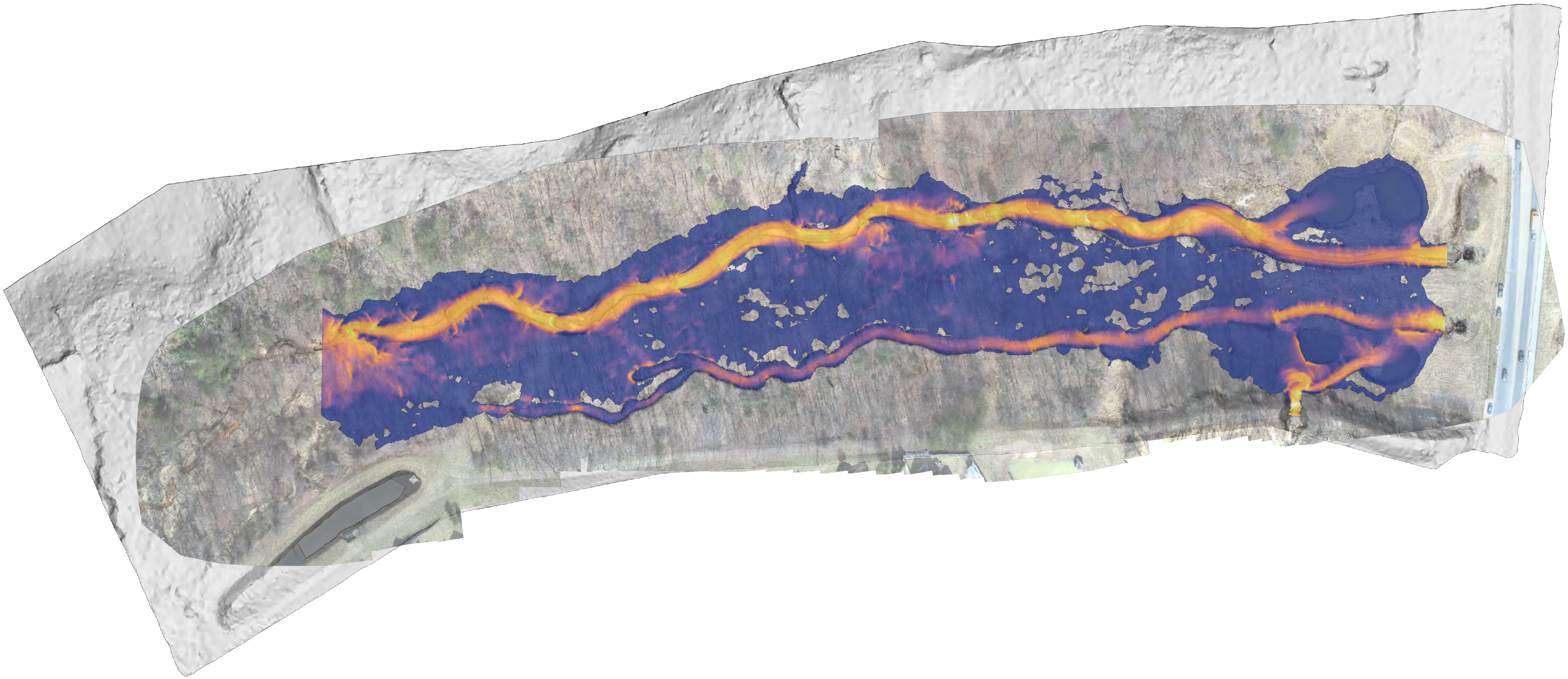

Two Dimensional Hydrodynamic Model Results:
Bear Branch
No Backwater From Culvert

50-yr Event Predicted Flood Velocities

Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 Feet

N

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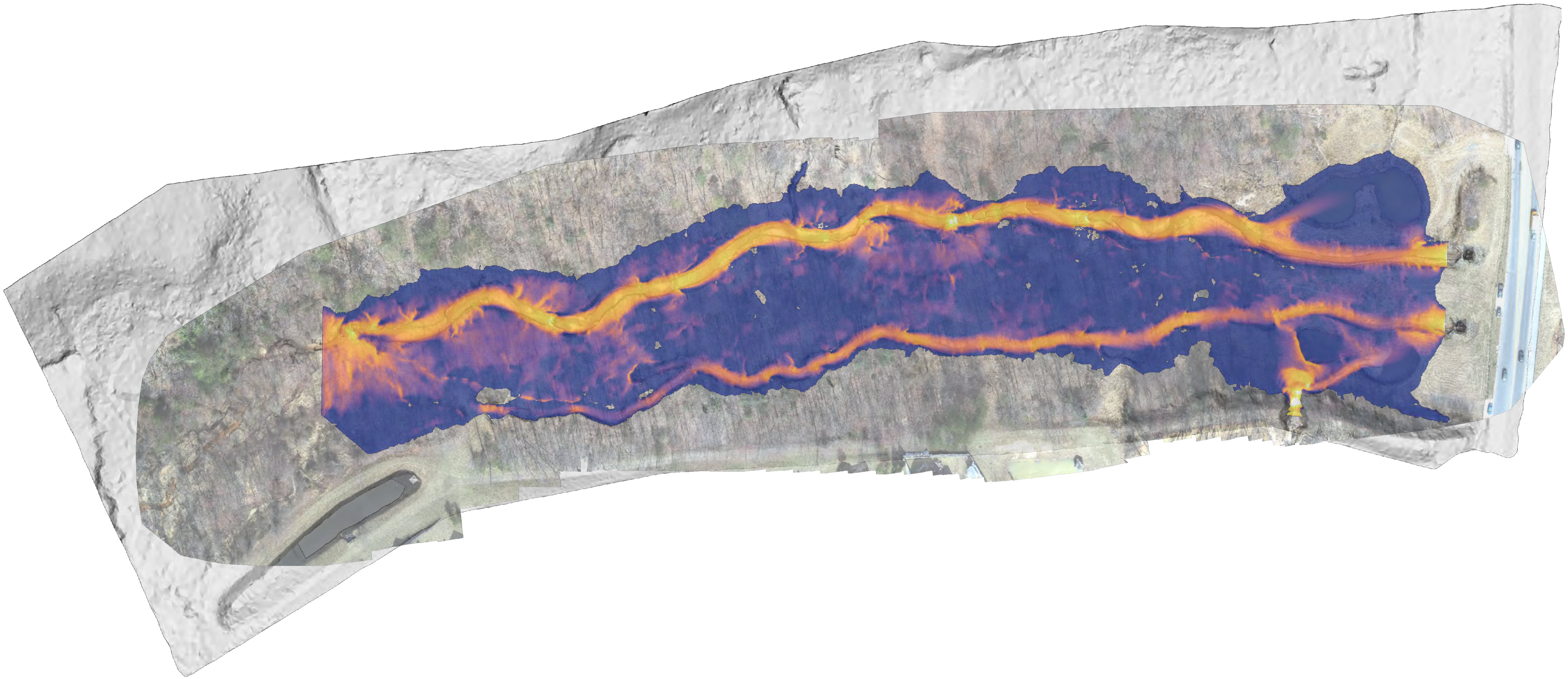

Two Dimensional Hydrodynamic Model Results: Bear Branch No Backwater From Culvert

100-yr Event Predicted Flood Velocities

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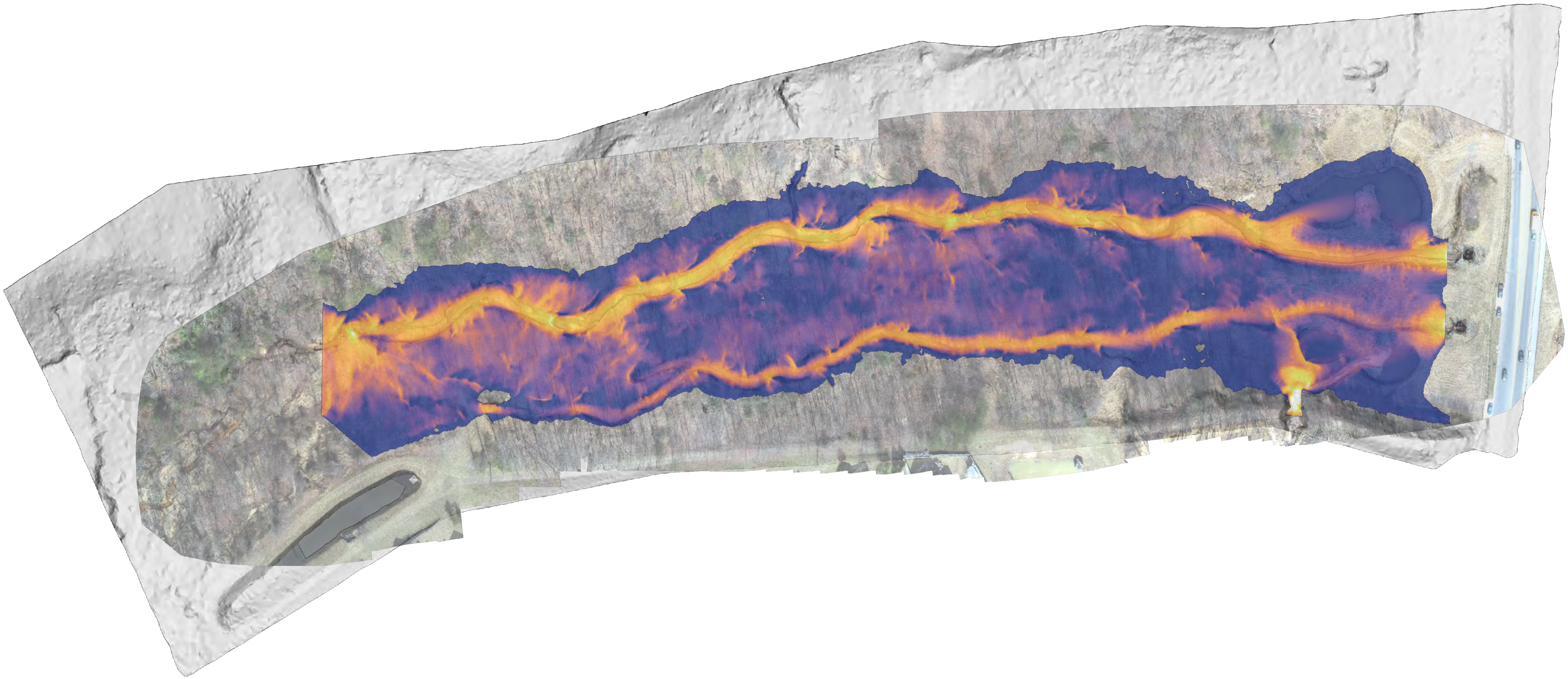

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 Feet

N

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Two Dimensional Hydrodynamic Model Results:
Bear Branch
No Backwater From Culvert

Climate Change Scenario (100-yr + 33%)

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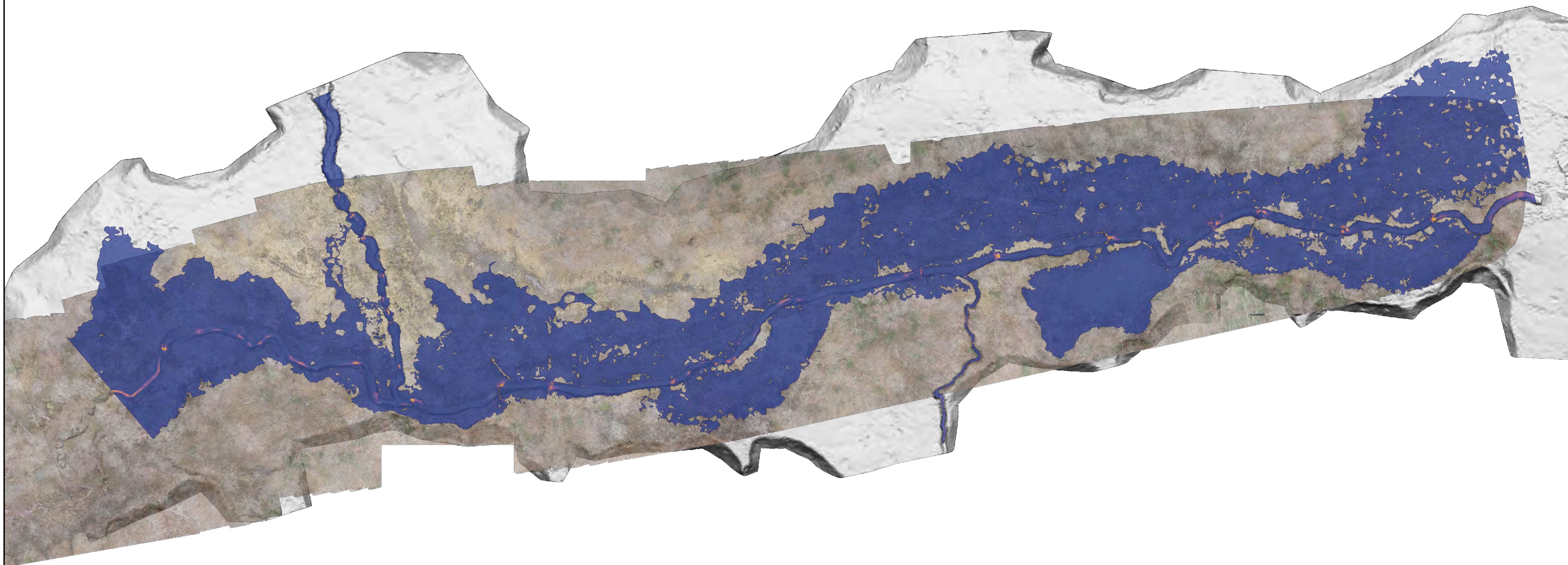

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 320 Feet

N

Two Dimensional Hydrodynamic Model Results: Bacon Ridge

Largest Event During Study

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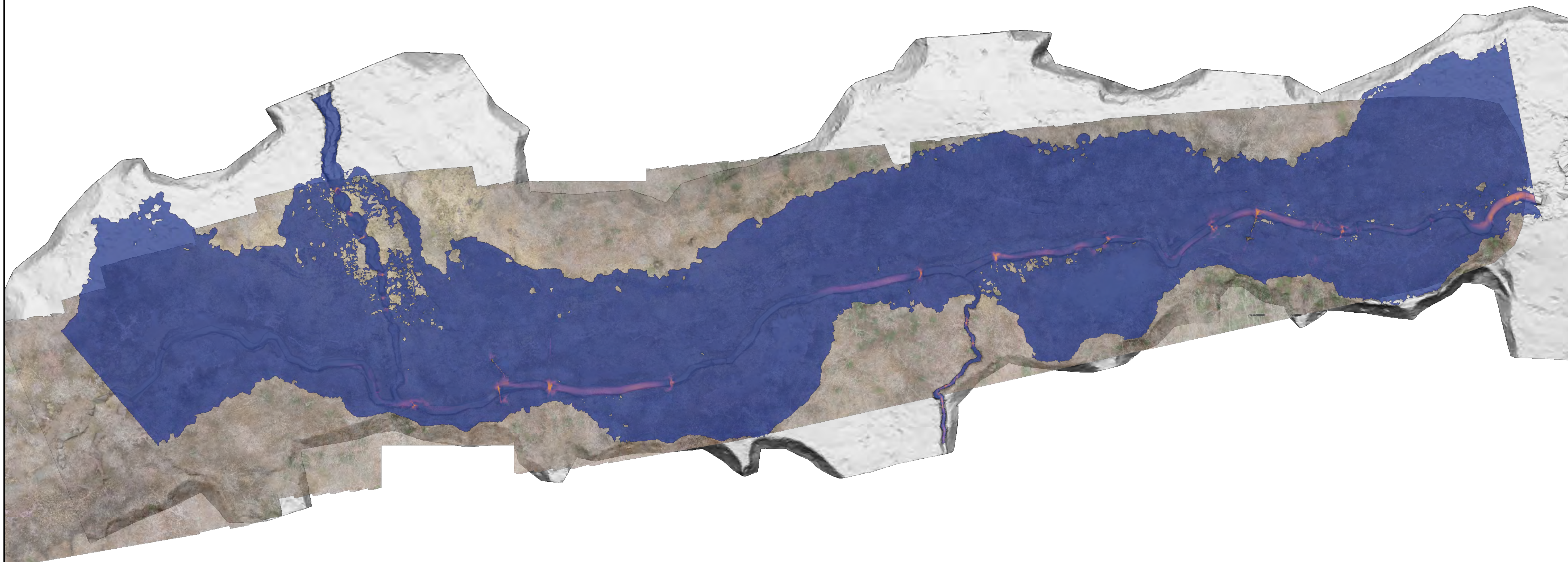

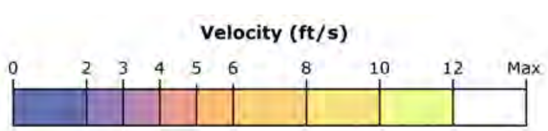

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 320 Feet

N

Two Dimensional Hydrodynamic Model Results: Bacon Ridge

2-yr Event Predicted Flood Velocities

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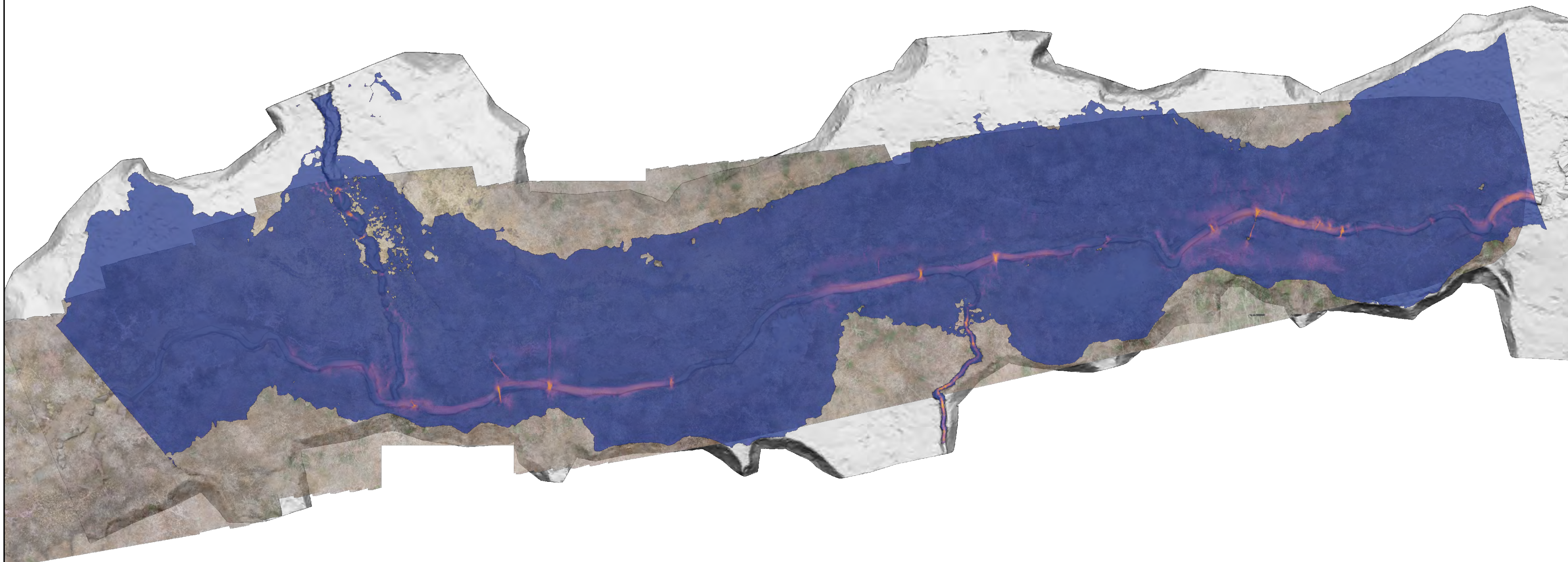

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 320 Feet

N

Two Dimensional Hydrodynamic Model Results: Bacon Ridge

10-yr Event Predicted Flood Velocities

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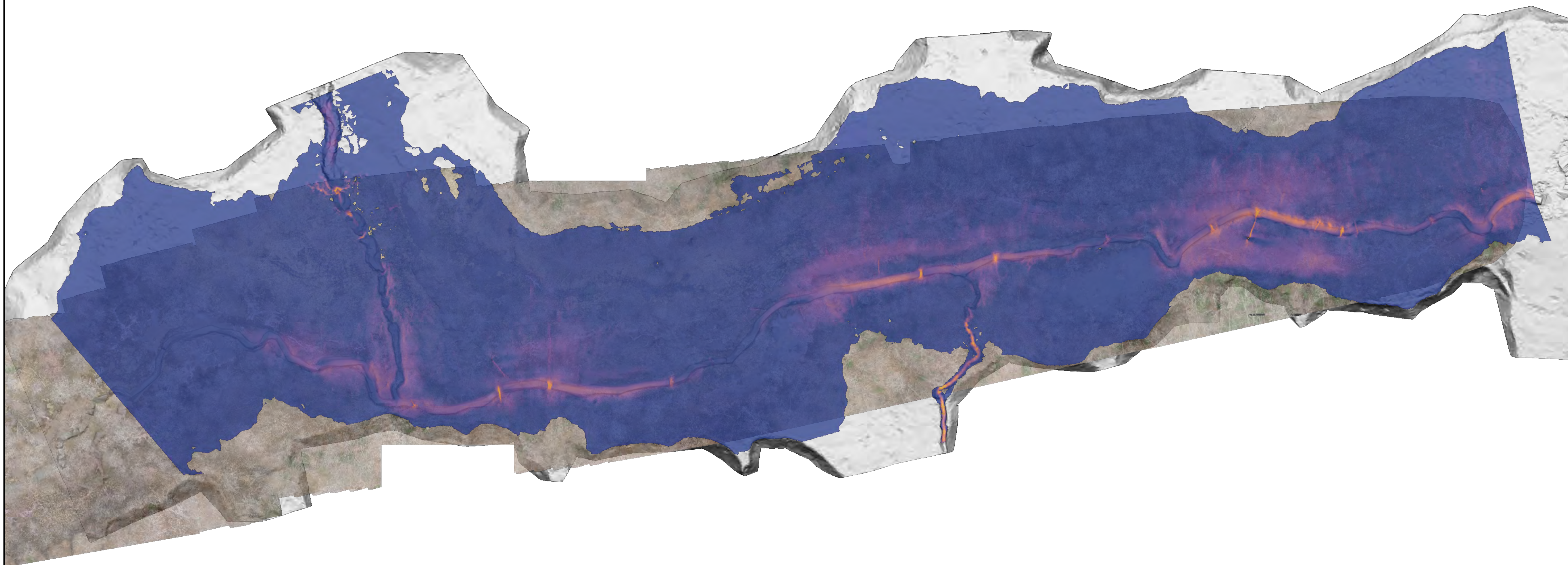

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 320 Feet

N

Two Dimensional Hydrodynamic Model Results: Bacon Ridge

50-yr Event Predicted Flood Velocities

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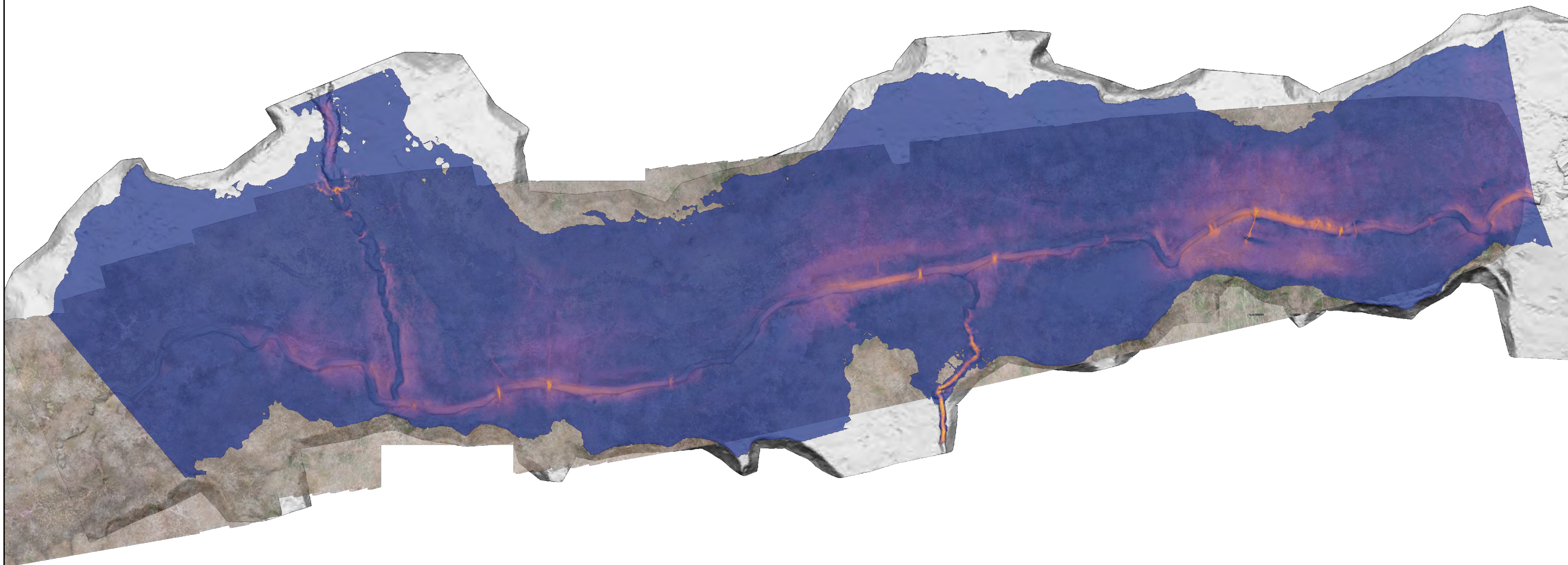

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 320 Feet

N

Two Dimensional Hydrodynamic Model Results: Bacon Ridge

100-yr Event Predicted Flood Velocities

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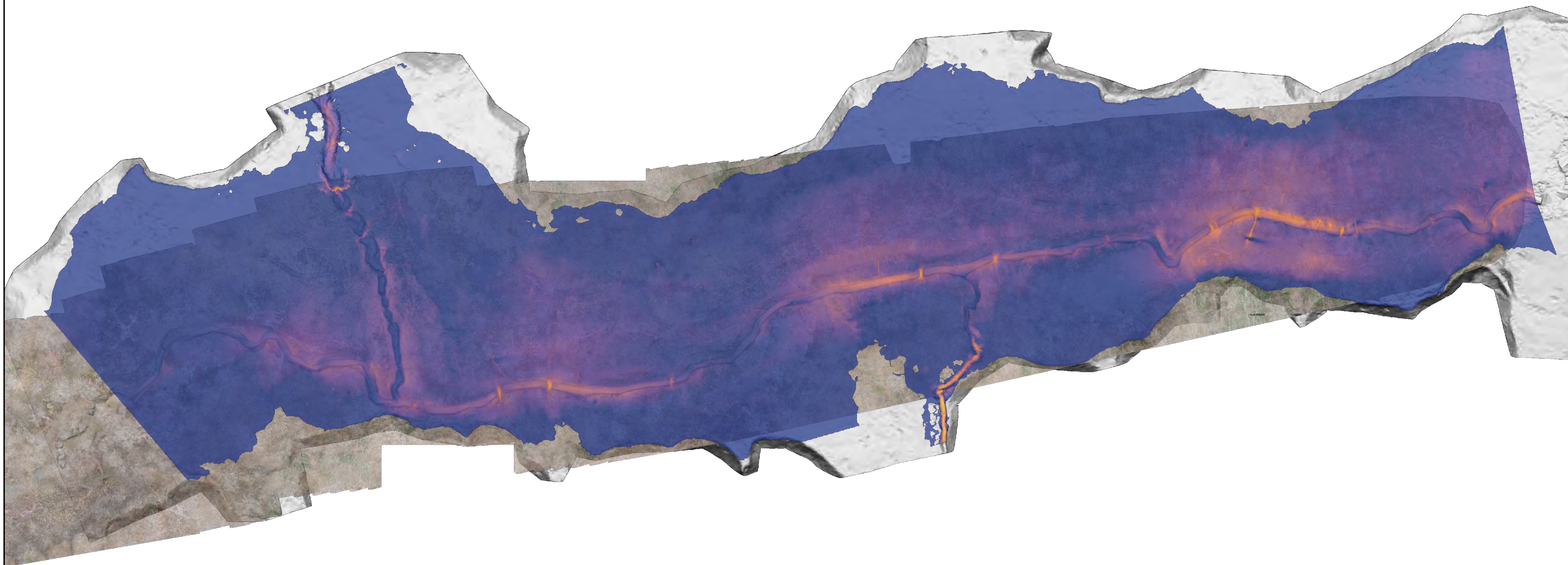

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 80 160 240 320 Feet

N

Two Dimensional Hydrodynamic Model Results: Bacon Ridge

Climate Change Scenario (100-yr + 33%)

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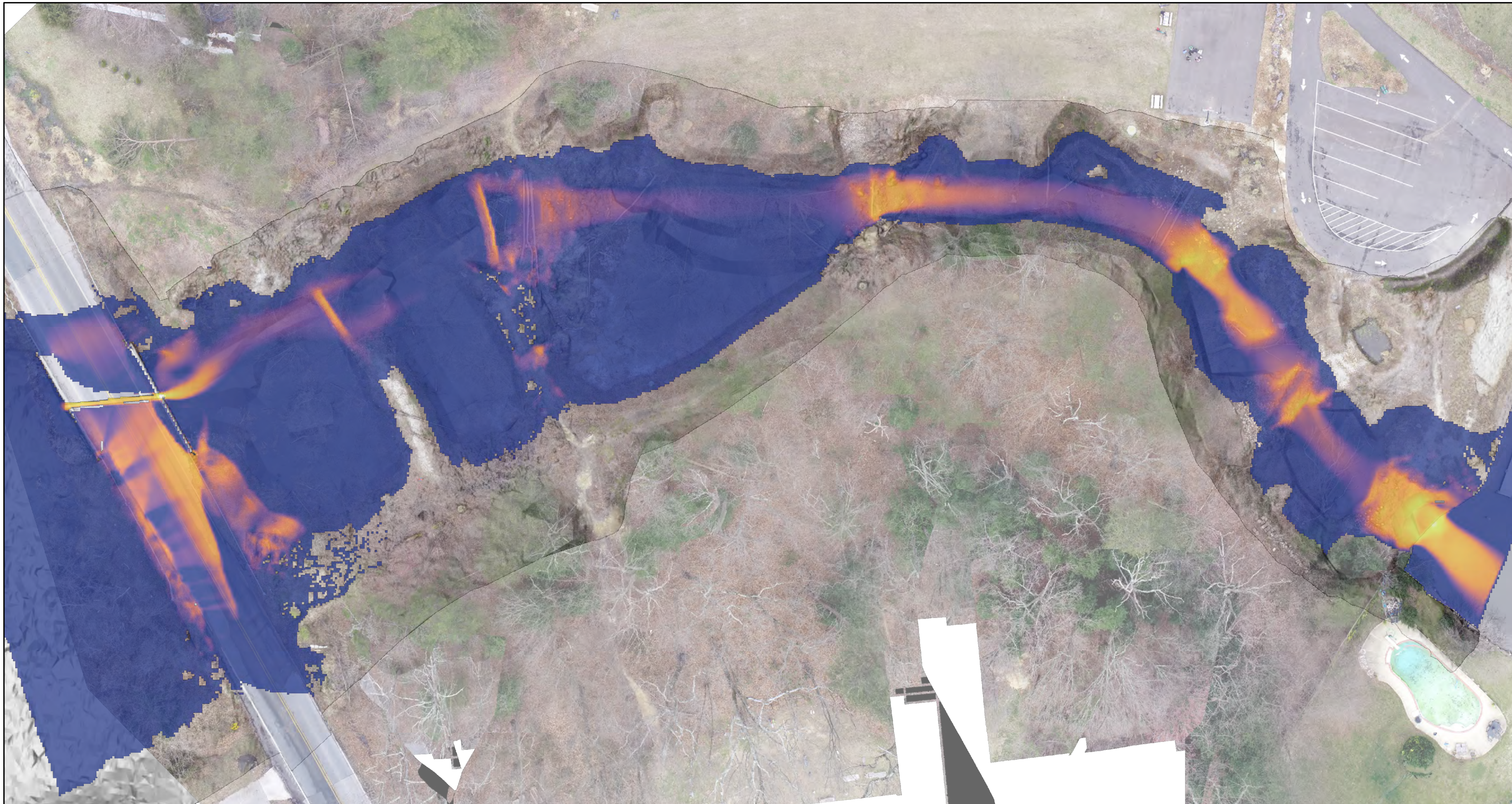

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

Two Dimensional Hydrodynamic Model Results: Cattail Creek (Berrywood)

Largest Event During Study

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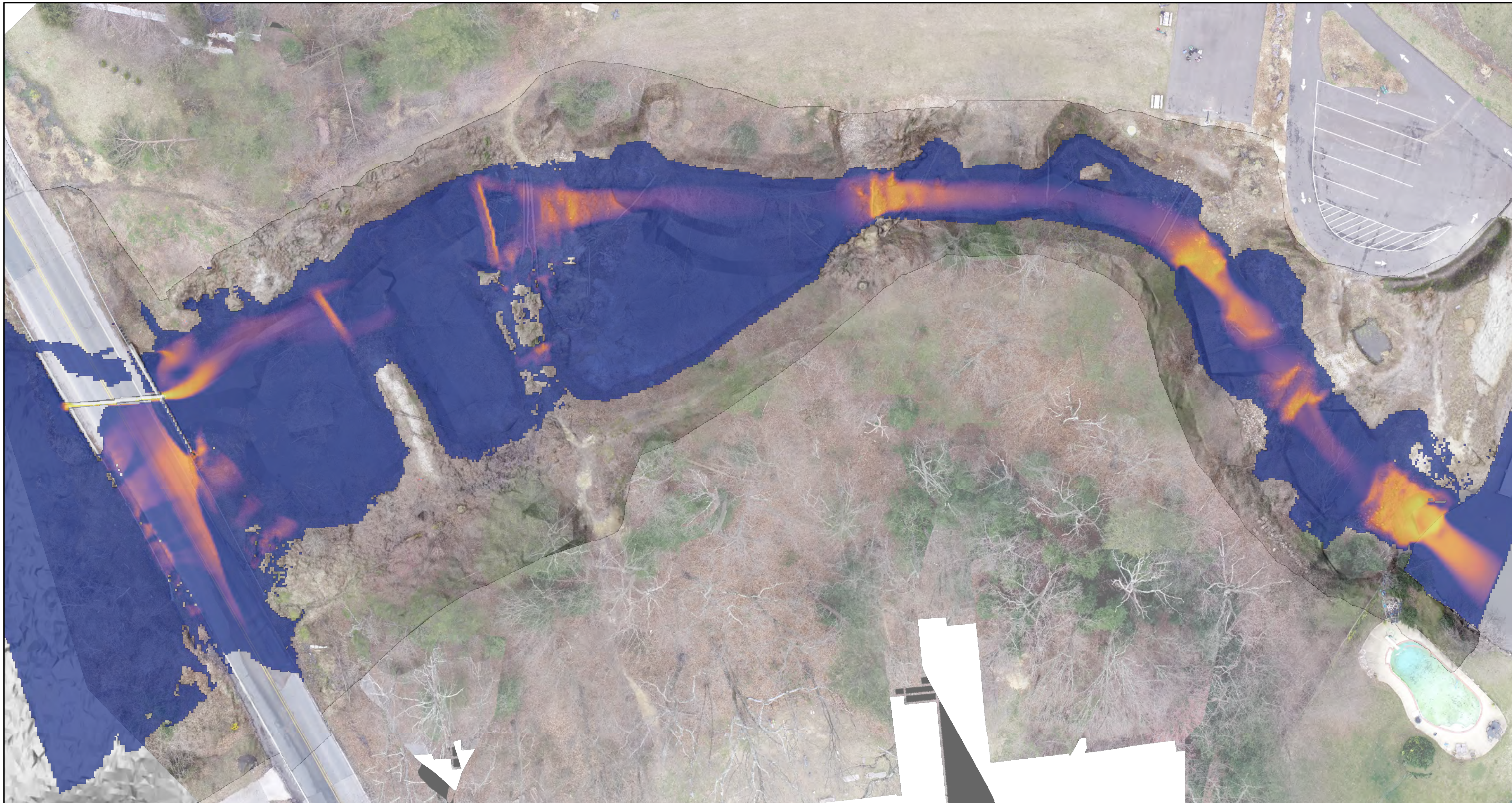

Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 20 40 60 Feet

N

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Two Dimensional Hydrodynamic Model Results: Cattail Creek (Berrywood)

2-yr Event Predicted Flood Velocities

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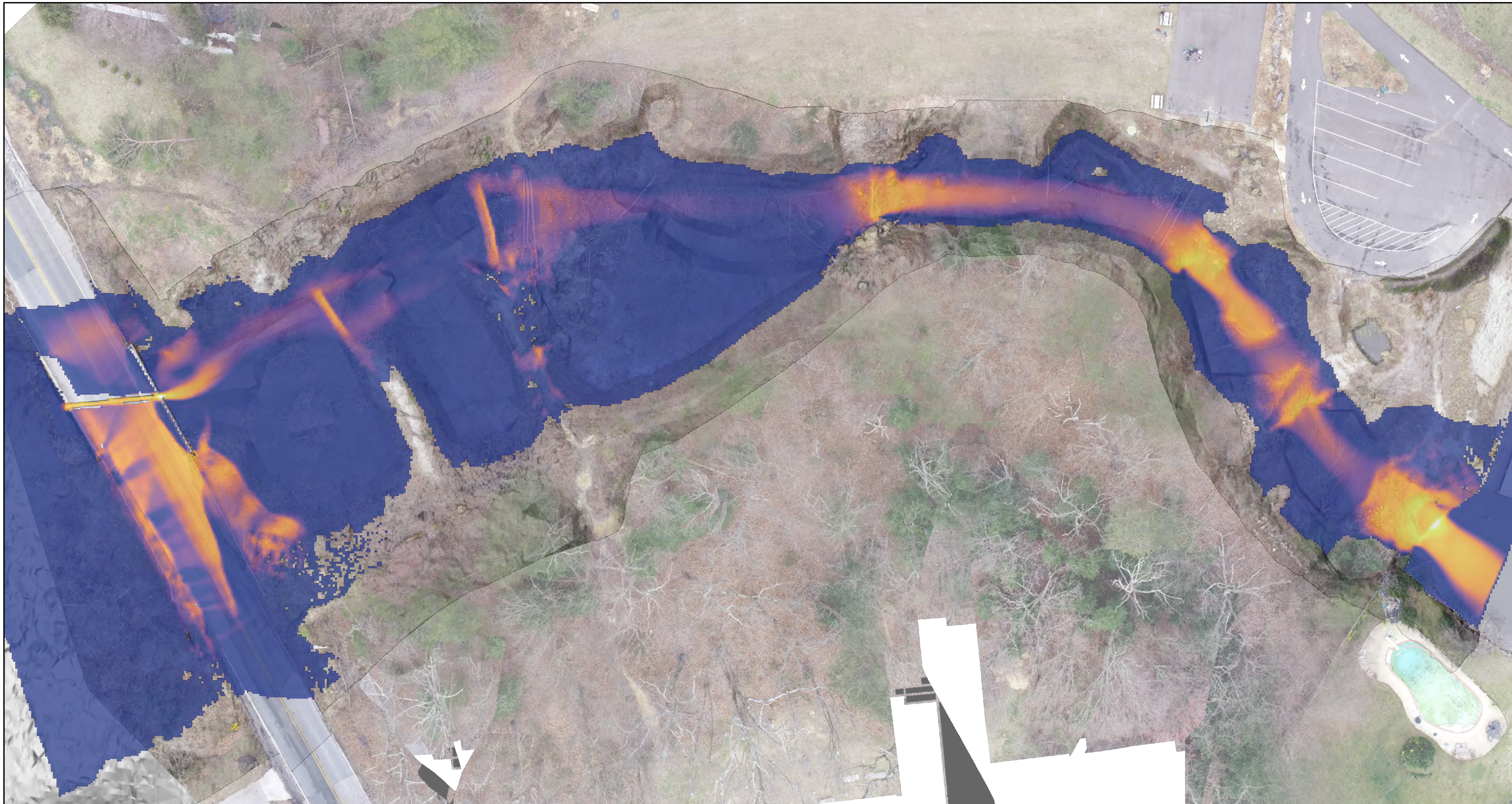

Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 20 40 60 Feet

N

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Two Dimensional Hydrodynamic Model Results:
Cattail Creek (Berrywood)

10-yr Event Predicted Flood Velocities

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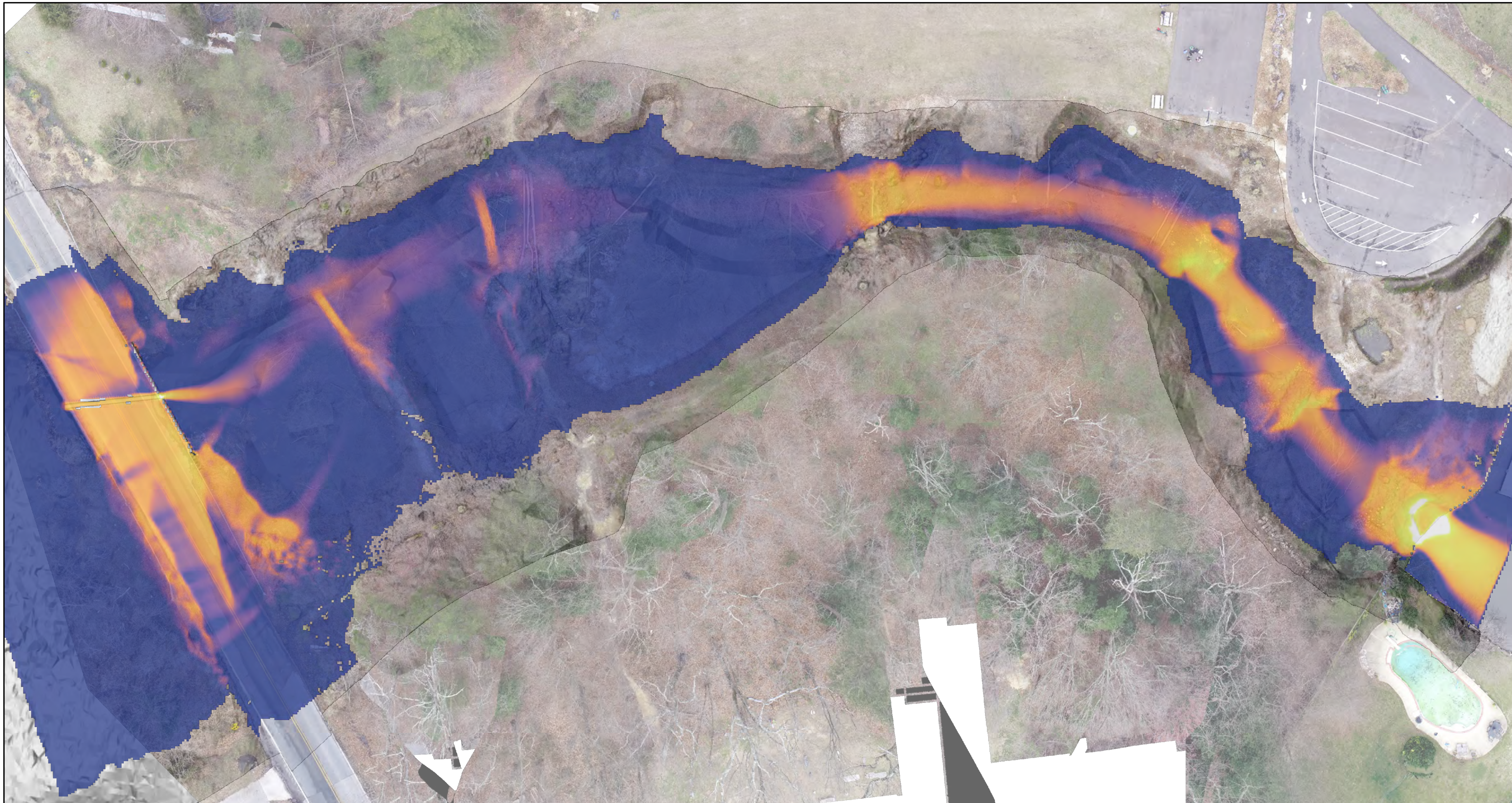

Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 20 40 60 Feet

N

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Two Dimensional Hydrodynamic Model Results: Cattail Creek (Berrywood)

50-yr Event Predicted Flood Velocities

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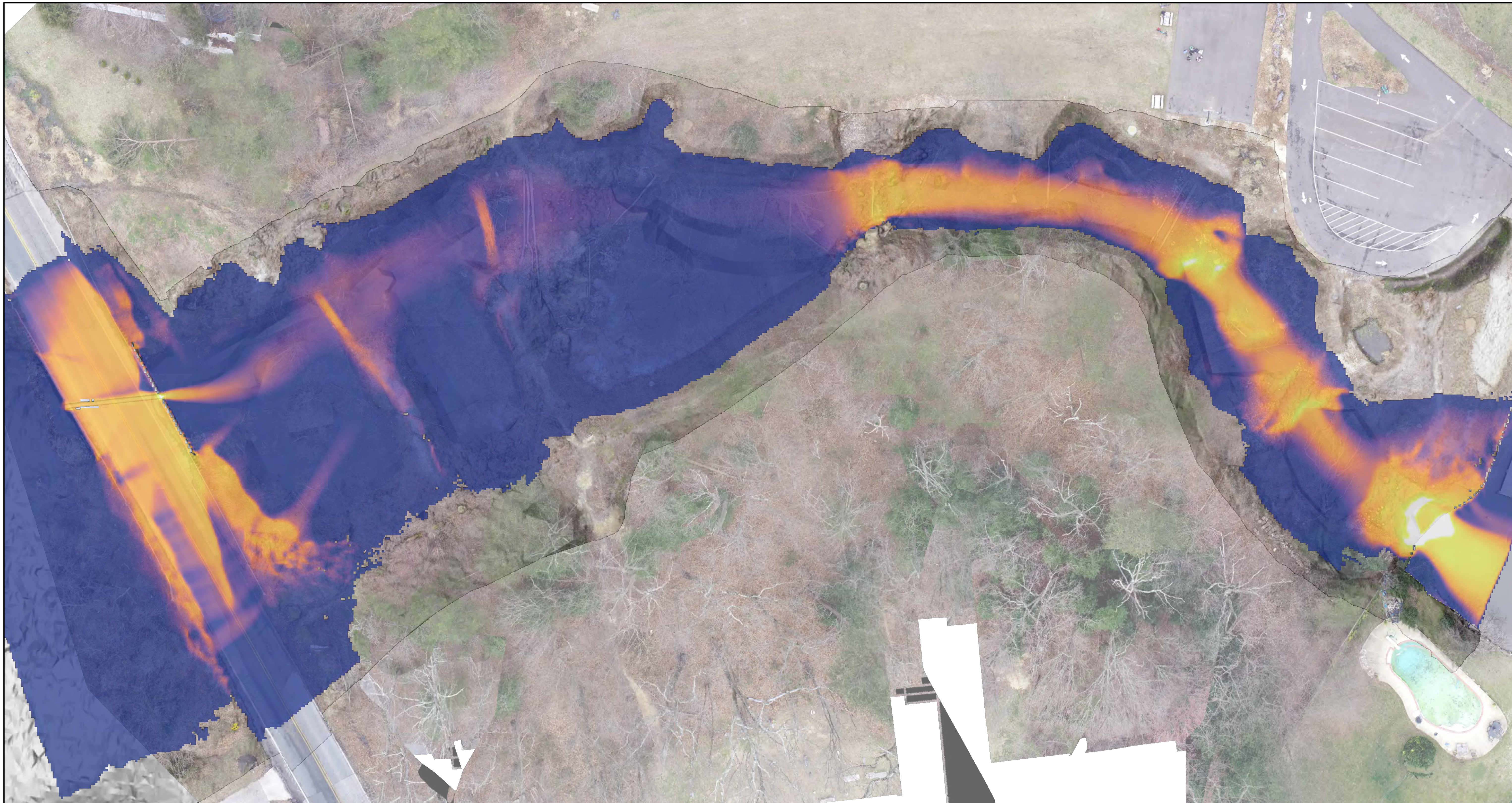

Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 20 40 60 Feet

N

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Two Dimensional Hydrodynamic Model Results: Cattail Creek (Berrywood)

100-yr Event Predicted Flood Velocities

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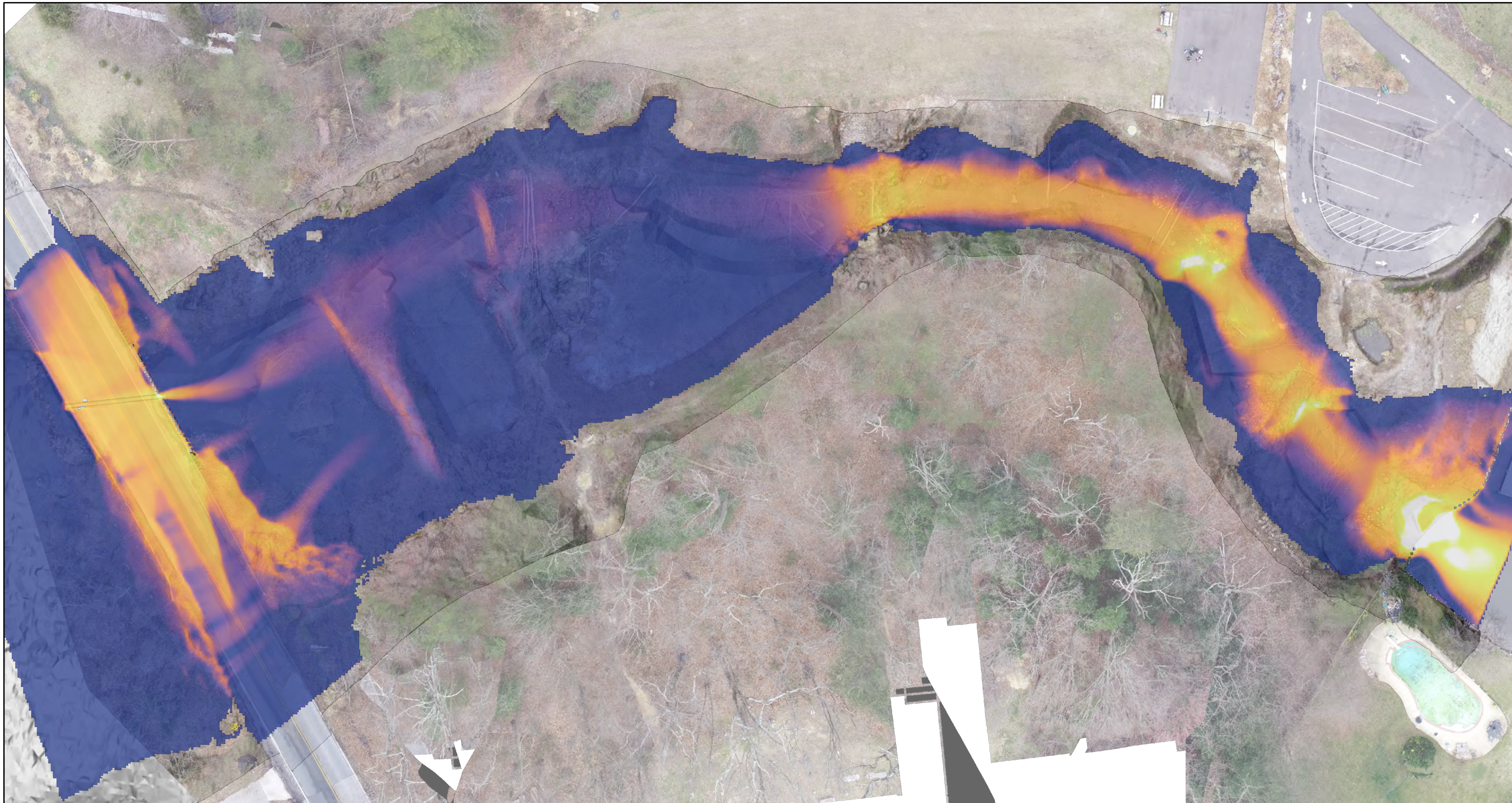
Restoration Research Award Program Funding Partners:



Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE. STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 20 40 60 Feet

N

Two Dimensional Hydrodynamic Model Results:
Cattail Creek (Berrywood)

Climate Change Scenario (100-yr + 33%)

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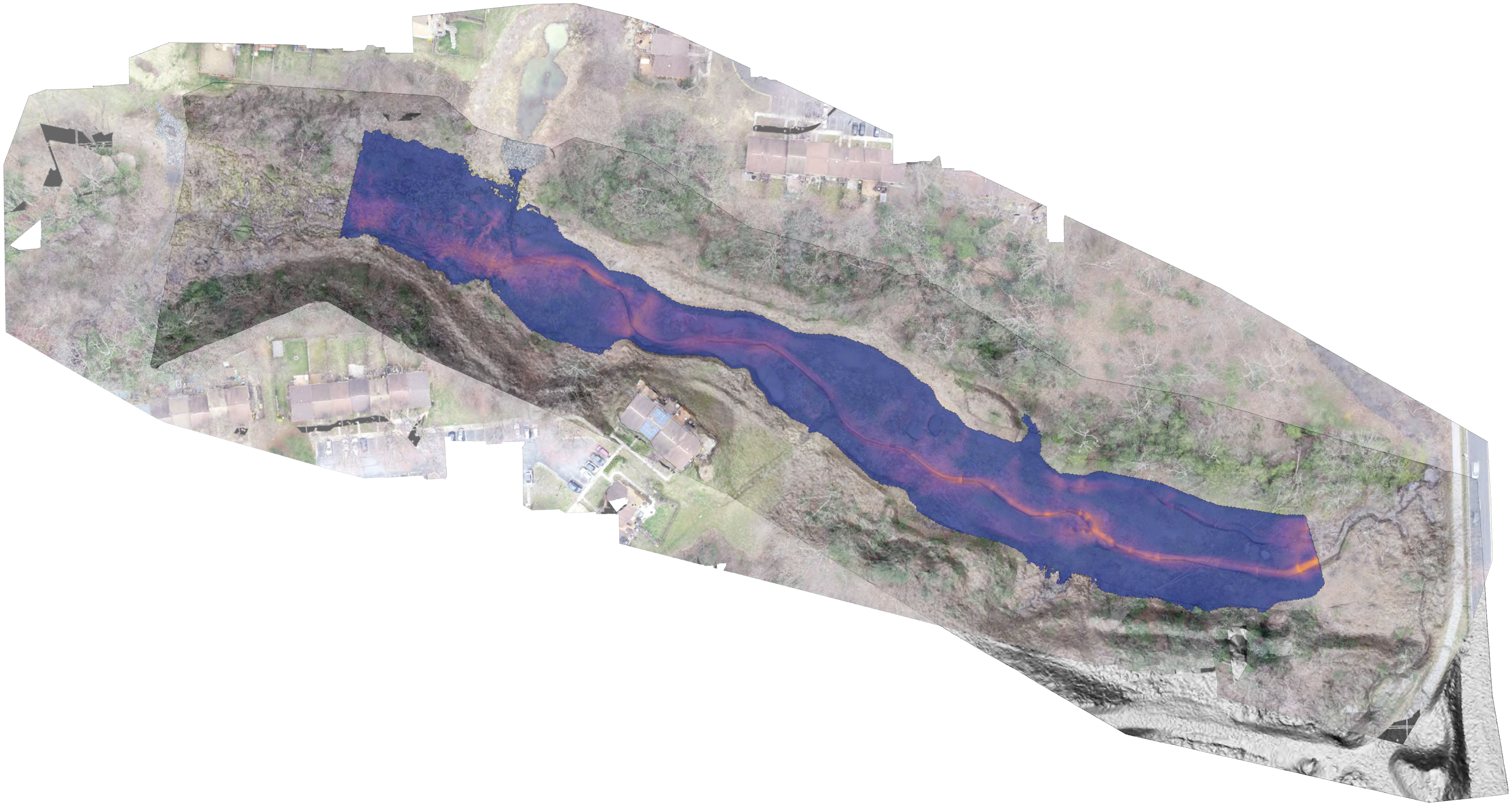

Velocity (ft/s)

0 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 | Max

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 40 80 120 160 Feet

N

Two Dimensional Hydrodynamic Model Results: Cat Branch

Largest Event During Study

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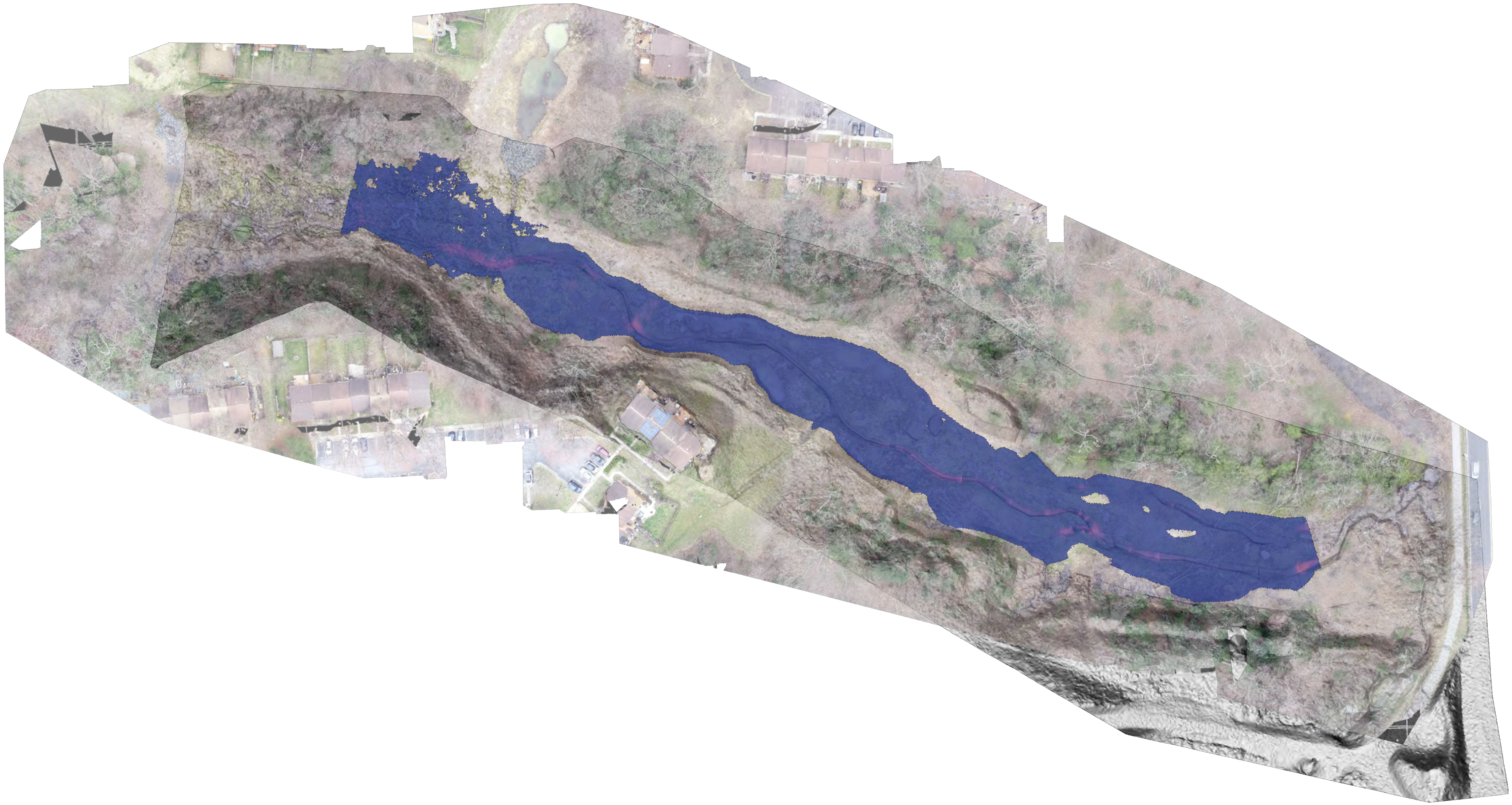

Velocity (ft/s)

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UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 40 80 120 160 Feet

N

Two Dimensional Hydrodynamic Model Results: Cat Branch

2-yr Event Predicted Flood Velocities

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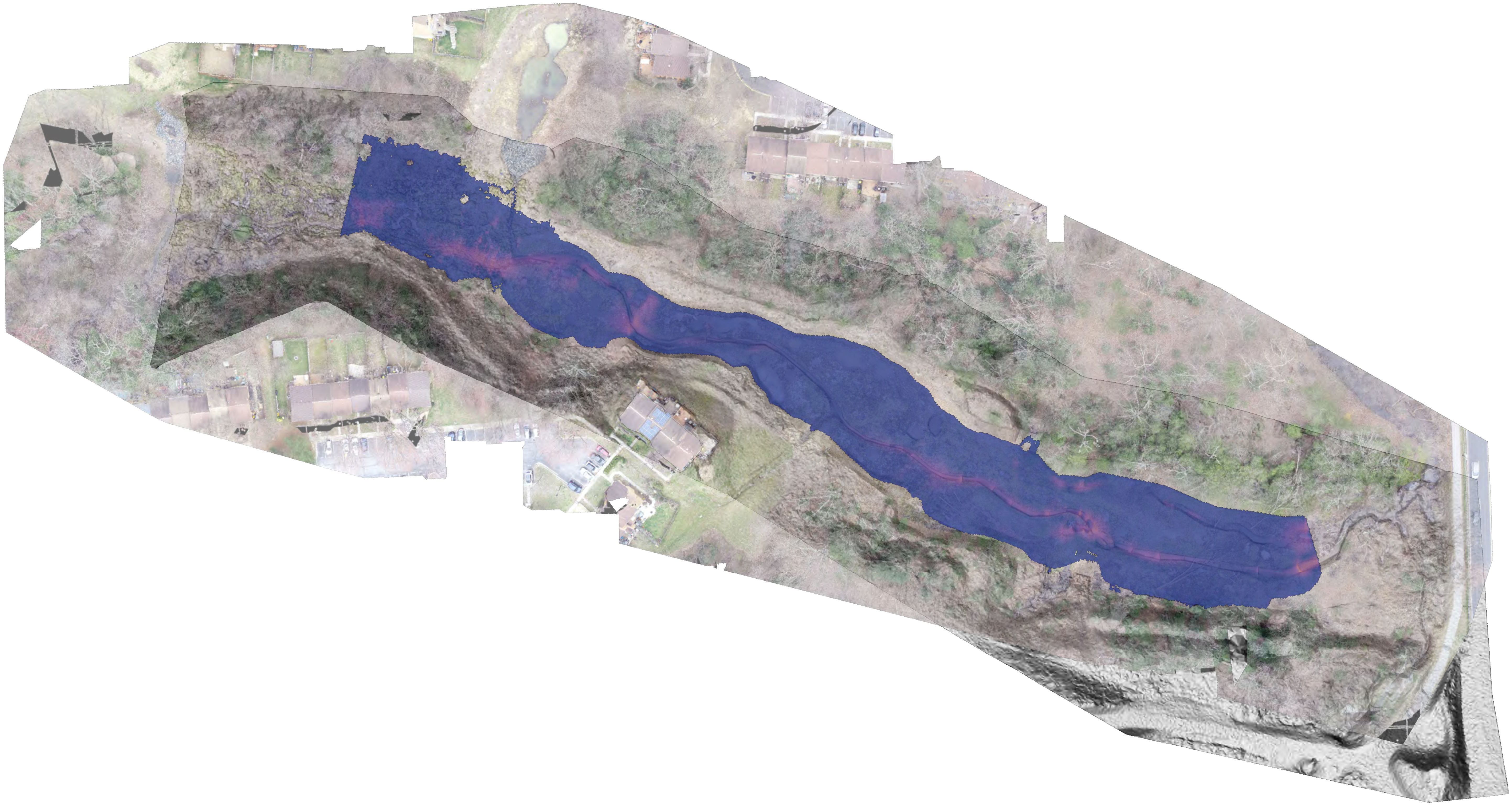

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 40 80 120 160 Feet

N

Two Dimensional Hydrodynamic Model Results:
Cat Branch

10-yr Event Predicted Flood Velocities

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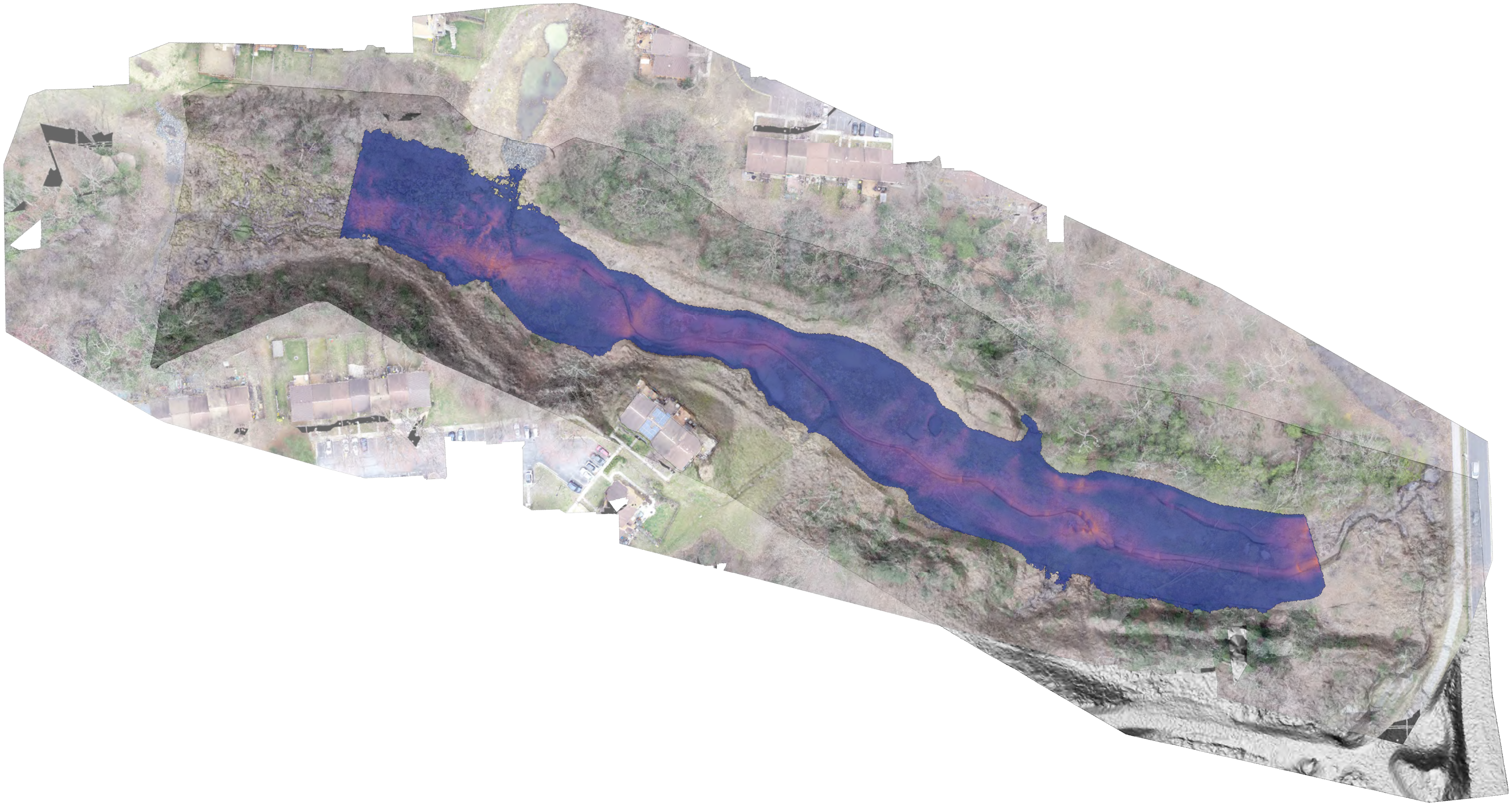

Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE.
STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 40 80 120 160 Feet

N

Two Dimensional Hydrodynamic Model Results: Cat Branch

50-yr Event Predicted Flood Velocities

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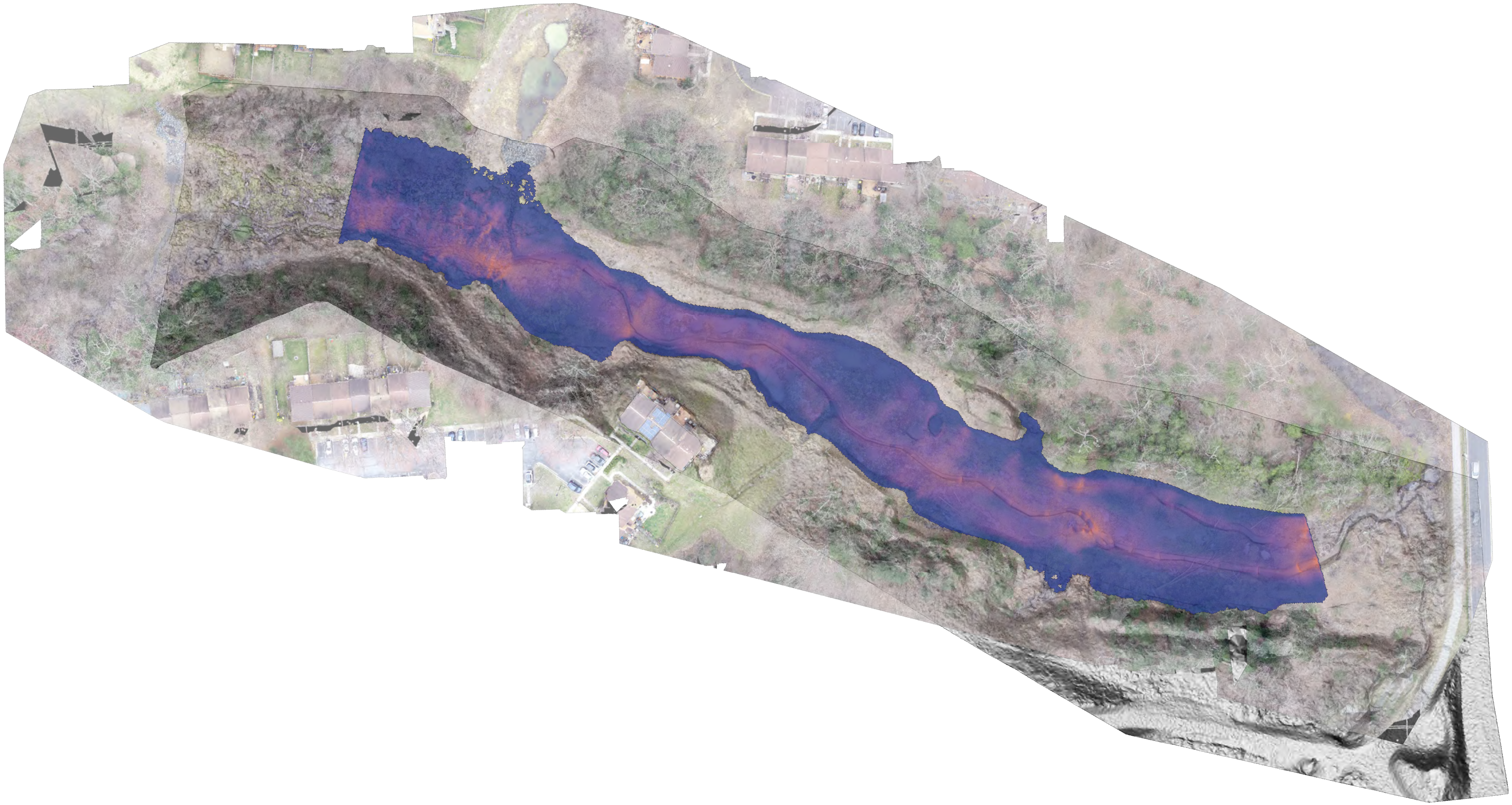
Restoration Research Award Program Funding Partners:



Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

UNIVERSITY OF LOUISVILLE STREAM INSTITUTE

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 40 80 120 160 Feet

N

Two Dimensional Hydrodynamic Model Results: Cat Branch

100-yr Event Predicted Flood Velocities

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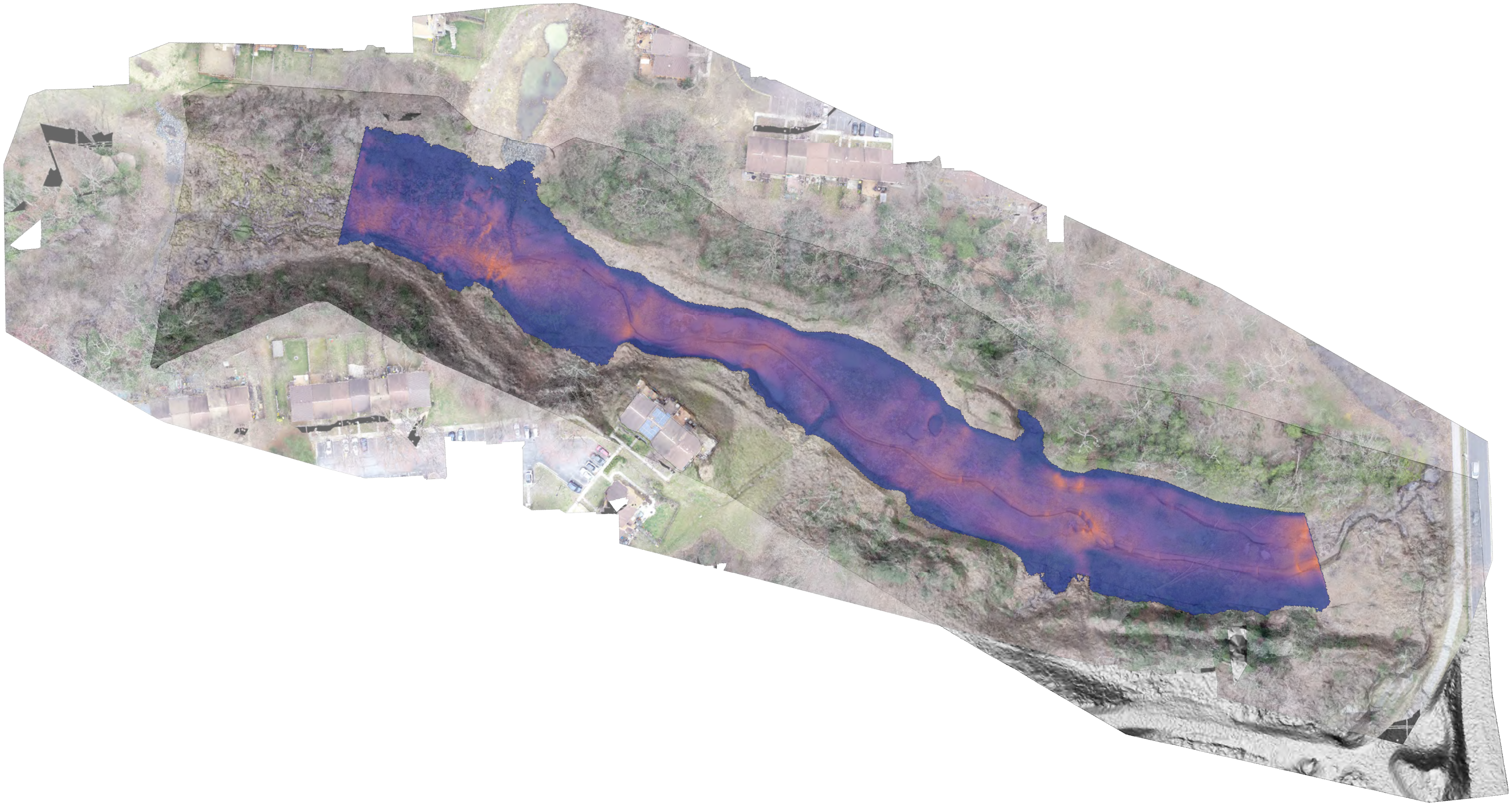
Restoration Research Award Program Funding Partners:



Velocity (ft/s)

0 2 3 4 5 6 8 10 12 Max

Aerial imagery collected on 2021-03-17.
Flow direction is from left to right.

0 40 80 120 160 Feet

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Two Dimensional Hydrodynamic Model Results:
Cat Branch

Climate Change Scenario (100-yr + 33%)

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