Columbia River Project Water Use Plan

Lower Columbia White Sturgeon Habitat Restoration Alternatives

Reference: CLBWORKS-27

BC Hydro and Power Authority

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July 2020

Lower Columbia White Sturgeon Habitat Restoration Alternatives

FINAL REPORT




Prepared for:

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EXECUTIVE SUMMARY

White Sturgeon in the Canadian portion of the Columbia River were listed as endangered under Canada's Species at Risk Act (SARA) in 2006. Natural recruitment of White Sturgeon in the transboundary reach of the Columbia River is insufficient to maintain a self-sustaining population (UCWSRI 2012). Although existing adult White Sturgeon have successfully spawned at multiple river locations, insufficient young are surviving through early life stages to become sexually mature adults. It is generally agreed that the onset of damming in 1968 had an adverse impact on habitat conditions due to alteration of flow, turbidity and passage conditions; however, the Columbia River Water Use Plan Consultative Committee concluded that anything more than opportunistic operational flow changes faced significant practical and financial impediments (CRWUP CC 2005). Although the decline in White Sturgeon was not noted until the 1990s (Hildebrand and Parsley 2013), McAdam (2013, 2015) determined that failure began in the 1967 - 1977 period, and used a weight of evidence approach to identify geomorphological change (e.g., increased fine substrates at spawning sites) as the most plausible explanation for recruitment failure.

The overall objective of this project was to determine the biological and technical feasibility of spawning substrate restoration at spawning locations on the lower Columbia River. BC Hydro identified three White Sturgeon study areas of interest, including Keenleyside (river kilometer, as measured downstream from Hugh Keenleyside Dam, (rkm) 0.1 to 1.25), Kinnaird (rkm 13.4 to 18.4) and Waneta (rkm 56.0 to 57.2). The Keenleyside area has two inflow sources, one from the Hugh Keenleyside Dam (HLK) tailrace and the other from the Arrow Lakes Generating Station (ALH) tailrace. The Waneta area is at the confluence of the lower Columbia River and the Pend d'Oreille River.

A background review of existing hydrological, geomorphic, and biological conditions in the lower Columbia River was completed, as well as a summary of White Sturgeon habitat requirements and previous restoration efforts for White Sturgeon in other locations. Restoration feasibility was assessed with field data collection and modelling-based analysis of existing substrate, hydraulics, sediment transport, and biological conditions within each of the three study areas. Field work consisted of four field trips at different flow conditions, during which bathymetry data, hydraulic data, and substrate characteristics were measured at the potential restoration locations to assess physical habitat conditions and parametrize and calibrate hydrodynamic and sediment transport models. Underwater imagery and videos collected during the four field trips were processed to generate spatial maps of various substrate characteristics for each area. Hydrodynamic and sediment transport modelling was undertaken using River2D and two sediment transport models to generate predictions of hydraulic conditions at multiple flows for each of the three study areas and to answer questions related to sediment transport and habitat suitability for current and post-restoration conditions. Habitat suitability was assessed using the hydraulic simulations and sediment conditions to generate spatial predictions of recruitment and spawning suitability and identify locations with high potential for successful restoration.

Specific restoration alternatives were identified and then evaluated during two workshops facilitated by BC Hydro and attended by consultants, First Nations, provincial and federal agencies, and local power producers. Workshop One was held May 13-14, 2019 to identify restoration alternatives and develop performance measures to compare and prioritize alternatives based on the available field data and initial modelling results. Restoration alternatives were evaluated qualitatively during the workshop and a shortlist of six restoration alternatives was selected for further evaluation, including five options at Keenleyside and one at Waneta. These alternatives included variations on placements of substrate or in situ substrate cleaning in known egg deposition zones. Restoration alternatives for Kinnaird were considered, but there was too much uncertainty surrounding spawning and rearing locations to pursue restoration activities at this time. Performance measures were developed to assess alternatives with respect to substrate mobility, substrate condition, habitat suitability, expected biological response, and feasibility.

Based on the objectives determined during Workshop One, additional field work and modelling were undertaken to further characterize the shortlisted restoration alternatives. The list of performance measures identified during Workshop One was expanded and refined to 11 prior to Workshop Two. Based on the performance measures, the highest-ranking alternative was to place ideal spawning substrate throughout the ALH tailrace spawning area. Placement of ideal spawning substrate in the upper portion of the ALH spawning area, and placement of smaller than ideal material throughout the ALH spawning area were also high-scoring alternatives.

Workshop Two was held on February 6, 2020 to review new field data and analysis completed since Workshop One, consider the preliminary ranking, determine which alternatives to pursue, and to develop initial considerations for restoration design, monitoring, cost, and timelines. Participants recommended an alternative to be advanced to the next phase, which consisted of placement of stone within the ALH tailrace spawning area. The recommended placement was confined to the downstream trajectory from previously identified spawning locations. Additional alternatives were suggested for subsequent consideration and analysis (i.e., after implementation of the ALH placement). Restoration alternatives for Waneta were discussed, but ALH was chosen as the immediate focus due to greater physical and biological uncertainties in the Waneta reach.

The recommended restoration approach for Phase 2 consists of placement of multiple grain size mixtures within the ALH spawning area in zones where the specific mixtures will be stable and resistant to fines infilling. The zones were identified with sediment transport modelling using mixtures that include different proportions of material within the range suitable for sturgeon (20 to 300 mm). It was determined that 6,500 m^2 of material could be placed and that infilling or mobilization would not occur within approximately 50% of this area for at least a few years. At Waneta, shore-based augmentation near the river left bend apex was found to be worthy of further consideration if a biological benefit is observed following implementation of the Keenleyside treatment.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF MAPS

LIST OF APPENDICES

LIST OF ACRONYMS

LCR – Lower Columbia River

PDO – Pend d'Oreille River

ALH – Arrow Lakes Generating Station

HLK – Hugh L. Keenleyside Dam

WAN – Waneta

EDZ – Egg deposition zone

EDZ DS – immediately downstream of egg deposition zone

UCWSRI – Upper Columbia White Sturgeon Recovery Initiative

CRWUP CC – Columbia River Water Use Plan Consultative Committee

WUP – Water Use Plan

KP – Knight Piésold

NHC – Northwest Hydraulic Consultants

GLS – Grant Land Surveying Inc.

DFO – Department of Fisheries and Oceans

WSC – Water Survey of Canada

USGS – United States Geological Survey

TWG – Technical Working Group

RDCK – Regional District of Central Kootenay

MOTI – Ministry of Transportation and Infrastructure

ADCP – Acoustic Doppler Current Profiler

1. INTRODUCTION

The Upper Columbia White Sturgeon Recovery Initiative (UCWSRI) confirmed that the level of natural recruitment of White Sturgeon (*Acipenser transmontanus*) residing in the transboundary reach of the Columbia River is insufficient to maintain a self-sustaining population, which is referred to as recruitment failure (Hildebrand and Parsley 2013). During the Columbia River Water Use Plan (CRWUP) process, the Consultative Committee (CC) agreed that a key focus of fish management in the Columbia River mainstem should be on White Sturgeon (CRWUP CC 2005).

The focus of this study is on the lower Columbia River (LCR), which is located in the West Kootenay Region of British Columbia and extends 57 km from Hugh L. Keenleyside (HLK) dam to the Canada-USA Border. The three White Sturgeon spawning areas of interest include Keenleyside (river kilometer (rkm) 0.1), Kinnaird (rkm 13.4 to 18.4) and Waneta (rkm 56.0 to 57.2). The general boundaries for the Keenleyside spawning area extend from HLK and Arrow Lakes Generating Station (ALH) to approximately 1.25 km downstream (adjacent to Rialto Creek) as described in Terraquatic Resource Management (2011) and shown in Map 2. The exact location that spawning occurs in the Kinnaird area is unknown and as such, the area of interest encompasses a larger section of river (approximately 5 km) downstream from Highway 3 bridge (rkm 13.4 to rkm 18.4; Map 1). The Waneta spawning area extends approximately 1 km from downstream of Waneta dam to the Canada/USA border (Hildebrand and Parsley 2013; Map 3).

White Sturgeon in the Canadian portion of the Columbia River were listed as endangered under Canada's Species at Risk Act (SARA) in 2006. This listing also includes populations of White Sturgeon from the Nechako, Kootenay, and Fraser rivers. The listing for the Columbia River population is directed primarily at White Sturgeon found between the Canada-US border and Revelstoke Dam. There are estimated to be approximately 1,200 mature White Sturgeon in this area with the majority found downstream of HLK in the LCR (Irvine *et al.* 2007; Wood *et al.* 2007), and approximately 40 adults estimated upstream of HLK in the middle Columbia River (DFO 2014).

The UCWSRI began recovery efforts in 2000 with the goal of building a healthy future for White Sturgeon in the LCR in British Columbia, Canada and Washington, USA (Hildebrand and Parsley 2013). Although existing adult White Sturgeon have successfully spawned in multiple river locations (Pend d'Oreille and Columbia River Confluence: Golder 2009; ALH tailrace: Terraquatic Resource Management 2011; Revelstoke: Wood 2019), insufficient young are surviving through the early life stages (i.e., egg, larva, and juvenile) to become sexually mature adults. The exact causes of recruitment failure among sturgeon found in the LCR remain uncertain. However, it is generally agreed that the onset of building the Canadian Columbia Treaty dams in 1968 have had a negative impact in several key areas including, but not limited to, habitat suitability and access, fish movement, and food availability. Additionally, the operation of dams for power and flood control on the Columbia River has substantially altered the range of daily water level fluctuations, turbidity levels, and seasonal flow regimes with reduced flows in the spring and early summer and increased flows in the winter. A logical recovery response would therefore be to alter the hydrograph in the lower Columbia reach to mimic the natural flow regime as much as possible, especially in the spring/summer during White Sturgeon spawning and early life stage periods. The CRWUP CC considered such a mitigative measure, but concluded that anything more than opportunistic operational changes faced significant practical and financial impediments (CRWUP CC 2005). Significant freshet flows were experienced in 2011 from PDO and 2012 from LCR, with 2012 being higher than could be achieved operationally, and White Sturgeon population responses (detectable recruitment) to these flow years are still being evaluated under Columbia WUP monitoring programs (CLBMON-28 and CLBMON-29).

As an initial response to the uncertainty regarding the cause(s) of recruitment failure, the UCWSRI Technical Working Group (TWG) undertook a recruitment failure hypotheses review between 2006 and 2008 (Gregory and Long 2008; described in detail in Section 2.1.4). The purpose of the review was to reach consensus on those hypotheses which best explained White Sturgeon recruitment declines in the Columbia system, to identify research required to better define the pathways of impact, and to define mitigative measures or management responses with the best likelihood of alleviating the causes of recruitment loss. The process considered impacts including flow regime effects and the benefits of cover provided by the suspended sediment load at spawning sites in the LCR. The process identified the following hypotheses along with related potential mitigative measures:

a) Changes in flow patterns (magnitude and timing) and reduction in turbidity reduce the survival of early life stages:

- i) Turbidity augmentation;
- ii) Flow manipulation – depth and velocity; and
- iii) Backwater habitat influence manipulation.

b) Diminished suitability and availability of habitat (primarily related to substrate conditions) near spawning areas has led to reduced survival of early life stages:

- i) Substrate modification – cleaning; and
- ii) Substrate modification – addition.

c) Changes to fish community have resulted in increased predation on eggs, free embryos, larvae and juvenile sturgeon and significantly reduced survival:

- i) Predation control program – general; and
- ii) Walleye reduction program.

d) Food of the appropriate type and size is not available at the right time and place to promote survival of young sturgeon:

- i) Fertilize transboundary reach;

ii) Seeding of varial zones; and

iii) Embayment fertilization.

The initial CC report's recommendation was primarily targeted at turbidity augmentation in the LCR. However, more recent work has identified multiple competing hypotheses (Gregory and Long 2008) resulting in modifying CLBWORKS-28 Lower Columbia River – Planning and Assessment of White Sturgeon Turbidity Experiments to incorporate up to date information. This included examining the feasibility of physical works that were developed to test twelve hypotheses that addressed recruitment failure in the LCR (McAdam 2013; McAdam 2015). Using recruitment hindcasting in combination with a weight-of-evidence evaluation, eleven hypotheses (overfishing, connectivity, contaminants, habitat diversity, total gas pressure, turbidity, temperature, flow regulation, nutrients and food supply, and fish species composition) were considered implausible due to poor explanations for recruitment failure. Although alternate mechanisms of recruitment failure may be possible, the geomorphological change (e.g., increased fine substrates at spawning sites) hypothesis was identified by this study as the most plausible explanation for recruitment failure providing direction regarding preferred restoration approaches that could possibly result in a positive effect on recruitment. Accordingly, the overall objective of this project is to determine both the biological and technical feasibility of spawning substrate restoration at White Sturgeon spawning locations on the LCR. The Project will consist of three phases including:

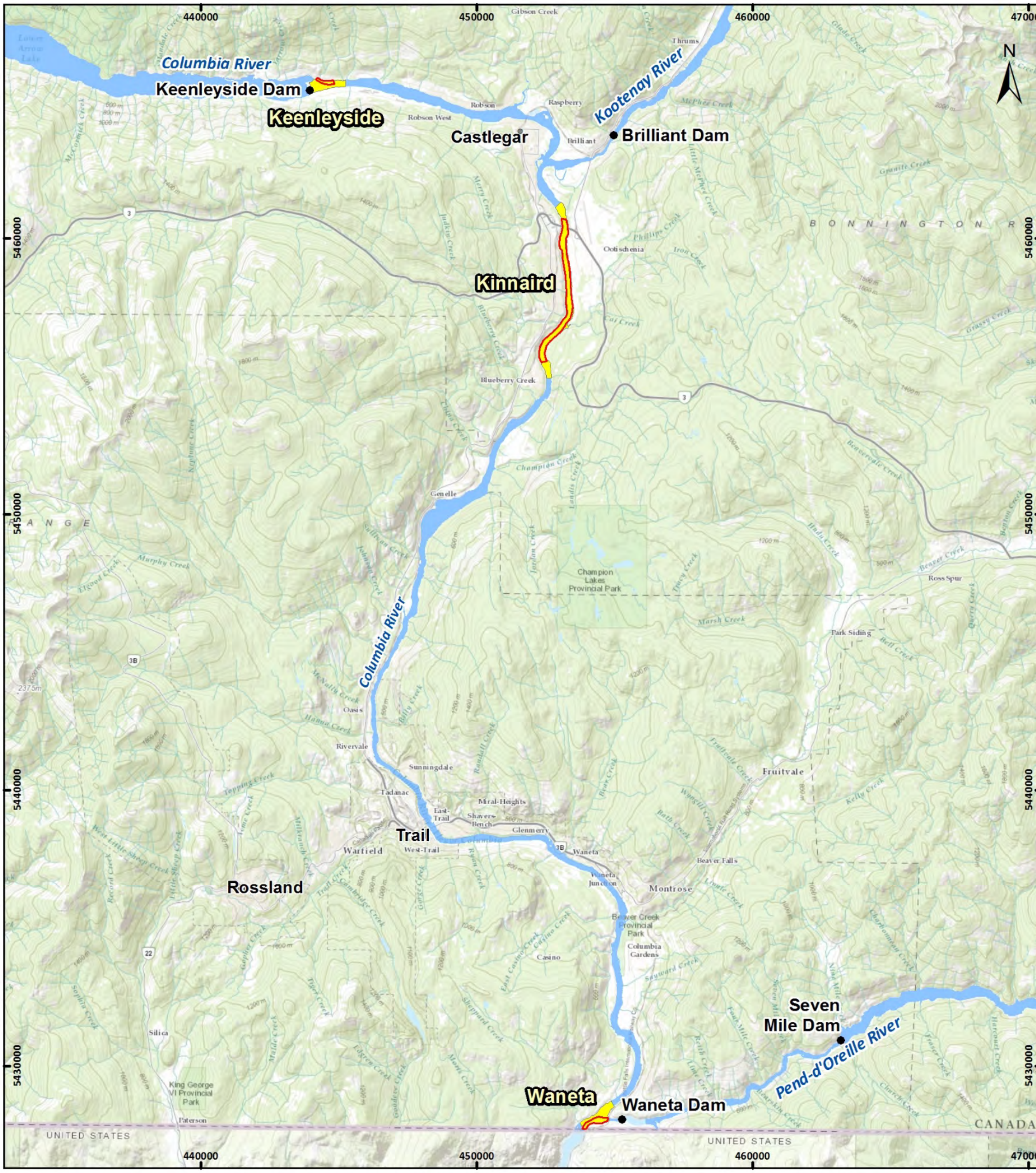
Phase 1 Identification – characterize existing habitat, develop restoration options and evaluate the feasibility of each option;

Phase 2 Definition – development of preliminary designs associated with recommended options emerging from Phase 1; and

Phase 3 Implementation – completion of the design selection in Phase 2.

Ecofish Research Ltd. (Ecofish) in collaboration with Knight Piésold (KP) and Wood PLC were retained to support BC Hydro with Phase 1 of the project. The following section details the six tasks associated with Phase 1, as well as background information on hydrology and geomorphology in the LCR, a biological overview of White Sturgeon, and a summary of existing information on habitat conditions in the LCR.

Project Overview



Legend

- Reach
- Spawning Areas
- Columbia River Dams

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 1 2 3 4 5 6 7 8 km

Scale: 1:200,000

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Coordinate System: WGS 1984 UTM Zone 11N

ECOFISH RESEARCH

Map 1

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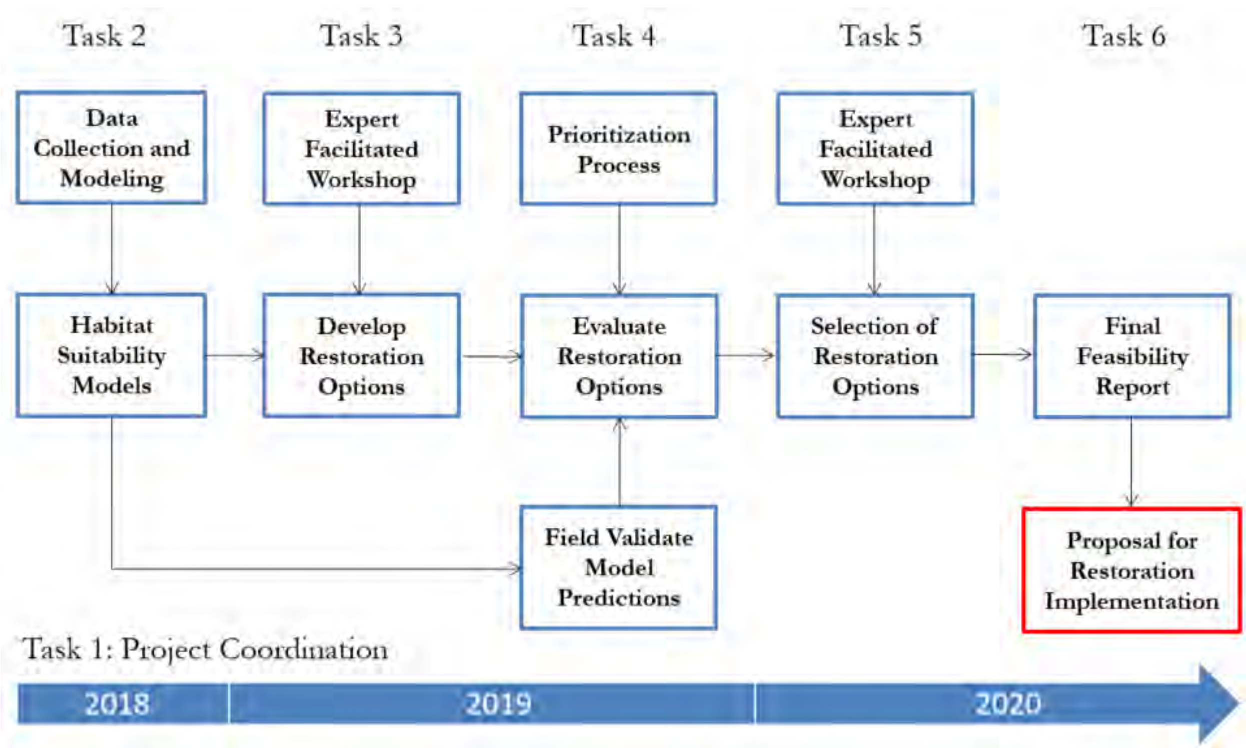
2. OBJECTIVES AND BACKGROUND

2.1. Project Objectives

The overall objective of the Project is to determine the feasibility of spawning substrate restoration at White Sturgeon spawning locations on the LCR. Feasibility was assessed primarily for biological, hydrotechnical, and constructability considerations; however, cost and social factors were also considered at a high level. The project objectives were broken into six tasks, including project coordination (Task 1), physical data collection, analysis and reporting (Task 2), restoration alternative development (Task 3), evaluation (Task 4), selection (Task 5), and feasibility analysis and final reporting (Task 6). Details of Tasks 2 through 5 are provided below. Each of the tasks are outlined in Figure 1 and discussed in more detail in the following sections.

Figure 1. Task breakdown and workflow used to deliver CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Alternatives.



2.1.1. Task 2 – Data Collection and Analyses

This task involved the evaluation of current spawning habitat conditions including water velocities, depths, substrate composition, and other important physical variables at each of the three spawning areas in the LCR. The purpose of data collection was to allow for description of existing conditions, including suitability for White Sturgeon, and evaluation of restoration alternatives if deemed necessary. The selected data collection and analysis approach was tailored to address known uncertainties in terms of habitat suitability and anticipated uncertainties related to the feasibility of restoration approaches. The level of field and analysis effort was similar for Waneta and Keenleyside. Given the uncertainty of exact spawning location in Kinnaird, the level of effort was conducted at a level sufficient to identify potential spawning areas based on the preferred White Sturgeon spawning criteria as described in the Upper Columbia White Sturgeon Recovery Plan (Hildebrand and Parsley 2013).

2.1.2. Task 3 - Development of Restoration Alternatives

This task involved a facilitated workshop where results from Task 2 describing existing spawning habitat conditions were reviewed. The purpose of the workshop was to develop potential substrate restoration alternatives and evaluation criteria, based on both biological requirements of the species and results from physical data collection. This workshop occurred during May 2019 and was attended by relevant experts in White Sturgeon biology representing First Nations, provincial and federal agencies, and local hydropower producers.

2.1.3. Task 4 - Evaluation of Restoration Alternatives

The purpose of this task was to evaluate the restoration alternatives selected during the workshop completed for Task 3. The evaluation included ranking of the various restoration alternatives developed from a physical perspective based on considerations of both existing and proposed sediment transport characteristics, substrate conditions, habitat suitability, biological response, and feasibility. Existing conditions were carefully assessed to ensure that proposed treatments would provide a substantial improvement, since the limiting condition to existing habitat is not entirely clear. The metrics were added to a prioritization table that was used to rank projects using the physical metrics that were developed as part of this task or that were assigned during the Task 3 workshop. Additional field data collection was also considered in order to address data gaps or data requirements that were identified during the analysis phase of Task 2. A report detailing the results of Tasks 2-4 was prepared in advance of Workshop Two to aid with ranking refinement. These results are detailed in the following sections.

Given that other White Sturgeon restoration projects have experienced issues with fines infilling (Nechako - McAdam *et al.* 2018) and scour of placed material (Revelstoke – Crossman and Hildebrand 2012), it was determined that predicting sediment transport conditions would increase the potential for success of any project that assesses the risk of these two processes. Assessing these transport processes for proposed restoration alternatives is complicated by (1) regulated flow conditions, (2) hydraulic variability within treatment areas, (3) uncertainty inherent of sediment transport models, and (4) the requirement to balance fines flushing with coarse material stability. Given this complexity, the metrics used to compare potential projects were dominated by sediment transport conditions.

2.1.4. Task 5 - Selection of Restoration Alternatives

This task involved a second workshop to examine the results of the evaluation of restoration alternatives conducted in Task 4. This workshop occurred during February 2020 and was attended by relevant experts in White Sturgeon biology. Uncertainties in substrate condition discussed during

Workshop One were re-evaluated in light of the data collected during August 2019. The prioritization table for the alternatives identified for further evaluation during Workshop One was reviewed and a decision was made to pursue placement of material at ALH, and to further consider additional alternatives following an assessment of effectiveness of the initial alternative.

2.1.5. Task 6 – Final Feasibility Report from All Tasks

This task involved preparation of this report, which provides the results of the feasible assessment of restoration alternative(s) and development of recommendations based on the results of Tasks 2-5. The purpose of this report is to document the work completed for each of the tasks. The report represents the findings for Phase 1 of the project and builds off the interim reports and memos submitted in previous years (West *et al.* 2018, 2019, 2020). The contents include:

- Background information (including raw data) summarizing all the information compiled as part of this study;
- Identification of restoration alternatives selected as feasible for Phase 2 and description of the recommendation rationale and tradeoffs made between all alternatives considered as part of this project;
- Potential environmental concerns/risks for each recommended site;
- A schedule with key tasks and a preliminary estimate of costs for implementing the recommended site; and
- Coordination required with other programs under the White Sturgeon Management plan.

2.2. Hydrology and Geomorphology

Understanding the morphology of Columbia River aids in developing a conceptual model to support hydraulic and sediment transport modelling and requires knowledge of three key processes including sediment supply, hydrologic regime, and river bed material mobility.

The major tributaries of the LCR include the Kootenay River and the Pend D'Oreille River. Since the early 1900s several dams have been constructed on the LCR and its tributaries. The earliest were Bonnington, South Slocan and Corra Linn, constructed on the Kootenay River and Thompson Falls on Pend D'Oreille River, all built before 1932. River regulation has impacted the hydrology and geomorphology of the LCR. However, the most substantial flow changes (regulation) occurred in the 1960s and 1970s with construction of the Columbia River Treaty dams, including Hugh Keenleyside and Mica dams on the Columbia River mainstem, as well as the Duncan and Libby dams in the Kootenay River watershed.

The following sections describe pre- and post-regulation sediment supply, hydrology, and morphology of the LCR.

2.2.1. Sediment Supply

There are/were several natural lakes in the Columbia River watershed including Arrow Lakes, Slocan Lake, Kootenay Lake, and Lake Pend d'Oreille. These natural lakes would have trapped all bedload and much of the suspended load entering the lakes and thus sediment supply to the LCR was relatively low even before the onset of dam construction. The combined watershed area of minor tributaries and residual areas downstream of these lakes is 7% of the total Columbia River watershed area at the US Border (NHC 2007).

Suspended sediment gauging by Water Survey of Canada (WSC) on the Columbia River at Birchbank (located between the Kinnard and Waneta study areas) indicates that the annual suspended load in 1966, prior to regulation at Keenlyside, was 850,000 Mg or a specific yield of 10 $Mg/km^2/yr$ (NHC 2007). Flows were approximately average in 1966 and thus likely represent typical suspended sediment conditions pre-regulation. The specific yield is quite low compared to other similar sized BC watersheds (Church *et al.* 1989) and most of the sediment is likely supplied by erosion of glaciofluvial terraces and incised tributaries along the LCR, rather than from upland areas (NHC 2007).

Hydroelectric facilities built on the Columbia River lakes (and Brilliant Dam and Waneta Dam, not located at natural lake outlets) likely had a relatively minor impact on sediment supply to the LCR. For example, McAdam (2013) reports a reduction in turbidity (generally indicative of suspended silt and clay transport) at Castlegar following construction of HLK, from a low average turbidity of 1.5 NTU prior to 1974 to an even lower 0.6 NTU after 1974. For bed material transport, the effect of natural lakes and dams is more distinct; bedload transport through a lake or reservoir can be assumed to be effectively zero.

2.2.2. Hydrologic Regime

Prior to regulation, the annual hydrograph of the LCR was dominated by a nival (snowmelt) freshet, typically rising in April and peaking in May or June and then receding through the summer and autumn. Annual low flows occurred in January to March. Unlike sediment supply, hydroelectric development has significantly altered the hydrologic regime of the LCR in terms of annual flow distribution (shape of the annual hydrograph) and the magnitude/frequency of peak flows.

Following regulation, the mean annual discharge is relatively unchanged (e.g., McAdam 2013) but the shape of the annual hydrograph has been redistributed with higher flows in fall and winter, and reduced freshet flows in the spring (Figure 2 to Figure 5). Peak daily flows at the US Border (USGS Stn. 12399500) have been reduced significantly with 2-year and 10-year floods pre-regulation (1938 to 1967 period of record) of approximately 9,200 m^3/s and 12,600 m^3/s, respectively, compared to 5,300 m^3/s and 7,700 m^3/s post-regulation (1968 to 2004 period of record) (NHC 2007). It should be noted that peak flow statistics may be misleading in regulated rivers due to the combination of stochastic hydrologic processes and dam operation regulation. Columbia River daily flows, upstream of Pend D'Oreille River at the WSC station Columbia River at Birchbank (08NE049) and at the USGS station Columbia River at International Boundary

(12399500) are shown on Figure 6. The largest flow on record since regulation on Columbia River at Birchbank is 6120 m^3/s, which occurred in 2012. It is noted that although there are 11 dams on Pend D'Oreille River, the reservoirs have relatively low storage volumes and tend to affect the snowmelt freshet less than Columbia River dams (Figure 3). Relatively large flows were recorded at the USGS station Columbia River at International Boundary in 1997, 2011, 2012 and 2018 due largely to Pend D'Oreille flows. Peak daily flows during these four years ranged from 8,350 m^3/s to 7,480 m^3/s.

Figure 2. Mean monthly discharge at Birchbank WSC (Stn. 08NE049).

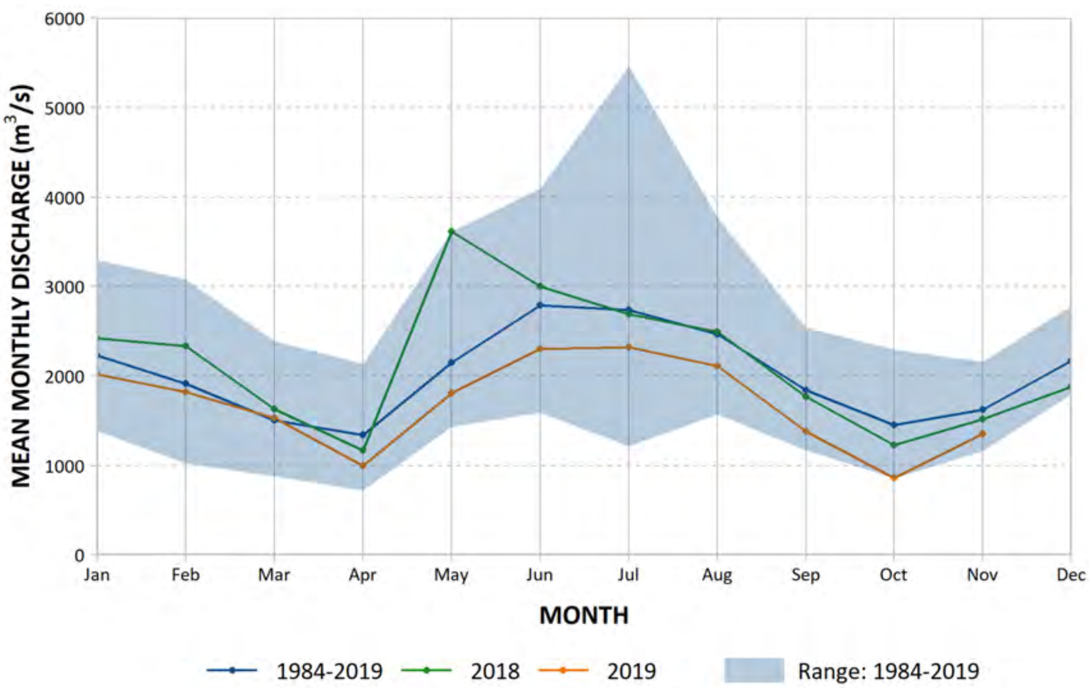


Figure 3. Mean monthly discharge from Pend D'Oreille River.

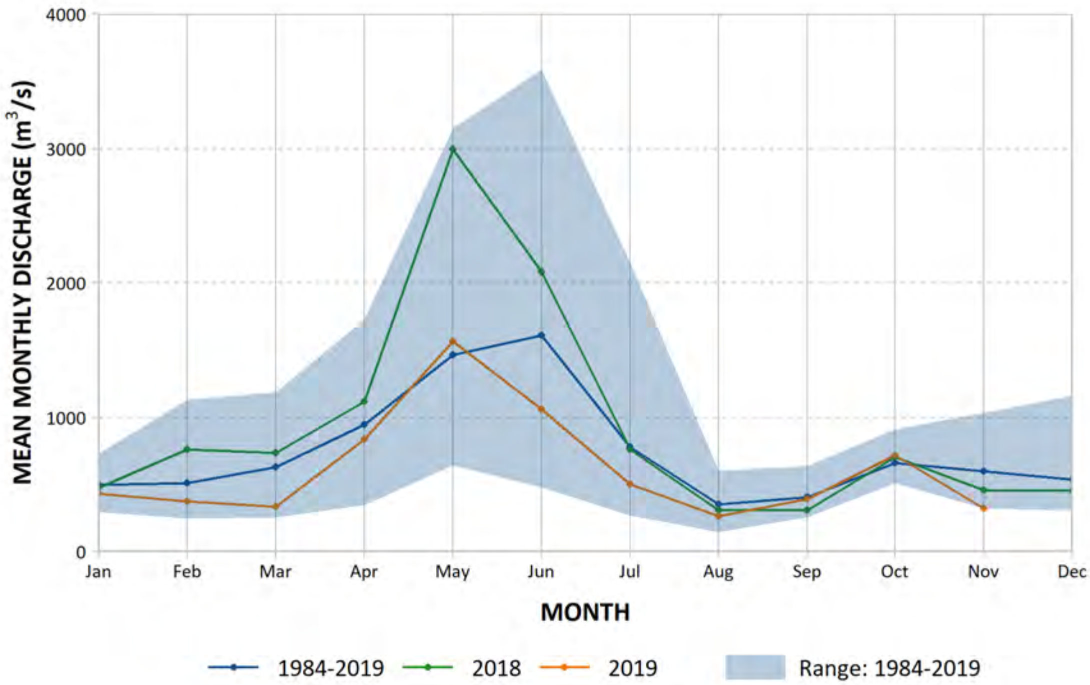


Figure 4. Mean monthly discharge from ALH.

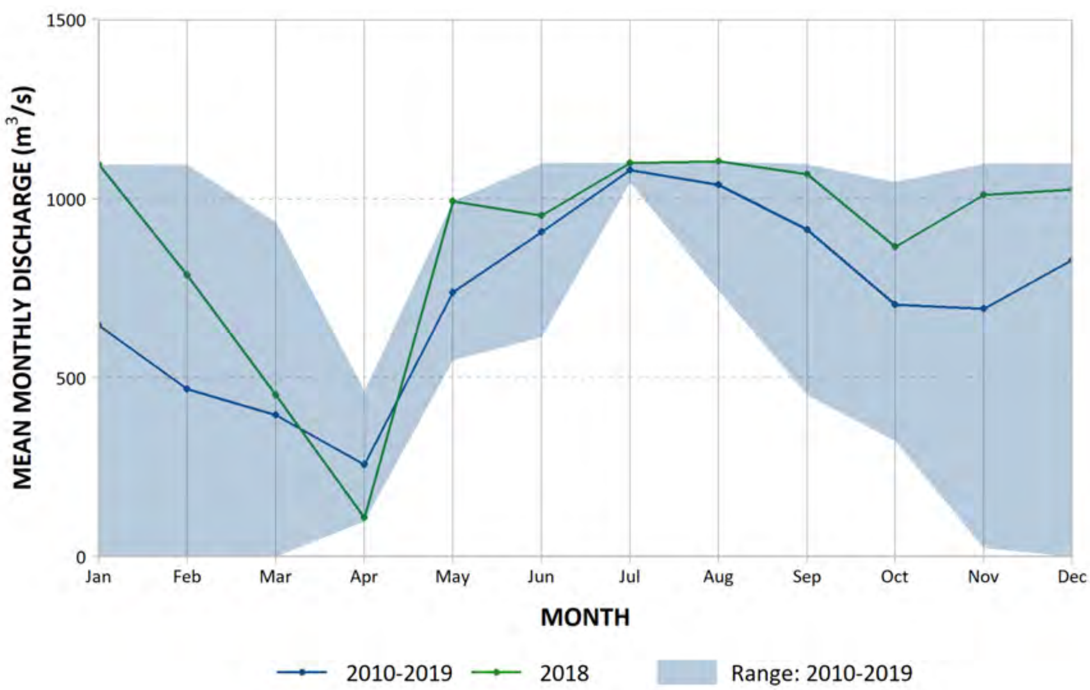


Figure 5 Mean monthly discharge from HLK.

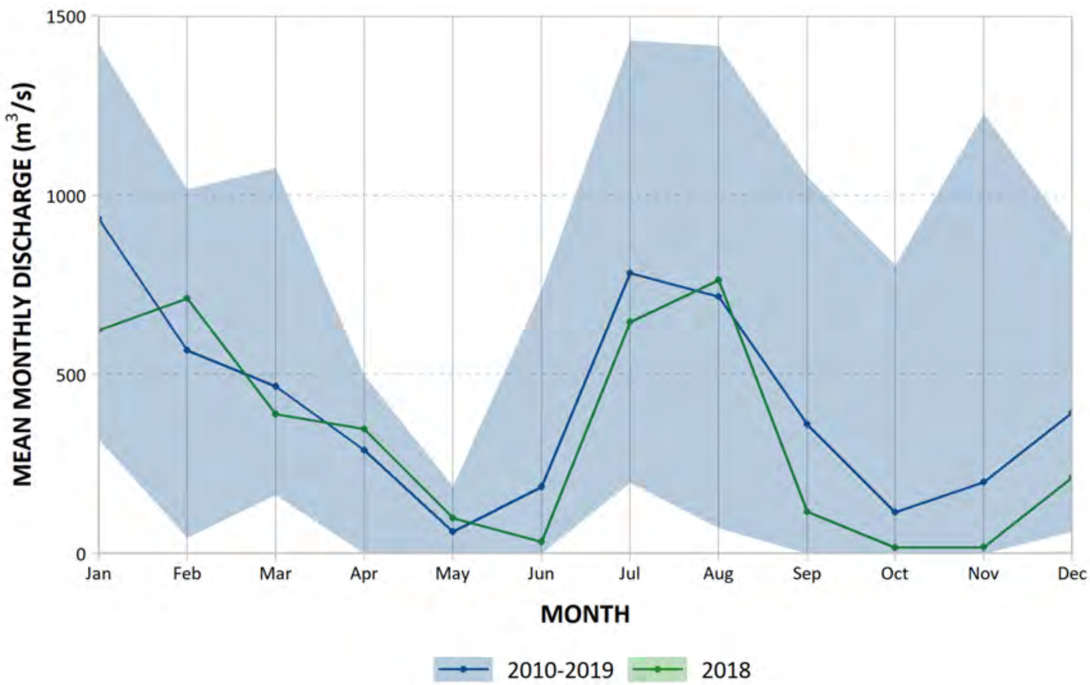
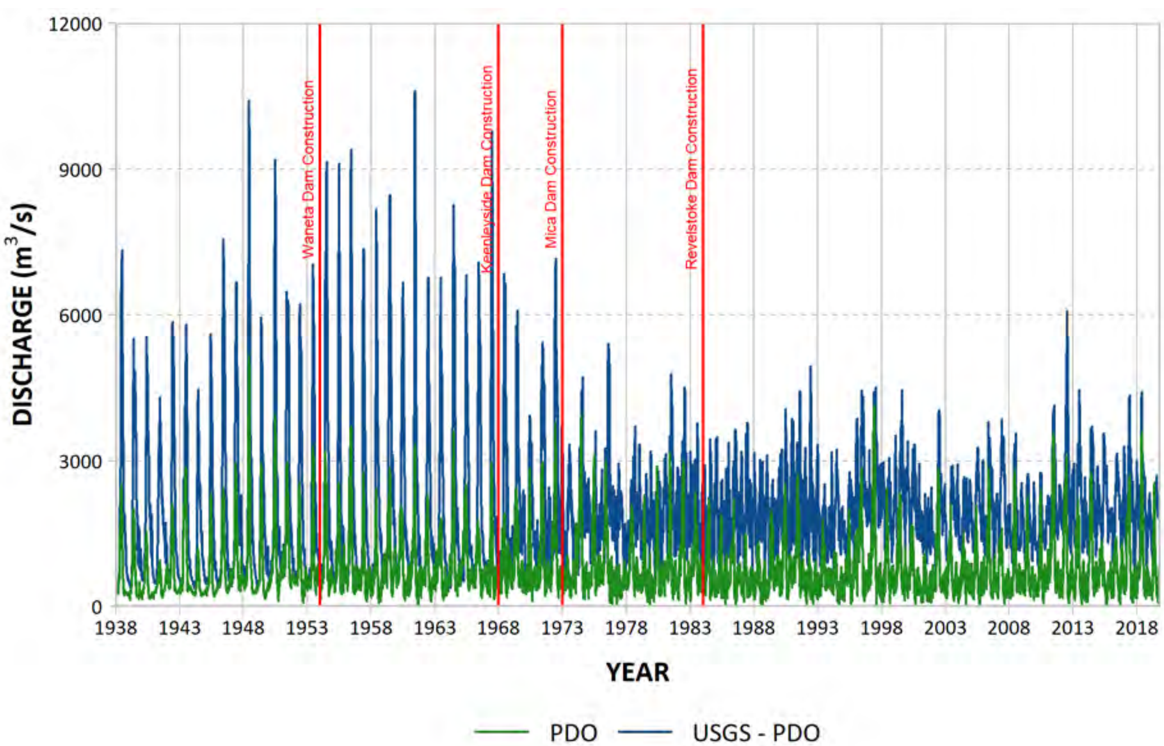


Figure 6. Daily flow records on Columbia River upstream and downstream of Pend D'Oreille River confluence.



2.2.3. Geomorphic Setting

The LCR has carved down through the valley-bottom glaciofluvial deposits. The river is entrenched to the point that during the 1948 and 1961 floods-of-record, overbank flooding was minimal. The riverbed consists primarily of coarse bed material with occasional bedrock outcrops. The coarse bed material likely consists primarily of glaciofluvial lag material; the finer fractions having been eroded away from the surface layer, but finer materials remain below this armour layer (see Appendix A). NHC (2007) conducted a specific-stage analysis at the WSC Birchbank gauge and found that pre-regulation variations were minor and that the rating curve has not needed revision since 1966. This result supports the concept that at a reach scale, the Columbia River is stable, and the framework bed material is infrequently mobile. However, at a local scale, site specific hydraulics and sediment supply may create local variability where the finer fraction of bed material (matrix material) may be more frequently mobilized and deposited at the bed surface.

2.2.4. Cause of Infilling

The coarse bed material framework (gravel, cobble, boulder) of the LCR is, and always has been, relatively immobile, as described above. The supply of finer bed material sediment (sand and granule) is relatively low, limited to incised glaciofluvial slopes and small local tributaries. Prior to regulation, the fine bed material supply from these sources would have been regularly flushed from the Columbia River bed surface by spring freshet flows. Since the onset of flow regulation, there is more potential for these materials to accumulate on the bed surface in local areas where the regulated hydraulic conditions are not sufficient to flush them away.

2.3. Biological Overview

2.3.1. General Spawning & Early Life History of the Species

White Sturgeon life history characteristics include a long life span, delayed maturation, and intermittent spawning. These characteristics make the species vulnerable to changes that have occurred over the last century in the mainstem Columbia River. The following information provides a background of basic White Sturgeon life history and habitat preferences.

White Sturgeon in the Canadian portion of Columbia River do not reach sexual maturity until a relatively large size and advanced age (e.g., 25-30 years depending on sex and population; Hildebrand and Parsley 2013 and references cited therein). White Sturgeon spawn intermittently with females spawning every 3 to 4 years and males having the ability to spawn every year (Hildebrand and Parsley 2013). Spawning typically occurs at water temperatures between 10°C and 18°C, with most spawning occurring at temperatures between 13°C and 18°C. Mature fish in spawning condition migrate to spawning reaches and are thought to select suitable spawning sites based on combinations of water velocity, turbulence, depth, and substrate composition (Hildebrand and Parsley 2013). White Sturgeon are broadcast spawners and eggs released by one or more females are fertilized by one or more males; it is believed that females spawn all their eggs within a short period of time (Hildebrand and Parsley 2013). The eggs rapidly sink and each egg forms an adhesive coating in about 5 minutes (range 2-13 minutes; Markov 1978), which allows them to adhere to the riverbed. Some localized dispersal of eggs is expected due to spawning typically occurring in high water velocities. Hatch occurs within 4-21 days after fertilization; warmer water temperatures decrease incubation time (Wang *et al.* 1985) and about 120 accumulated thermal units are required to reach hatch (Boucher *et al.* 2014). Egg mortality is higher when spawning occurs at temperatures over 18°C (Wang *et al.* 1985). Upon hatch, White Sturgeon yolk-sac larvae are photophobic and attempt to remain in interstitial spaces in the substrate (McAdam 2011; Crossman and Hildebrand 2012). Once the yolk-sac is absorbed, individuals emerge as feeding larvae, enter into the water column to assist with downstream dispersal, and begin to forage over the open bottom. Feeding larvae have a benthic-oriented volitional drift that is primarily nocturnal (McAdam 2012, Howell and McLellan 2014).

2.3.2. Spawning & Early Life History Habitat Suitability

Spawning habitats used by White Sturgeon in regulated areas of the Columbia River generally occur in fast-flowing waters over coarse substrates with hydraulic complexity such as turbulent areas of the mainstem or major tributary confluences, high velocity runs near rapids, or downstream from dams (Hildebrand and Parsley 2013). Several researchers have indicated that by spawning in these habitats, the negatively buoyant adhesive eggs are deposited over surfaces free of fine sediments that could suffocate eggs, that eggs are dispersed to reduce clumping and disease, and that turbulent areas may preclude egg predators (e.g., Parsley *et al.* 1993; McCabe and Tracy 1994; Parsley *et al.* 2002; Perrin *et al.* 2003 as cited in Hildebrand and Parsley 2013). Studies in spawning areas indicate that suitable habitats have substrates mainly comprised of gravels and cobbles (and boulders to a lesser degree) with intermediate interstitial spaces, near bottom water velocities >1 m/s (Parsley *et al.* 1993; Perrin *et al.* 2003; van der Leeuw *et al.* 2006; Hildebrand *et al.* 2016; Hatten *et al.* 2018), a depth range of 3-25 m (although depth may not be a critical habitat factor as indicated in Hildebrand and Parsley 2013), and water temperature conditions from 10°C to 18°C. Water turbidities similar to those in the uregulated Fraser River (average 42 NTU; Perrin *et al.* 2003) may also increase survival of early life stages (Gadomski and Parsley 2005). It is believed that small substrate (e.g., gravel) with interstitial spacing is important for survival of yolk-sac larvae by providing hiding habitat that they can use to avoid predators (McAdam 2011) while age-0 and older juvenile White Sturgeon tend to be found over substrates of hard clay, mud, silt, and sand (from microhabitat criteria curves in Parsley and Beckman 1994). Age-0 are those animals born within the past year, from transformation to juvenile until January 1, which have not yet reached one year of age.

2.3.3. Lower Columbia River White Sturgeon Spawning & Early Life History

Spawning in the LCR occurs in late June through mid-August when water temperatures reach 14°C and flows are typically on a descending pattern (e.g., Hildebrand and Parsley 2013; BC Hydro 2017a), with approximately 75% of spawning occurring before 10 July and 90% prior to 15 July (ASL *et al.* 2007 as cited in Hildebrand and Parsley 2013). Most mature males in spawning condition in the LCR were greater than 150 cm and age-25, whereas females were greater than 170 cm and age-30, which is similar to that reported downstream in the Columbia River in the U.S. (Hildebrand and Parsley 2013). Known spawning sites in the LCR are located below ALH, 3 km downstream of the Lower Kootenay River (LKR) confluence at Kinnaird, and at the PDO confluence below Waneta Dam (main site). Spawn timing at the three sites varies slightly with spawning at Waneta generally occurring from mid-June to early-August while spawning at ALH and Kinnaird generally occurs from mid-July to mid-August.

Spawning (documented through egg collections) occurs annually at the Waneta area and downstream of ALH in some years, though it is not known if the ALH site is used annually for spawning and continues to be the focus of additional monitoring. Spawning also occurs on an annual basis in the Kinnaird area, as egg and larval captures have been collected since 2007 (e.g., BC Hydro 2017b). However, the main geographical boundaries of the spawning location at Kinnaird where eggs are deposited remain uncertain. The majority of spawning days occur on the descending limb of the hydrograph at water temperatures above 14ºC. In addition to these known locations in Canada, spawning south of the international border occurs at multiple sites on an annual basis.

Larvae have been collected near the ALH spawning area, downstream of Kinnaird, and from the Waneta spawning site downstream into the U.S. Larval catch has predominantly consisted of young (1-3 days post hatch) individuals; however older feeding age larvae (>10 days post hatch) have been collected at all spawning locations. High numbers (10s of thousands) of larvae have been collected on the U.S. side of the Columbia River suggesting that hiding habitat exists from the Canadian/U.S. border downstream to Northport, Washington (BC Hydro 2017a). Further downstream in the U.S. near Marcus, Washington there are extensive areas of sand/silt sediments which should be suitable habitat for age-0 White Sturgeon. However, bottom trawl and fall gillnetting efforts targeting age-0 wild sturgeon have failed to capture larvae or age-0 White Sturgeon (Hildebrand and Parsley 2013 and references therein; Howell and McLellan 2017; Smit *et al.* 2016). Small-mesh benthic gill net surveys have been conducted in Lake Roosevelt annually in the fall (mid-late October) since 2001 to monitor natural recruitment of White Sturgeon. The gill net gear used in Lake Roosevelt since 2004 (excluding 2005-2007) is identical to standard gear for recruitment indexing in Bonneville, the Dalles, John Day, and McNary reservoirs of the Columbia River. Despite known annual spawning and survival of Transboundary Reach sturgeon to at least the first-feeding larval stage (i.e., exogenous feeding), no age-0 White Sturgeon and very few older wild juveniles have been captured to date. Given that the gillnet and bottom trawl gears are successful in capturing age-0 fish in the fall at downstream U.S. Columbia River impoundments at comparable levels of sampling intensity, the failure to capture age-0 White Sturgeon in the Transboundary Reach suggests survival following the transition to exogenous feeding is poor. White Sturgeon recruitment failure (i.e., no survival past first feeding larval stages) in the Transboundary Reach has been ongoing for several decades (Hildebrand and Parsley 2013).

Although the decline in White Sturgeon was not noted until the 1990s (Hildebrand and Parsley 2013), McAdam (2015) used estimated ages of captured fish to hindcast recruitment to identify when recruitment failure began. McAdam (2015) segregated fish into four discrete spawning groups based on fidelity to capture locations, and determined the year of the initiation of recruitment failure for three of the groups including Keenleyside, Waneta, and one using the upper Lake Roosevelt area downstream from the international border. The recruitment hindcasting showed that the timing of recruitment failure was similar for the Keenleyside (1967) and Roosevelt (1968) groups and occurred a decade later for the Waneta group (1977). In addition, McAdam (2015) showed that in the post-recruitment failure period for all areas, the Waneta area continued to produce a few fish, albeit at levels too low to sustain the population, suggesting that the Waneta area currently provides slightly better habitat than the other areas for successful recruitment.

2.3.4. LCR Recruitment Failure Hypotheses Related to Substrate Condition

Larval hiding has been identified as an important life history characteristic for White Sturgeon and it is thought to be critical for growth and development during early life history (e.g., Kynard *et al.* 2010; McAdam 2011 as cited in Crossman and Hildebrand 2012). It is believed that hiding larvae put endogenous reserves towards growth and development rather than expend those reserves searching for suitable hiding habitat or maintaining position in unsuitable habitat, and that this may be a key factor in explaining recruitment failure during early life stages (Gregory and Long 2008 as cited in Crossman and Hildebrand 2012).

Substrate condition as a factor in recruitment failure for White Sturgeon began with studies in the Kootenai River where sands and highly mobile bedload was implicated in the suffocation of incubating White Sturgeon eggs (Paragamian *et al.* 2001; Kock *et al.* 2006). McAdam *et al.* (2005) subsequently noted a temporal correlation between recruitment failure and a substrate change in the Nechako River. A timeline of age-0 relative recruitment (based on fish ages) was compared against geomorphic conditions determined from historic images and site-specific riverbed elevation changes, which revealed the link between an avulsion into the Nechako River near Cheslatta Falls, significant aggradation of the river channel, and the subsequent loss of White Sturgeon recruitment downstream.

The role of substrate as a factor in recruitment failure received additional support when the UCWSRI Technical Working Group (TWG) undertook a structured decision-making process in 2007-2008 with the primary purpose of developing a well-defined and broadly agreed-upon set of hypotheses that explain the recruitment failure of the White Sturgeon population in the LCR (Gregory and Long 2008). The work also identified required research actions and feasible mitigation alternatives based on the hypotheses. Over a series of five workshops, the initial "straw dog" list of over 100 hypotheses for recruitment failure was reduced to five for the LCR. One hypothesis (labeled as LC2/LC4 in Gregory and Long (2008)) addressed the diminished suitability and availability of habitat (primarily related to substrate conditions) downstream of spawning areas which led to reduced survival of early life stages (age 0-365 days; the smaller or younger the juvenile, the more likely the effect). The effect pathway described the following: dam installation and operations combined with natural and industrial sources of sediments have in-filled substrate interstices or overlain substrates rendering them unsuitable for use by early life stages. Juveniles then succumb to a combination of reduced food availability (impacting growth) and predation (during search for food and habitat). Many participants placed a high relative weight on the contribution of alterations in substrate condition and availability as the result of sediment additions and on another hypothesis regarding the inability of flows to clean the substrate (LC9/LC10; Gregory and Long (2008)) to promote production of appropriate food for first-feeding fish. Mitigation alternatives related to substrate included cleaning substrates using artificial means to remove accumulated fines or direct addition of new rock to increase the suitability of spawning areas and clean gravel to increase hiding habitat for young larvae. These hypotheses were developed prior to any detailed assessments of quality or quantity of available habitat for White Sturgeon in the LCR.

The Structured Decision Making process to explore and evaluate recruitment failure hypotheses (Gregory and Long 2008) prioritized research needs including a number related to habitat mapping and modeling and substrate habitat effects on larval hiding, dispersal, and health. Subsequently, McAdam (2011) conducted laboratory studies to examine substrate condition on habitat use and survival of early life history (1 day post-hatch to 15 day post-hatch) White Sturgeon. McAdam (2011) concluded in part that the behavioural responses of larval sturgeon (immediate hiding at hatch followed by downstream passive dispersal at the onset of exogenous feeding) are critically dependent on ambient substrate and flow conditions. The inability of young fish to hide after hatch led to greater drift and zero survival when exposed to predators.

McAdam (2015) used a weight-of-evidence approach to evaluate the potential cause of recruitment failure of White Sturgeon in the Transboundary reach of the Columbia River. He used an eco-epidemiological approach and considered twelve hypotheses. It is important to note that this approach cannot determine causation - it is intended to identify leading hypotheses (McAdam 2015). He began by hindcasting historical recruitment of three sub-populations (groups) of White Sturgeon within the Transboundary reach to create a timeline of recruitment from the 1940s through 1995. Discontinuities (breakpoints) in the recruitment index timeline were assumed to identify recruitment declines. These breakpoints differed among the three groups. Hypotheses were ranked by assigning structured scores (subjectively) to nine criteria for each hypothesis. A single prevailing hypothesis was identified (geomorphic change) as most supported; flow regulation, nutrients and food supply, and fish species composition also received support. McAdam (2015) concludes "while substrate change is represented as a single hypothesis in the weight-of-evidence evaluation, evidence from laboratory and field studies indicates multiple direct (e.g., suffocation, predation) and indirect (e.g., decreased food availability) mechanisms by which increased fine substrates in the vicinity of spawning habitat may increase egg and larval mortality". McAdam *et al.* (2018) also noted that field studies in the LCR and Nechako demonstrate that larval catch is dominated by young yolk-sac larvae at most spawning sites, which is indicative of diminished quality of larval hiding habitat.

2.4. Condition of Habitats in the LCR

2.4.1. Previous Habitat Assessments/Modelling

The following is a high-level summary of some of the main habitat assessment and habitat modelling programs that have been undertaken in the LCR. In particular, the study conducted by

Fissel *et al.* (2017) at the Waneta eddy is summarized to provide background information for additional comparisons that will be made with the current program.

One of the earliest LCR habitat models (1D HEC-RAS) was completed by BC Hydro during their Water Use Planning consultation (2002-2003). Golder (2014a) initially updated the 1D HEC-RAS model and then used River2D hydraulic modelling in 2011 to calibrate water surface elevations in the Columbia and Kootenay rivers from this updated model for the Mountain Whitefish Egg Loss Modelling program (CLBMON-47). The River2D models were not validated under high flow conditions (Golder 2014a). Fissel and Jiang (2002) constructed a 3D ASL-COCIRM model and used it to simulate hydraulic conditions in the Waneta Eddy at the PDO confluence. NHC (2007) investigated LCR substrate characteristics and slag transport at the Waneta study reach using both BC Hydro's original 1D HEC-RAS model and Fissel and Jiang's (2002) ASL-COCIRM model results and included a review of substrate characteristics, data gaps and provided recommendations for additional data collection. Substrate mapping conducted by BC Hydro (2017a) used a Tritech Starfish sidescan sonar to collect riverbed images in 2010 and 2011 to describe and classify physical habitat in the LCR between HLK and the US border. Additional substrate mapping was also conducted at the ALH (Golder 2014b) and Waneta spawning reaches (Golder 2016, 2017 as cited in Fissel *et al.* 2017).

2.4.1.1. Waneta Delft 3D Flow & Sediment Dynamics Numerical Model

Fissel *et al.* (2017) used the Delft 3D flow and sediment dynamics numerical model to produce a high-resolution representation of 3D hydrodynamic flow patterns and sediment transport dynamics of the Columbia-PDO confluence to study whether a hypothesized change in substrate occurred at the White Sturgeon spawning and rearing grounds at Waneta as per McAdam (2015). Modelling of erosion and movement of fine river sediments provided insights into river bed net deposition and aggradation of materials within the egg deposition area (Fissel *et al.* 2017). However, limited observations of fine sediment transport rate, supply, and boundary conditions gave rise to uncertainties in the estimates of net deposition rates for the Columbia River. The model was also not designed to simulate erosion from the highly mixed range of sediment types observed within the Waneta sturgeon egg deposition zone (Fissel *et al.* 2017). Comparison of the results from this project to those of Fissel *et al.* (2017) is provided in Section 6.2.5.

2.4.2. Current Conditions in Known Spawning Areas

Habitat conditions for the three known LCR spawning areas are further described below (from upstream to downstream). In general, depths are not limiting and velocities appear to be adequate in most years in the three known LCR spawning areas. However, water temperature conditions at Waneta at the tail end of the spawning period can exceed those considered optimal for development (dependent on water year).

Keenleyside (rkm 0.1) – Sampling conditions at ALH when eggs and larval were collected included water temperatures ranging from 11°C to 18°C and mean water depths between 5 and 9 m (BC Hydro 2015b, 2016). Near-bottom water velocity patterns during the ADCP survey in 2002, when discharges from ALH and HLK were 1060 m^3/s and 497 m^3/s, respectively, revealed a distinct high-velocity (1.0 to 1.7 m/s) plume leaving the ALH tailrace (Golder 2014b). High-rated sturgeon spawning substrates with appropriate interstitial spaces have been observed within 500 m of ALH and generally coincided with higher bottom velocities (Golder 2014b). It was concluded that the area within 400 m of the ALH tailrace provided suitable spawning habitat for White Sturgeon based on known spawning activity and the depth, velocity and substrate conditions evaluated (Golder 2014b).

Kinnaird (rkm 12.8 to 18.2) – Larvae have been collected when water temperatures were between 13°C to 19°C at mean water depths between 4 and 7 m (BC Hydro 2015b, 2016, 2017b). Information on water velocity and substrates at the Kinnaird spawning sites were not available for this review. Note that the entire LCR riverbed has been mapped with sidescan sonar and delineated habitat into 10 acoustic classes; these classes have not been ground-truthed to produce final substrate maps (BC Hydro 2017a).

Waneta (rkm 56.0) – Based on an analysis of egg distributions on egg mats placed in the Waneta area from 2000 to 2005, results of a 3D numerical model of the Waneta spawning area indicated that over 95% of the eggs were situated in areas with near-bottom flow velocities >1.0 m/s over the entire egg incubation period (Hildebrand and Parsley 2013). Eggs and larvae have been collected when water temperatures were between 10°C and 22°C at mean water depths of between 4 and 8 m (BC Hydro 2015b, 2016, 2017b). Substrates at an approximate 170 m long section of stream length within the main egg deposition area near the shore were characterized in March 2016 as coarse gravel and generally free of fine sediment (Fissel *et al.* 2017). There is active and ongoing erosion of the over-steepened slope adjacent to the Waneta spawning area and Fissel *et al.* (2017) indicated that this likely introduces substantial gravel and sand to the area on an annual basis during high PDO flows. Modelling indicated that total annual Columbia River fine sediment deposition was approximately 18-90 mm for a typical flow year and 24-120 mm for a low PDO flow year; the large range was due to limited suspended sediment observations and from modelling uncertainties (Fissel *et al.* 2017). The model-derived estimates of erosion under freshet flows suggested that much of the coarse sediment substrates would be disturbed and eroded; although the model may overestimate the disturbance and erosion of very coarse particles (pebbles, cobbles and boulders) by a factor of 5-10 (Fissel *et al.* 2017). Overall, the deposition of Columbia River fine sediments that occurs much of the year under low PDO flows appears to be less than the capacity of the larger PDO freshet discharges to remove these deposited sediments (Fissel *et al.* 2017). This implies that while there are fine sediments being deposited over the spawning area, they are removed during freshet although the quantity of sediment and when it occurs remains unknown (Fissel *et al.* 2017).

2.5. Sturgeon Habitat Restoration Examples Applicable to the LCR

Given that the White Sturgeon population in the LCR is unable to sustain itself, habitat restoration here will require rejuvenation or re-creation or a combination of these two approaches as outlined in McAdam *et al.* (2018). Below is a high-level overview of some specific restoration examples that may be applicable to the LCR. These include examples that focus on site-scale restoration of substrates for spawning and early life history requirements (Columbia and Nechako rivers White Sturgeon; Lake Sturgeon Spawning Reefs), reach-scale restoration actions that consider habitat connectivity, flow and flow regimes, channel hydraulics and complexity, and temperature (Kootenai River White Sturgeon), and the re-creation of Lake Sturgeon spawning habitat adjacent to historical areas (Lake Sturgeon Rupert River Hydro Quebec).

Columbia River Revelstoke Reach Substrate Enhancement – Crossman and Hildebrand (2012) modified existing armoured riverbed conditions within the only known spawning site in the Revelstoke Reach of the upper Columbia River located 6 km downstream of Revelstoke Dam as current habitat conditions are considered unsuitable for egg incubation and early larval hiding. A mixture of larger and smaller angular rock was used to increase substrate complexity and provide interstitial spaces for egg settlement and for larvae to hide. The rock was placed in an area 100 m in length, 10 m wide and 0.6 m thick within the river thalweg below the minimum water level to avoid dewatering of eggs or larvae. The rock material used was considerably larger and the enhanced area was smaller when compared to other similar field studies (see references cited in Crossman and Hildebrand 2012). Overall, Crossman and Hildebrand (2012) demonstrated that larvae released over the placed substrates showed a greater tendency to hide, remained in the substrate regardless of the flow conditions, and dispersed downstream volitionally compared to the control site. Visual assessments of the substrate after 9 months showed that conditions appeared unchanged but after 1.5 years the modified substrates were widely dispersed downstream of the original location due to the high water velocities below Revelstoke Dam, a load-following facility (Crossman and Hildebrand 2012). McAdam *et al.* (2018) noted that this study demonstrates the importance of a thorough evaluation of the site-specific hydraulics on substrate retention and maintenance prior to construction, since the highly variable flow regime in the study area resulted in the downstream displacement of restored substrate.

Nechako River Substrate Enhancement & Substrate Cleaning – In-river physical enhancement of spawning substrates for Nechako White Sturgeon has been completed within two areas (each having 2,100 m^3 in volume and 0.3 m depth) of the Vanderhoof spawning reach (NHC 2013, McAdam 2017, McAdam *et al.* 2018). The substrate mixture was designed to be physically stable and provide interstitial habitat suitable for yolk-sac larvae (McAdam *et al.* 2018). Enhancement areas have been monitored for infilling (e.g., NHC 2013), and use by spawning White Sturgeon (McAdam 2017). Due to the difficulty in ascertaining actual spawning and early life history survival, additional biological monitoring is occurring to determine success (McAdam *et al.* 2018). Cleaning experiments via mechanical substrate scarification have also been conducted due to infilling at one of the sites (NHC 2013, NHC 2017, McAdam 2017).

Results of biological monitoring conducted after habitat augmentation (2011) have shown that White Sturgeon have been detected in the area of the two enhanced spawning areas during the spawning period although detections have not occurred in all years at one of the enhancement areas (McAdam 2017). It should be noted that spawning and egg collection has also been observed within the Vanderhoof spawning reach in non-remediated sites indicating that fish are not necessarily attracted to the enhancement areas. Larval sampling has captured older larvae subsequent to the 2011 gravel additional experiment, although the numbers of captured larvae continue to be low (McAdam 2017). Juvenile-specific sampling has captured wild juveniles that were thought to be produced from the 2011 brood-year and it has been inferred that this may be recruitment in response to the substrate augmentation program conducted in 2011 (McAdam 2017; McAdam *et al.* 2018); results are still pending for substrate cleaning (NHC 2017; McAdam *et al.* 2018). Additional studies are planned to further confirm these observations. This project highlighted the trade-offs between constructing habitat where White Sturgeon currently spawn, or where high-quality spawning habitat could be created. The results of the study suggest that spawning site selection does not necessarily correlate with the best spawning material, which could indicate that enhancing existing spawning areas could be more successful than creating new spawning areas.

Lake Sturgeon Spawning Reefs – Spawning habitat for lake sturgeon (*A. fulvescens*) in several areas throughout their range has been improved through construction of artificial spawning reefs using rip-rap, natural rock, and broken limestone (e.g., Roseman *et al.* 2011; Johnson *et al.* 2006; Folz and Meyers 1985). Roseman *et al.* (2011) suggested that ideally, spawning beds could have been given a wedge shape with thin leading edges oriented upstream to maximize hydraulic pressure on the face of each bed to facilitate scouring of fines during higher flows. Boulders have been placed downstream of some artificial spawning reefs to provide current breaks designed to attract spawn-ready fish. McAdam *et al.* (2018) also indicated that one of the key lessons learned from the various Lake Sturgeon habitat remediation projects is the need for a long term, comprehensive monitoring of physical changes in the restored areas and the biological effects. They also indicated the optimum number, location and size of restored spawning sites are important considerations when knowledge of present and historical use is limited (McAdam *et al.* 2018).

Kootenai River Habitat Restoration Program - This is an ongoing large-scale ecosystem-based river habitat restoration effort begun in 2009 and to be implemented over a period of 10-15 years across an 88 km reach of the Kootenai River in northern Idaho. The effort is expected to benefit multiple fish and wildlife species, including endangered Kootenai River White Sturgeon, by addressing limiting factors through active restoration or changes in management. Limiting factors include stream morphology, riparian vegetation, aquatic habitat, and constraints related to river and floodplain stewardship. Restoration techniques include:

- Excavation or dredging to create additional depth in specific areas, or to change the water velocity;
- Regrading of river banks to prevent erosion and encourage plant growth;
- Construction or enhancement of floodplain areas to store sediment and restore riparian vegetation, as well as revegetation of floodplains;

- Construction or enhancement of wetlands to help filter and store sediments, supply nutrients, and create habitat;
- Construction, enhancement or reconnection of side channels to provide habitat for fish, reduce sediment and reconnect floodplains;
- Installation of bank structures such as bioengineering, large woody debris, and sod and wood toe structures to prevent or reduce bank erosion, and to facilitate development of bank vegetation; and
- Installation of instream structures such as boulders, logs or pilings to redirect flow to protect banks, create pools, and alter hydraulics.

Work completed in 2015 included construction of two islands and excavation of two pools. Work completed in 2016 included excavation of a pool where an existing gravel bar and eroding island existed and the construction of two large pool-forming structures, wood structures and construction of floodplains. The pools provide places for White Sturgeon and other fish to rest and feed. The chain of multiple pools also creates a deeper channel that may help White Sturgeon migrate upstream to areas where better spawning habitat is available. The pool-forming structures help to redirect flows away from the river bank and also create eddies and other complex habitat used by fish. Work completed in 2018 included the construction of two rock structures that extend into the river from the river bank. These rock structures will redirect river flows to create habitat complexity for fish. Rock was also placed on the river bottom using a barge to provide surfaces for White Sturgeon eggs to stick, and interstitial spaces between the rocks where larvae can hide.

Additional information can be found at http://restoringthekootenai.org

Lake Sturgeon - Rupert River Hydro Quebec Projects – Impacts to Lake Sturgeon spawning habitat by construction of two powerhouses on the Rupert River were addressed via flow regimes, weirs and a physical spur to maintain water elevations, and construction of fish passage channels and spawning grounds. A 2,060 m^2 spawning ground composed of two plateaus (6 m x 86 m) connected by a 12 m long slope with an 8% gradient (McAdam *et al.* 2018). The restoration included about 40 rock islets made up of 3-4 boulders to provide shelter from the current (McAdam *et al.* 2018). Monitoring of physical conditions (depths and velocities) from 2011 to 2014 showed that design criteria were met, physical integrity of the grounds were maintained, and the site was used by spawning Lake Sturgeon. Future monitoring to demonstrate juvenile recruitment is planned although the results based on adult, egg and larval monitoring demonstrate that the in-stream flow regime and constructed spawning grounds at this site have effectively preserved Lake Sturgeon spawning habitat (McAdam *et al.* 2018). The constructed design integrates various flow regimes and includes keeping the area dewatered outside of the spawning season which prevents infilling. This project highlights the need for integrating various flow conditions as part of the construction design and future maintenance regime.

3. SUMMARY OF WORKSHOP ONE

A workshop was held May 13-14, 2019 to identify restoration alternatives and develop performance measures (PMs) to compare and prioritize alternatives. Workshop participants are listed in Table 1. The workshop participants were presented with summaries of preliminary field data and modelling results, including substrate classification, hydrodynamic model simulations, habitat suitability modelling, and sediment transport modelling. The participants provided recommendations for additional field data and analysis to help with prioritization of alternatives prior to Workshop Two planned for February 2020.

The following subsections describe the restoration alternatives selected and the additional field data collection and analysis recommended by workshop participants.

Table 1. Participants at Workshop One held from May 13-14, 2019.

Workshop Participant	Affiliation	Dates Attended[1]
Dean Watts	DFO	May 13-14
Erin Gertzen	DFO	May 13
Steve McAdam	FLNRORD	May 13-14
Will Warnock	FLNRORD	May 13-14
Simon Gauthier-Fauteux	FLNRORD, NHC	May 13
Vahab Pourfaraj	FLNRORD	May 13
Andre Zimmerman	NHC, UBC	May 14
David De Rosa	ONA	May 13-14
Misun Kang	KNC	May 13-14
Robyn Laubman	Secwepemc	May 13
Wendy Horan	CPC	May 13-14
René Dion	Hydro Quebec	May 13-14
James Crossman	BC Hydro	May 13-14
Katy Jay	BC Hydro	May 13-14
Margo Sadler	BC Hydro	May 13-14
Todd Hatfield	Ecofish Research Ltd.	May 13-14
David West	Ecofish Research Ltd.	May 13-14
Mike Parsley	Consultant (USGS retired)	May 13-14
Toby Perkins	Knight Piesold Ltd.	May 13-14

1. 2019

3.1. Selection of Restoration Alternatives

Example sturgeon restoration alternatives were presented during Workshop One, including substrate placement on Columbia River near Revelstoke, BC, on Nechako River near Vanderhoof, BC, and on a series of rivers in Quebec. The treatment on Nechako River also included cleaning of the placed substrate a few years after placement. Participants then brainstormed alternatives for each spawning location in the LCR. The size of footprint and specific location of each alternative was guided by professional judgement and preliminary field data and modelling, with the intention of refining the alternatives using Task 4 analysis. Selection of appropriate locations for restoration considered existing spawning areas, hydraulic conditions, existing substrate, and sediment transport characteristics. When the initial alternatives were defined, they were grouped into one of three tiers: Tier 1 – high potential, Tier 2 – moderate potential, and Tier 3 – unfeasible at this time. All PMs were quantified for Tier 1 alternatives; simple PMs were quantified for Tier 2 alternatives; and Tier 3 alternatives were omitted from further assessment. A summary of the selected alternatives and associated notes from Workshop One are provided Table 2.

During the workshop, it was determined that Keenleyside was the location where spawning habitat restoration was most likely to be biologically successful and technically feasible. This was a result of the area being used only intermittently for spawning, as opposed to annual spawning at Kinnaird and Waneta, and the alternatives for enhancing and extending the current spawning habitat being less complex than the other two locations. The top three alternatives for Keenleyside consisted of placement of a mixed-composition rock substrate with mobile and immobile sizes. The placement would cover and/or extend the current egg deposition zone (EDZ) and a section downstream of the EDZ (referred to hereafter as EDZ DS).

Placement of smaller, moderately mobile gravel was also considered, with the intent of promoting substrate mobilization and flushing of fines on an approximately annual basis. Substrate cleaning was also considered, via expelling fines from the existing substrate using a raking-like mechanism or injection of pressurized air or water.

Since Waneta is the main spawning site for the LCR, it was determined that proof of concept (e.g., implementation of one of the Keenleyside alternatives) may be required prior to further consideration of restoration for this location. Smaller tests of scour and subsequent infilling were discussed, along with the idea of creating spawning habitat adjacent to the existing EDZ. It was decided that placement of spawning substrate immediately upstream of the primary EDZ should undergo detailed evaluation as part of Task 4.

The geometry of each alternative was decided based on input from workshop participants. A similar thickness of placement material was proposed for each alternative, consisting of 600 mm or two times the thickness of the largest grain size (similar to Crossman and Hildebrand 2012). Workshop participants noted that a thicker substrate placement could increase the risk of larval White Sturgeon becoming trapped in the substrate. The topography of the placement alternatives consists of a uniform surface, rather than a varied geometry such as that applied at Rupert River (Dion, pers comm. 2019). A simplified geometry will limit the potential for backwatering of the ALH and the confluence of PDO tailraces, while still providing hydraulic variability due to the natural slope of the channel bed.

Various alternatives were discussed for Kinnaird but it was decided to omit these alternatives from detailed evaluation due to uncertainty of EDZs and concerns of technical feasibility. It was decided that more field monitoring is required to determine EDZ locations at Kinnaird. Therefore, only limited data and analysis are presented for Kinnaird in the following sections.

Table 2. Summary of restoration alternatives identified in Workshop One.

Rank	Brief Description	Site[1]	Discussion notes from May 2019 Workshop
	Tier 1		
1	Ideal sturgeon substrate placement at EDZ DS (immediately downstream of egg deposition zone)	ALH	· Large risk to current fish when constructing (applies to all placement options) · Risk of infilling with sand considering that current area has sand in interstitial spaces (applies to all placement options) · Spawning currently occurs but not fully functional.
2	Ideal sturgeon substrate placement at EDZ and EDZ DS	ALH	· See details for Option 1 and 3
3	Ideal sturgeon substrate placement at EDZ	ALH	· Risky to existing spawners
4	Substrate Cleaning at EDZ and EDZ DS	ALH	· May result in loss of existing quality material · Cleaning has been shown to be helpful in Nechako · Uncertain how to clean, how to keep desired substrate in, how to measure substrate leaving · Large risk to current fish when constructing (applies to all options) · Uncertain what substrate is beneath surface.
5	Gravel Placement at EDZ and EDZ DS	ALH	· Could be same benefits as placement · Larvae will benefit but egg won't if substrate is too small · May wash out too quickly before spawning occurs, since spawning does not occur each year · Added complexity could benefit spawning/egg deposition and improve incubation and hiding conditions · Possibility to select a size that will move at ideal frequency
6	Ideal sturgeon substrate placement at Waneta restoration area (upper extent of EDZ adjacent to river left failing slope)	WAN	· High likelihood of fines infilling · Risks of covering sculpin and small mouth bass habitat · Fish are spawning there already · Intergovernmental issues with transport of placed material over border

[1] ALH = Arrow Lakes Generating Station; WAN = Waneta; KIN = Kinnaird.

Table 2. Continued.

Rank	Brief Description	Site[1]	Discussion notes from May 2019 Workshop
	Tier 2		
7	Flow deflector in ALH tailrace	ALH	· Backwater concerns with ALH tailrace
8	Rock placement at HLK tailrace	ALH	· Risk of sand infilling · Moderate uncertainty of whether sturgeon will begin using this location to spawn.
9	Rock augmentation downstream on left bank	WAN	· Already gravel supply from eroding slope · Intergovernmental issues with transport of placed material over border
10	Multiple small rock placements with controls	KIN	· Uncertainty of where sturgeon currently spawn, requires further analysis
11	One large rock placement near bridge	KIN	· Potential to impact existing rainbow trout habitat · Constructability limited by high velocity and depth · Place material may easily transport along the bed due to low roughness / high embeddedness · Uncertainty of where sturgeon currently spawn
12	Rock augmentation near bridge	KIN	· Material would be too dispersed, requires large quantity · Could transport right through reach and deposit in non-spawning areas · Risk to current rainbow trout populations · Easy to implement
13	Substrate cleaning	KIN	· challenging to clean with depth and velocity · Uncertainty of where to clean · Substrate may be too embedded to dislodge
	Tier 3		
14	Extend groyne on river right of ALH tailrace	ALH	· Likely too many hurdles to implementation due to affects to dam operations and existing fish habitat.
15	Rock augmentation by PDO bridge	WAN	· Too far for substrate to travel, would disperse · Intergovernmental issues with transport of placed material over border
16	Substrate cleaning	WAN	· Risk of slag mobilization and loss of existing high quality material · Uncertain how to clean, how to keep desired substrate in, how to measure substrate leaving · Constructability challenges due to side slope · Intergovernmental issues with transport of placed material over border

[1] ALH = Arrow Lakes Generating Station; WAN = Waneta; KIN = Kinnaird.

3.2. Requested Additional Field Data Collection and Analysis During Workshop One

During the May 2019 workshop, data collected to calibrate hydrodynamic models and characterize existing habitat conditions were presented. Participants reviewed existing conditions, data resolution, and types of information, and it was determined that additional data collection during summer/fall of 2019 would be beneficial to models and to develop a better understanding of existing conditions.

A key conclusion from the workshop was that a clear understanding of existing substrate conditions is crucial to development of successful restoration alternatives. Review of sample images indicated that existing substrate condition appears suitable in many locations within the proposed restoration areas, which indicates possibly limited benefits of the proposed restoration actions. It was decided that additional images should be collected in and near the specific restoration areas, and that substrate images from each field trip in these areas should be re-examined to extract more qualitative and quantitative information about rearing suitability and transport conditions. The requested additional information to be captured included armouring, roughness, fines percentage, general rearing suitability, and degree of fouling. It was recommended that a sturgeon expert should assign scores for each of these metrics for each image and also confirm embeddedness scores completed during Task 2.

Sediment transport was deemed to be extremely important and it was decided that grain size distribution should be calculated within and near the restoration areas, as well as qualitative assessment of evidence of recent transport. The grain size distribution and fines percentage would allow the application of a sediment transport model that can assess transport of specific grain size classes by accounting for the effects of interactions between grains of different sizes on sediment stability, such as fine material hiding and coarse material interlocking (Wilcock and Crowe 2003). Furthermore, it was decided that additional substrate images in the proposed restoration areas and EDZs would be helpful for detecting changes between 2018 and 2019.

Although not specifically defined during the workshop, additional flow simulations were recommended to identify worst-case conditions for scour and deposition and thresholds for sediment transport. These simulations were also expected to allow for refinement and optimization of the restoration alternatives to promote longevity. Collection of additional hydraulic data was also recommended to confirm accuracy of the hydrodynamic model during typical spawning conditions.

Participants at the meeting noted that it would be useful to determine the materials embedding the coarse material (e.g., silt, sand, gravel). Such an assessment would require a sample at depth within the substrate (e.g., freeze core). Sampling of this nature was considered to be unfeasible for this project given the water depth and large substrate size.

4. METHODS

The following methods include details related to the initial habitat characterization for Task 2, and the evaluation of restoration alternatives for Task 4. The materials prepared for Task 2 included preliminary hydrodynamic and sediment transport modelling results to help guide the selection of restoration alternatives. During Task 4, these preliminary results were refined using additional field data and more robust analysis methods. Methodology during Task 4 was guided by outcomes from the Task 3 (first) workshop. Additional analysis was also completed following Workshop Two to refine the details of the recommended alternatives. To simplify the presentation of field data collection and analysis, the components from Task 2, Task 4, and Task 6 have been integrated in the following sections.

4.1. Field Data Collection

4.1.1. Overview

Field data were collected during the summer and autumn of 2018 to 2019 over four field trips to assess physical habitat conditions and to parameterize and calibrate hydrodynamic and sediment transport models. A summary of the data collection during each trip is provided below.

- **Field Trip 1 (FT1)** – July 5-7, 2018 – High flows and spawning conditions: hydraulics, bedload transport, substrate conditions, and discharge measurements collected.
- **Field Trip 2 (FT2)** – August 14-16, 2018 – High/Moderate flows and spawning conditions: bathymetry, bedload transport, substrate conditions, and discharge.
- **Field Trip 3 (FT3)** – October 31 - November 2, 2018 – Low flows and rearing conditions: hydraulics, bedload transport, substrate conditions, discharge, ground based sediment sampling, and tracer stone placement.
- **Field Trip 4 (FT4)** – August 27-28, 2019 – Tracer stone retrieval, substrate conditions and hydraulics.

Field sampling focused on the three White Sturgeon spawning areas identified by BC Hydro, at Keenleyside, Kinnaird, and Waneta:

- **Keenleyside**: A 1.2 km section located immediately downstream from the Keenleyside Dam;
- **Kinnaird**: A 6.7 km section in the vicinity of Castlegar, BC; and
- **Waneta**: A 1.4 km section located immediately upstream from the Canada/USA international border and including the confluence of Pend d'Oreille River (PDO).

An overview map of the three study areas is provided in Map 1. The following subsections include a brief description of the methods for each of the field sampling activities.

4.1.2. Bathymetry

Bathymetry data were collected by Grant Land Surveying Inc. (GLS) during Field Trip 2. Based on early discussions with staff at the Comptroller of Water Rights it was decided that there was value in collecting an accurately georeferenced dataset that could be utilized for future studies. Each of the three study areas was surveyed with a horizontal resolution of approximately 4 - 6 m. GLS provided a registered BC Land Surveyor to complete this component of the data collection. A report describing the survey and processing methodology was prepared by GLS (Appendix B). Maps of the bathymetry are also provided in Appendix B. The development of surface topography and integration of terrestrial lidar data is described in Section 4.3.2.

4.1.3. Hydraulic Sampling

Hydraulic data was collected during Field Trip 1, Field Trip 3 and Field Trip 4. Depth, velocity, and discharge were collected with a Sontek M9 Acoustic Doppler Current Profiler (ADCP) and referenced to geodetic coordinates and an appropriate datum for comparison to existing datasets. The ADCP was attached to the boat via a cantilevered boom. Georeferencing was completed using the Sontek M9 built-in DGPS system, which is expected to have sub-meter accuracy. ADCP measured depth was added to the bathymetry data to determine water surface elevation in order to calibrate the hydrodynamic model. ADCP measured velocities were also used to calibrate the velocity distribution in the hydrodynamic model.

Discharge was extracted from the ADCP hydraulics transects that were completed in locations with ideal conditions for discharge measurement. The discharge measurements were compared against Water Survey of Canada (WSC), United States Geological Survey (USGS) gauging stations and gauge data from HLK, ALH and Waneta.

4.1.4. Substrate Surveys

Bathymetric substrate surveys were completed during each field trip. The objectives of substrate surveys were to characterize the current conditions across each study area. Substrate characteristics of interest included the dominant and subdominant substrate type, embeddedness, grain size distribution, roughness, armouring, evidence of recent transport, and the distribution of fines. These classifications were used to characterize the existing geomorphic conditions across each study area and identify areas that could be enhanced through restoration to support early life stages of White Sturgeon.

An underwater GoPro camera was used to capture and record substrate video throughout each study area. A custom weighting system was developed to provide stability in high-velocity conditions. This system consisted of a downrigger with the camera suspended at a fixed elevation above a heavy weight. During the four field trips, over 25 hrs of video was collected across a cumulative track extending over 100 km in length throughout Keenleyside, Kinnaird and Waneta. These videos were then converted to image still frames to facilitate efficient classification. A DGPS unit was used to georeference and link imagery from the GoPro based on a synchronized timestamp. Over 5,500 substrate annotations were made across the study area.

Substrate video surveys were collected with the duel intent of characterizing general conditions across each of the three study areas and providing detailed surveys of substrate habitat within the known spawning and proposed restoration areas. Survey efforts therefore targeted certain areas more intensively (see maps in Appendix B). Some locations were sampled multiple times over the four field trips in an attempt to assess short-term changes between seasons.

4.1.5. Ground-Based Sampling

During field trip 3 when flows were low, ground-based sediment sampling was conducted along dewatered bed areas. The ground-based sediment sampling consisted of Wolman pebble counts at distinct locations within each study reach. Two Wolman counts were performed at Keenleyside and Kinnaird and three were performed at Waneta. Wolman counts were collected by sampling stones along a 30 m tape at intervals of 0.5 m or 1 m, moving the tape up the shoreline once complete until at least 100 stones were measured. Grain sizes were binned into ½ Phi class sizes and used to calculate cumulative grain size distributions. At each sampling location, vertical images of bed material were also taken from 1.6 m above the bed within a 1 m x 1 m frame for scale reference. Ten images were taken for each Wolman count location, spaced 2.5 m – 3 m apart along the 30 m tape. Following these images, subsurface grab samples were also collected at three of the ten image locations by removing the coarse surface materials and collecting 1 kg samples of bulk sediment mixture for analysis of sand, silt, and clay content within the subsurface matrix. A detailed description of the data collection procedures and results of the ground-based bed material sampling is provided in Appendix A.

4.1.6. Sediment Transport Observations

4.1.6.1. Tracer Stones

During field trip 3, tracer stone transects were established near the shoreline at one location in each of the three study reaches. A total of 25 tracer stones were placed at Keenleyside and Kinnaird, and five tracer stones at Waneta. Stones from each location were painted white and placed in transects perpendicular to the shore. The size of stones selected included samples from the median size class in terms of B-axis width, and one size class above and below the median. Median sizes classes for Keenleyside, Kinnaird, and Waneta were 85 mm, 90 mm, and 260 mm respectively. Tracers were re-assessed August 27-28, 2019 (FT4) for evidence of movement indicating that transport had occurred throughout the period. Additional details and images of tracer stone deployments are provided in Appendix A. Details of secondary sources of sediment transport evidence are discussed in the following section.

4.2. Substrate Characteristics

Underwater imagery and videos were manually annotated and classified to generate spatial maps of various substrate characteristics for each area. Each image (or video frame) was georeferenced with a Differential-GPS unit so that substrate data could be linked to bathymetry and other spatial datasets. Various stages of review were undertaken to provide basic substrate attributes over large areas (for mapping) and detailed substrate annotations with additional attributes for selected restoration areas. Basic substrate attributes included a description of the dominant and subdominant substrate type as well as an average embeddedness score. Detailed substrate attributes included characterization of armoring evidence, fine deposition, evidence of recent transport, roughness and an overall qualitative characterization of the general rearing suitability. For selected locations, grain size distribution was also estimated. These annotations will assist with specific restoration alternatives.

4.2.1. Dominant and Subdominant Substrate

Dominant and subdominant substrate classes were visually assigned to substrate imagery for Keenleyside, Kinnaird and Waneta. This process involved reviewing imagery and then qualitatively assigning a grain size class according to size bins in Table 3. A down-rigger weight was visible in the image frame to provide a reference of scale. The purpose of this exercise was to generate coarse-scale maps of the substrate type across the entirety of the study areas (Appendix C). This data was then used as input for habitat suitability modelling, preliminary validation of sediment transport models and overall assessment of current conditions.

Table 3. Dominant and subdominant substrate classes used to characterize current conditions of Keenleyside, Kinnaird and Waneta.

Substrate Classification	Grain Size (mm)
(i) Impermeable	NULL
(b) Boulder	> 256
(c) Cobble	64 - 256
(cg) Coarse Gravel	16 - 64
(mg) Medium Gravel	4 - 16
(fg) Fine Gravel	2 - 4
(ff) Fines (sand/silt/mud)	< 2

4.2.2. Substrate Embeddedness

Substrate embeddedness was qualitatively assigned to substrate imagery across Keenleyside, Kinnaird and Waneta. Embeddedness classes were characterized from low to high according to Table 4. These embeddedness classes were previously developed to reflect White Sturgeon spawning and recruitment habitat in other areas of the Columbia River (Hatten *et al.* 2018). These classifications consider embeddedness as the portion of interstitial spaces covered by fines or otherwise theoretically unavailable to White Sturgeon eggs, larvae and other early life stages.

Table 4. Substrate Embeddedness Classification from Underwater Camera Imagery.

Class	Embeddedness Amounts
0 - Negligible	<5% of interstitial spaces covered by fines
1 - Low	6-25% of interstitial spaces covered by fines
2 - Moderate	26-50% of interstitial spaces covered by fines
3 - High	51-75% of interstitial spaces covered by fines
4 - Very High	>75% of interstitial spaces covered by fines
5 - N/A	Continuous fines

The classification of substrate embeddedness from imagery is inherently a subjective process and standardized methods are not available. We therefore relied on individuals with specific White Sturgeon habitat expertise and other biologists to describe typical conditions of each embeddedness class from Table 4. Several training sessions were held on standard imagery classification protocols with representative image sets for each embeddedness class (Figure 7 to Figure 10). During Task 2, one individual assigned embeddedness scores to the entirety of the substrate video collection to maintain consistency across study areas and surveys periods (approximately 25 hours and 5,638 image annotations). Two other White Sturgeon habitat experts assigned embeddedness scores to imagery from a smaller subset of the substrate video collection to assess consistency among categories and between individuals (n = 30 to 200 image annotations). Details of the uncertainty assessment are provided in Section 6.2.6. Detailed maps of all embeddedness classification points from Task 2 are provided in Appendix D. During Task 4, The White Sturgeon expert team re-classified embeddedness scores within and in the vicinity of the restoration areas for each of the Tier 1 alternatives, which included 229 images.

Figure 7. Sample embeddedness conditions for Class 1: Low Embeddedness.

Figure 8. Sample embeddedness conditions for Class 2: Moderate Embeddedness.

Figure 9. Sample embeddedness conditions for Class 3: High Embeddedness.

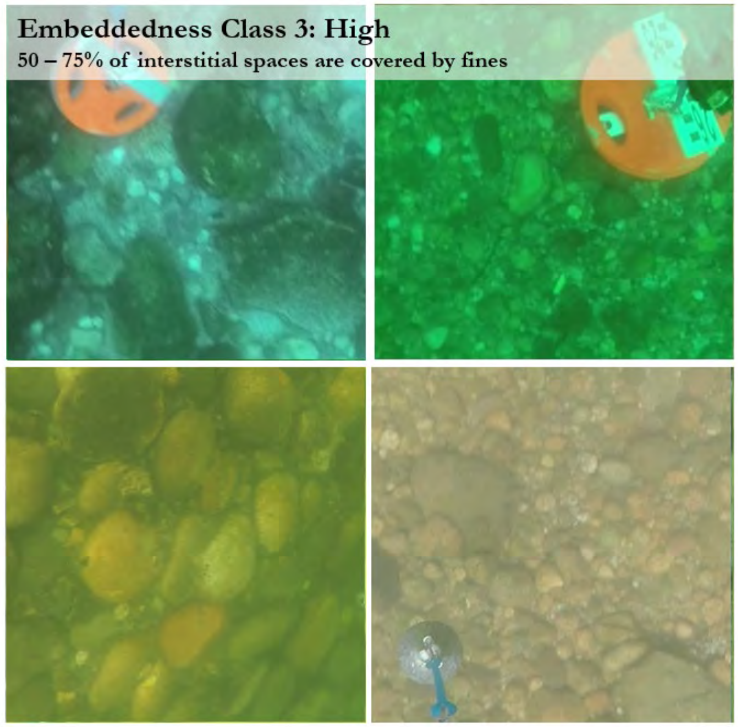
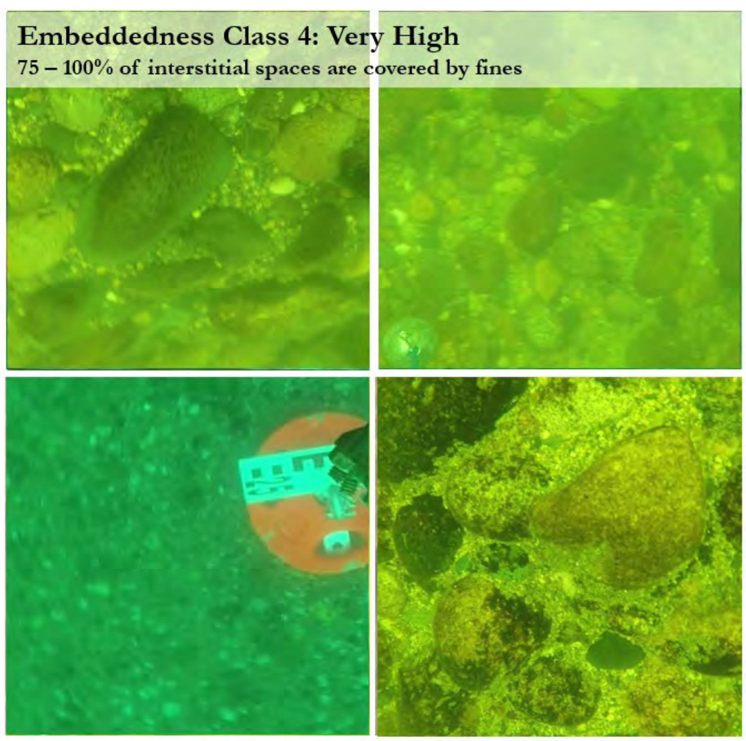


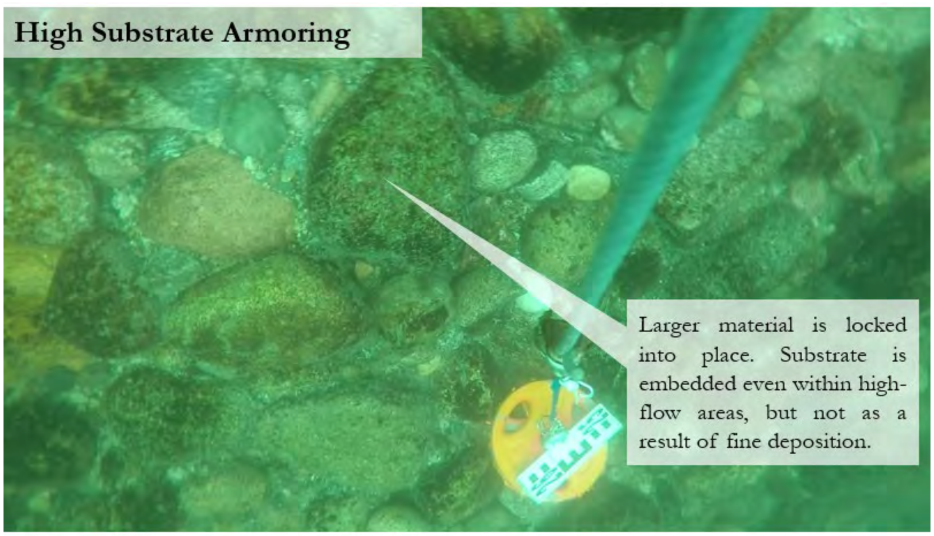
Figure 10. Sample embeddedness conditions for Class 4: Very High Embeddedness.



4.2.3. Substrate Armoring

Substrate armoring (or bed armoring) was defined as the interlocking of boulders, cobble and other materials under sustained flows to produce a substrate surface that is resistant to entrainment. It should be noted that the definition for armouring can vary amongst the geomorphology community, and it could be argued that this parameter should be referred to as compaction. Heavily armored substrates are often considered to be highly embedded, but not as a result of the deposition of fines. Substrate armoring condition was annotated for the 229 images assessed during Task 4 near the restoration areas of Keenleyside and Waneta. Evidence of substrate armoring was recorded as 0 for 'no armoring' or 1 for 'armoring present'. Figure 11 shows an example of severe substrate armoring, but it should be noted that most cases of substrate armoring were less severe and occasionally existed as armoring between cobble and boulders with low embeddedness (potentially still suitable habitat for early life stages of White Sturgeon).

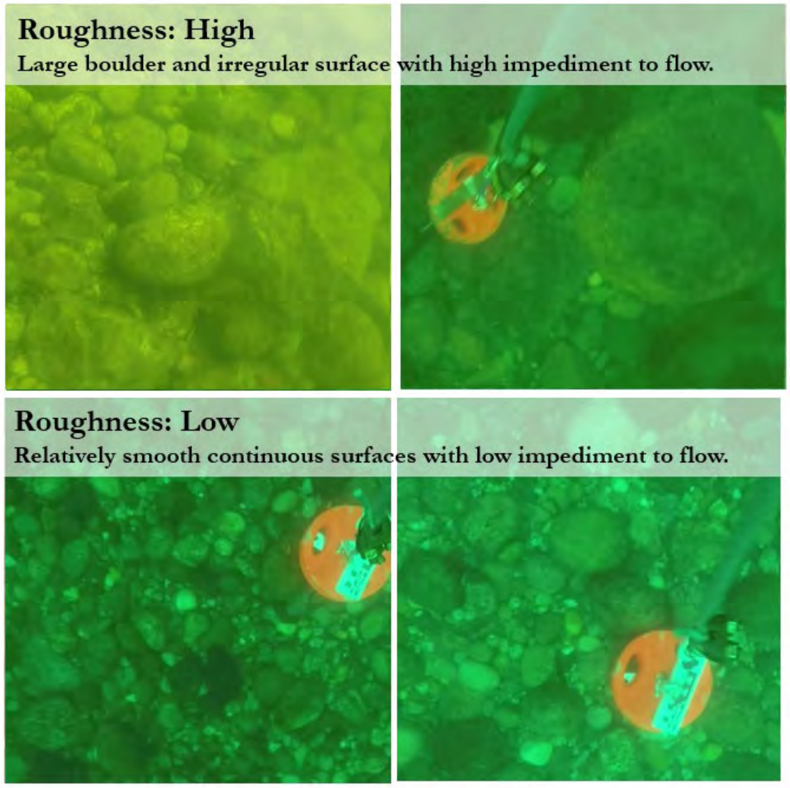
Figure 11. Example of a high substrate armoring.



4.2.4. Substrate Roughness

Substrate roughness was considered as an important attribute of current conditions that could influence the habitat suitability for early life stages White Sturgeon. High roughness was characterized as locations with irregular surfaces of boulder, cobble and other material that could reduce bottom velocities and enhance rearing habitats (Figure 12). In contrast, low roughness was characterized as locations with flat or continuous surfaces of cobble, gravel and other smaller material that would provide little impediment to flows. Substrate roughness was qualitatively characterized as Low, Medium or High for 229 locations near the restoration areas of Keenleyside and Waneta.

Figure 12. Example of high (top row) and low (bottom row) substrate roughness.



4.2.5. Additional Substrate Characteristics

4.2.5.1. Fines Percentage

Although substrate coverage by fines is already partially accounted for in the 'embeddedness' and 'dominant/sub-dominant' substrate metrics, an additional metric was developed to help evaluate fines percentage exclusively. Fines percentage was scored as 0, 10, 50 or 100% for 229 locations across the spawning and restoration areas of Keenleyside and Waneta (Figure 13).

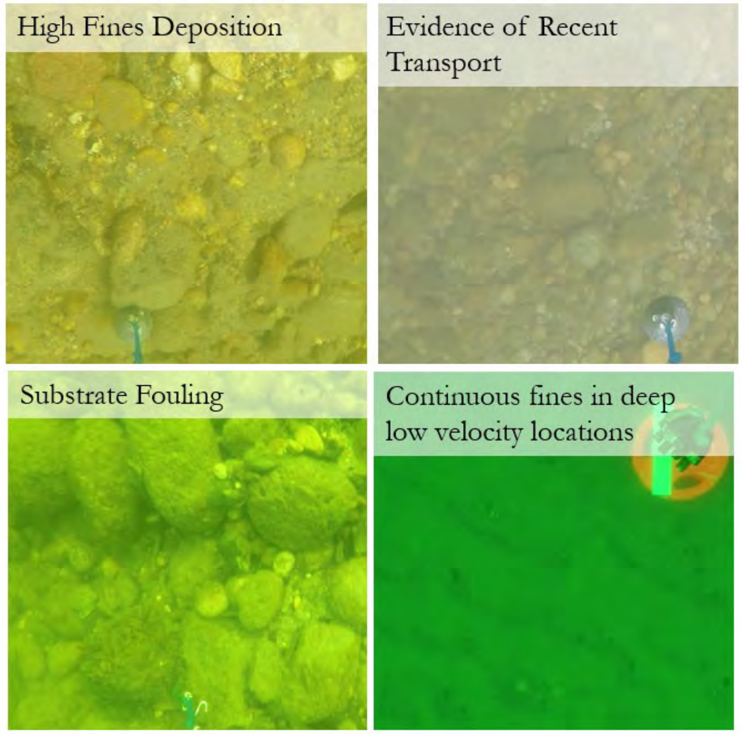
4.2.5.2. Evidence of Recent Transport

Recent transport was assumed to have occurred if stones were free of any fouling and had low embeddedness. Evidence of recent transport was annotated as 0 or 1 for 229 locations near the restoration areas of Keenleyside and Waneta (Figure 13).

4.2.5.3. Substrate Fouling

Substrate fouling by periphyton appeared to be exceedingly limited across the entirety of Keenleyside, Kinnard, and Waneta. Only a few isolated areas were identified with fouling over cobble and large boulders (Figure 13). Fouling characteristics were described anecdotally across each substrate area.

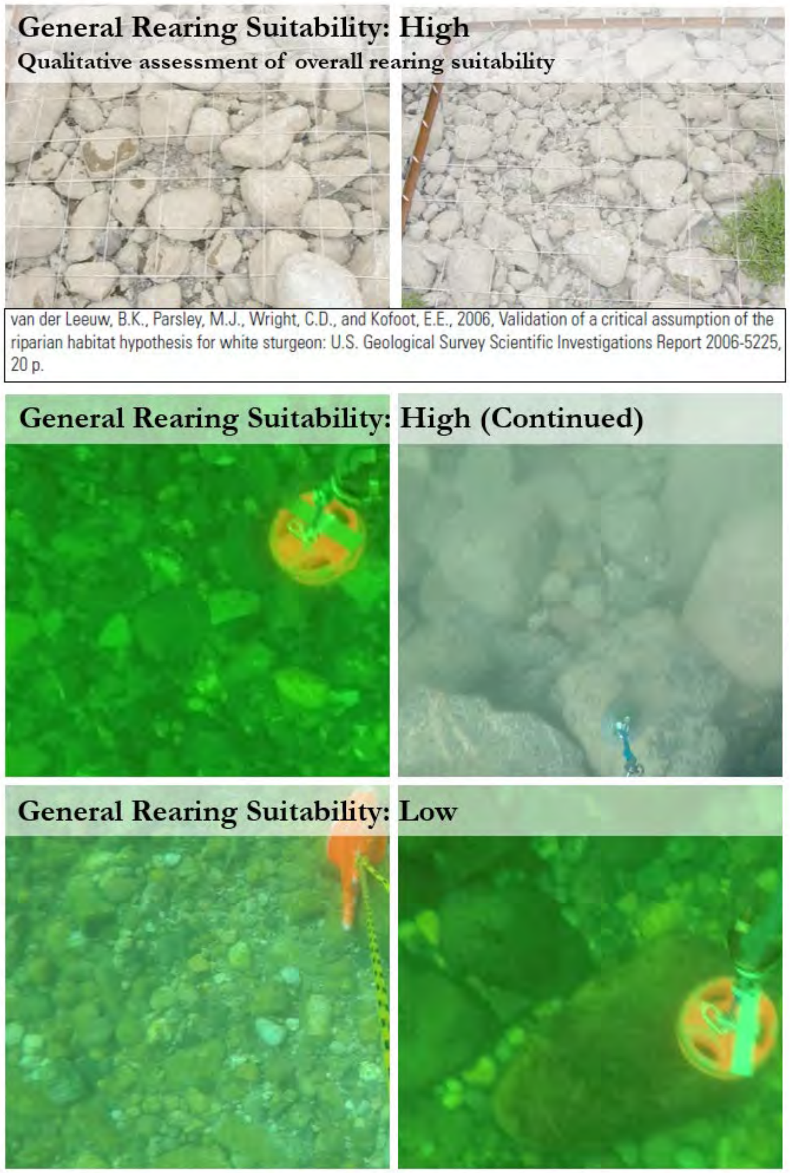
Figure 13. Examples of additional substrate characteristics.



4.2.6. General Rearing Suitability

To help synthesize substrate characteristics the general rearing suitability was assessed for 229 locations near the restoration areas of Keenleyside and Waneta. The general rearing suitability of a substrate image was qualitatively assigned as Low, Medium or High (Figure 14). This assignment jointly considered substrate type, embeddedness, armoring, roughness and other substrate characteristics. These assessments of rearing suitability consider hiding opportunities and interstitial spaces for early life stages and should not be confused with spawning habitat. The purpose for these assignments was to identify any major differences between study areas rather than providing a detailed output for mapping.

Figure 14. General rearing suitability for White Sturgeon assessed qualitatively. Top row shows suitable habitat from van der Leeuw *et al.* (2006); Middle row shows locations characterized as high rearing suitability in this study and the bottom row shows locations characterized as having low rearing suitability.



4.2.7. Area-Based Summaries of Substrate Characteristics

A key component of the substrate characterization was to assess the extent, distribution and relative quantity of different substrate conditions across the proposed and potential restoration areas at Keenleyside and Waneta. Initial attempts at creating continuous spatial classification were determined to be misleading due to the sparse distribution of points with detailed substrate attributes and the high degree of microsite variability between neighboring locations. We therefore chose to summarize detailed substrate attributes using a 10 m × 10 m grid. Annotated images were first summarized within each grid cell to account for duplicates in close proximity to each other. Grid cell values for each substrate attribute were then summarized as the proportional area coverage from the total survey extent (all grid cells) within each study area (e.g., count of grid cells showing 'evidence of recent transport' vs total grid cells assessed in study area).

4.2.8. Automated Grain Size Distribution

To provide a more quantitative understanding of substrate sizes and spatial patterns, selected images from the underwater imagery were also processed with the automated grain size distribution determination framework of Buscombe (2013). This method is based on characterizing the global power spectral density function of grey-scale pixel intensity from a given grain size image using a Morlet wavelet approach, which takes into account both the spectral and spatial information from the image. Because pixel intensity in an image of sediment is a continuous random field, a wavelet transformation can capture information on all scales of variability caused by different grain sizes. By computing power spectra for individual 1D transects (rows and columns) spaced throughout an image and averaging, a global power spectrum is calculated, which has been shown to successfully approximate the complete size distributions of grain axes without the need for manual classification or segmentation, calibration data, or large sample sizes. Buscombe (2013) tested the method on a wide range of grain size images from various sedimentary settings representing sand to cobble size materials and found root mean square errors (relative to traditional grid by number analyses) to be within tens of percent for percentiles across the entire grain size distributions. Conditions that support accurate grain size determination include an adequate sample size of individual grains visible in the image, and the ability to resolve the smallest particles of interest relative to the image resolution. Buscombe (2013) provides the wavelet method as stand-alone Python framework. Before applying the method to the underwater images from the Columbia River, a calibration analysis was performed with grain size data from ground-based sediment sampling on dry banks collected during field trip 3. For each of the three study reaches, the grain size distribution determined through Wolman pebble counts was compared to ten vertical bed material images from the same locations. This analysis allowed for a first assessment of method reliability in the conditions present on the local riverbed to account for the lack of available calibration data for underwater images themselves.

To apply the method to the video stills of bed substrate from the Columbia River, images were first selected based on several criteria for success: (1) clearly resolvable bed sediments, (2) reference object for scale visible in the image, (3) image close to vertical to avoid orthorectification issues, and (4) adequate sample size of grains visible in the image. 52 images that met these criteria were selected at Keenleyside and 36 were selected at Waneta. For each image, scale was determined by measuring the known distance from the reference object. Then, the reference object was masked out so it would not affect the wavelet calculation. The images were then batch processed with the Python script, yielding a grain size distribution for each image. Results for these images were assessed visually for a qualitative calibration in comparison with each image and it was determined that the wavelet method provides realistic measures of bed grain sizes in the underwater conditions. For each grain size distribution, the graphic standard deviation sorting index of Folk (1966) was also calculated as: $\frac{D_{84}-D_{16}}{4}+\frac{D_{95}-D_{5}}{6.6}$. Interpretations of this sorting index are shown in Table 5.

Table 5. Graphic standard deviation sorting index values (Folk 1966).

Sorting	
Very well sorted	<0.35
Well sorted	0.35 - 0.50
Moderately well sorted	0.50 - 0.70
Moderately sorted	0.70 - 1.00
Poorly sorted	1.00 - 2.00
Very poorly sorted	2.00 - 4.00
Extremely poorly sorted	> 4.00

4.3. Hydrodynamic Modelling

Hydrodynamic modelling using River2D (Steffler and Blackburn, 2002) was undertaken to generate hydraulic condition predictions at multiple flows for each of the three study areas (Keenleyside, Kinnaird, and Waneta). The purpose of the hydrodynamic modelling was to help answer major questions surrounding sediment transport, habitat suitability, current conditions, and potential future changes.

Each of the three study areas were modelled independently within the extents of the underlying high-resolution bathymetric data. Kinnaird was also subdivided into two sub-reaches (Kinnaird Upper and Kinnaird Lower), with overlap, to increase computational efficiencies. The spatial domains of the River2D modelling environments encompassed previously identified (or suspected) spawning areas and candidate areas that were believed to have restoration opportunities (Map 1).

4.3.1. River2D Description

River2D is a two-dimensional (2D) depth-averaged finite element hydrodynamic model that allows hydraulic predictions over complex surface topography. The hydraulic outputs of the model include depth, velocity, and shear velocity (a derivative of shear stress). The model outputs can also be manipulated to obtain Froude number. Model input parameters include surface topography, estimated surface roughness, inflow discharge, and the corresponding outlet water surface elevations.

4.3.2. Surface Topography Development

River2D requires detailed bathymetry in the form of a triangular mesh. The primary source of bathymetry was the high-resolution data collected by GLS (Appendix B). The GLS data were augmented with a higher resolution survey of the HWY 3 crossing region of Kinnaird provided by the Ministry of Transportation and Infrastructure (MOTI), a section of bathymetry that extended further into the Pend D'Oreille at Waneta that was provided by Teck Resources (described in Fissel *et al.* 2017) and Lidar data provided by RDCK. The Teck bathymetry data was collected before 2001 and during 2003-2004, whereas the MOTI data were collected during 2013. Bathymetric data were compiled using thin plate spline interpolation. Cross-validation error with the GLS data was less than measurement error from the instrument (0.10 m) suggesting bathymetric surveys sufficiently captured current conditions. To allow for modelling of high flows, bathymetry/topography data were required at the channel margins. Lidar data that covered down to the wetted edge at the time of data collection were provided by the Regional District of Central Kootenay (RDCK). Gaps between the Lidar and bathymetry data were infilled using linear interpolation.

The nodes that compose the mesh were set with a uniform spacing of 3 - 5 m for initial model runs, then refinements to the resolution were specified in locations with complex hydraulics (e.g., around bridge piers and near boundaries). The maximum node count of River2D and computation time requirements limited the node spacing that could be used; however, the node spacing is similar to the spacing of the bathymetry points and the scale associated with White Sturgeon habitat elements. River2D mesh elements were adjusted until the mesh quality index QI exceeded 0.5 (recommended by Steffler and Blackburn 2002). Additional nodes were added to areas within complex topography until the max element elevation difference fell below 0.3 m. The final number of nodes for each study area ranged from 46,863 to 104,065. Model calibration involved adjusting the inflow distribution, bed roughness and eddy viscosity parameters until River2D flow predictions matched reference points along ADCP transects for flow magnitude, direction and water surface elevation (WSE).

4.3.3. Boundary Water Surface Elevations

Boundary water surface elevations (WSEs) are required at the downstream extent of the River2D model domain for each flow scenario. For River2D calibration and validation runs, outlet WSEs were estimated from ADCP depth profiles and corresponding survey bathymetry. For all other simulated flow scenarios, we used either HEC-RAS model results, described in Bruce (2016), or existing gauge data provided by BC Hydro. For Keenleyside and Waneta, reference gauges at the HLK tailrace and USGS International Boundary station provided continuous water level and discharge data. These gauge records could be used for most simulations with previously observed flows. Exploratory stage-discharge rating curves were also estimated to cross-check values. Where available, WSE estimates from the ADCP surveys, gauging stations and HEC-RAS models were compared against each other to assess accuracy and uncertainty for each study area.

4.3.4. Bed Roughness

River2D uses a Keulegan roughness height layer to define boundary friction. The roughness heights can be specified as uniform value throughout the domain or varied. Roughness height can be estimated using the D85 grain size, with typical values ranging from 1 to 3 times the D85 (Steffler and Blackburn 2002). River2D roughness (ks) values were adjusted iteratively during model calibration from global reach-level values ranging from 0 to 1.50. Each model was then assessed with ADCP WSE data to determine if roughness values were either too low (high River2D velocities and lower predicted WSE) or too high, and then adjusted. Due to the water depth of each reach, adjustments to surface roughness has a minimal effect on modelled WSE performance.

4.3.5. Calibration/Validation

The parameterization of River2D models is an iterative process. Multiple parameters can be adjusted with the end goal of having hydrodynamic models match real-world observations (field data) as closely as possible across multiple flow scenarios. To prevent overfitting, we subdivided our field data into training sets (for model calibration) and testing sets (for model validation). Field trip 1 was used for model calibration (largest quantity of ADCP data) and field trip 3 and 4 were used for model validation. Separating calibration and validation to different field trips helped to ensure that models were robust and able to project to novel flow scenarios outside of the calibration conditions.

Adjustable model parameters in River2D included bed roughness, epsilon coefficients, the orientation of inflow and outflow boundaries, inflow WSE priors and steady flow runtime settings. The metrics used to assess accuracy included agreement between measured and modelled streamline direction, velocity magnitude, eddy size/location, and water surface elevation. Specialized model calibration and validation assessment plots were developed for each model run to identify discrepancies between the velocity and/or flow direction between ADCP data and River2D simulations.

Calibration consisted of running preliminary simulations with default values, then modifying calibration parameters to improve the accuracy of results. The entire study area was reviewed during each iterative model run, but the focal areas target the restoration areas, spawning areas and egg deposition zones. It should be noted that calibration and validation performance are lower near the boundaries of the model domains, as is typical of hydrodynamic modelling.

4.3.6. Simulated Flows

The flow combinations that were simulated with River2D were chosen to assess sediment transport conditions (coarse scour, fines deposition, fines flushing), habitat suitability, and to calibrate and validate the hydrodynamic and sediment transport models (Table 6). Simulations each have an alphanumeric code (e.g., K02). Missing codes represent simulations that were omitted from the results because they were supplanted by something closer to a threshold or a worst-case scenario of interest.

To provide an indication of restoration longevity, an effort was made to choose flows simulations based on return periods. Return periods estimates can be misleading in heavily regulated systems since statistical distributions commonly used to predict return periods are best suited to frequencies associated with natural hydrological processes. Given that ALH has a maximum discharge of 1100 m^3/s that is frequently reached, return periods were not calculated for Keenleyside. Instead, exceedance flows and average annual duration of specific flow conditions were assessed. At Waneta, the flows from PDO and Columbia River followed a more natural pattern that matched well with the Log Pearson Type III distribution commonly used for flood frequency analysis. Therefore, approximate return periods were calculated for each of these flow sources. Exceedance flows were also calculated for low flows from PDO.

To simplify the number of flow combinations that were simulated, the flow source with most influence on sediment transport conditions was selected for frequency analysis for each spawning area. Simulations from Task 2 were reviewed, and additional simulations were completed in an iterative fashion to identify threshold conditions for transport processes.

No Tier 1 restoration alternatives were selected at Kinnaird during Workshop One, and therefore the only simulations that were completed were those from Task 2 that were used for calibration, validation, and coarse scour risk.

Table 6. Flow distributions simulated with River2D hydrodynamic model.

Scenario Name[1]	Primary Simulation Purpose	Downstream Discharge (m³/s)	Flow from each source (m³/s)		Description	Days/year above or below[2]
Keenleyside		**Combined**	**ALH**	**HLK**		
K02	R2D Validation	779	779	0	Field Trip 3	NA
K04	R2D Calibration	1614	1100	514	Field Trip 1	NA
K06	Coarse scour	3256	1100	2156	Extreme high flow year (2012)	NA
K08	Coarse scour	4400	1100	3300	Extreme high flow year (1997)	NA
K09	Coarse scour	1100	1100	0	Expected to be worst case scour scenario based on preliminary runs	11
K10	Habitat suitability	1785	1100	685	Average spawning period flows	31
K11	Fines deposition	190	0	190	5th percentile low flow at HLK while ALH = 0	0
K12	Fines deposition	474	0	474	Mean annual flow at HLK while ALH=0	7
K17	R2D Validation	1304	1101	203	Field Trip 4	NA
K19	Coarse scour	1250	1100	150	Possible worst case scenario based on preliminary runs	NA
K20	Coarse scour	1400	1100	300	Possible worst case scenario based on preliminary runs	NA
Waneta		**Combined**	**PDO**	**CLB**		
W01	Fines deposition	1723	13	1710	5th percentile of annual low flows at PDO and mean at CLB while flows are less than PDO condition	0
W02	Fines deposition	2284.5	83	2202	50th percentile of annual low flows at PDO and mean at CLB while flows are less than PDO condition	1
W03	Fines flushing	3617	1570	2047	5-year return low freshet at PDO and mean at CLB while flows are less than PDO condition	NA
W05	Habitat suitability	3623	938	2685	Average spawning period flows	NA
W06	Coarse scour	8100	3700	4400	Extreme flow year (1997) ~ 40-yr return period for PDO	1
W07	Coarse scour	7957	3097	4860	Extreme flow year (2012) ~ 9-yr return period for PDO	3
W08	Coarse scour	6590	2779	3811	5-year return peak at PDO and mean at CLB while flows are higher than PDO condition	6
W10	Coarse scour	6164	1910	4254	5-year return peak at CLB and mean at PDO while flows are higher than CLB condition	26
W12	Calibration	3873	1174	2699	Field Trip 1	NA
W13	Validation	2025	764	1261	Field Trip 3	NA
W14	Validation	1925	53	1872	Field Trip 4	NA
W15	Tracer stone peak	4482	2584	1898	Peak PDO flow that occurred during tracer deployment	9
Kinnaird						
KIN01	Calibration	2,688	-	-	FT1	NA
KIN02	Validation	1,370	-	-	FT3	NA
KIN03	Coarse scour	6080	-	-	Extreme high flow year (2012)	9

[1] Missing values are scenarios that were considered but determined unuseful given results of other simulations.

[2] days per year above for peak flows and below for low flows, based on HLK and PDO flows except for W10 which was based on CLB.

4.4. Sediment Transport Modelling

To allow for assessment of substrate mobility metrics, two phases of sediment transport modelling were configured and validated. The first phase consisted of assessment using Shield's sediment transport equation (Shields 1936). This first approximation relied on hydrodynamic outputs and qualitative estimates of median grain size determined from visual bed sediment classification. This approach was used to (1) assess the stability of existing bed material during peak flows, (2) identify locations prone to deposition, and (3) assess the stability of a substrate addition treatment at ALH similar to that applied near Revelstoke (Crossman and Hildebrand 2012). It was determined that these questions could be reasonably assessed with this approach; however, more specific questions would require a more comprehensive sediment transport modelling approach.

Following the collection of additional substrate images and automated assignment of grain size distribution (see Section 4.2.8), the Wilcock and Crowe (2003) sediment transport equation was applied that can predict fractional transport of various grain sizes and takes grain hiding effects into account. The purpose of this extended assessment was to determine shear stress thresholds for fines deposition or coarse material scour for existing or proposed material. This analysis required modelling various flow combinations for HLK/ALH and PDO/LCR to determine when flows meet or exceed the determined thresholds and assessing the patterns within the spawning areas and for proposed restoration alternatives. Calculating the frequencies or durations of flows that are outside of the thresholds allows for the determination of scour or deposition risk, which can be used to answer questions such as how long until a given treatment becomes unsuitable due to transport conditions, or whether short term habitat degradation is possible due to fines deposition during critical spawning or rearing periods.

Transport threshold exceedance was modelled for the Keenleyside and Waneta areas using both Shields (1936) and Wilcock and Crowe (2003) models. For the Tier 1 restoration alternatives, transport conditions were assessed in the restoration areas defined during Workshop One. At Keenleyside, an HLK placement area was also included in plots to provide a general indication of how this Tier 2 alternative would perform.

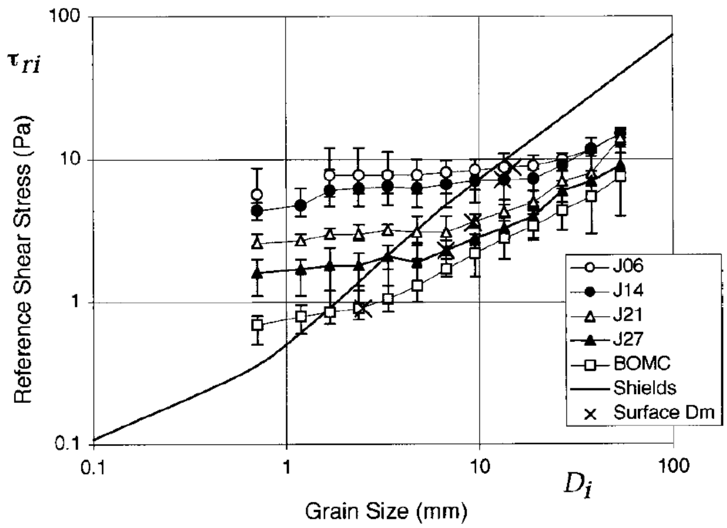
4.4.1. Single Grain Size (Shields 1936)

The Shields (1936) sediment transport model is a semi-empirical approach to defining the thresholds of sediment motion. The model is widely used and assesses sediment mobility for a single grain size (often the D50) that is representative of the sediment mixture under the assumptions of equal mobility of size fractions once the D50 becomes mobile. The critical shear stress for entrainment is based on experimental observations of thresholds for different size classes and is expressed as a non-dimensional shear stress termed the Shields parameter. Following analysis methods applied by Knight Piésold (2012) for a Peace River competency analysis, a Shields parameter of 0.047 was applied, which accounts for progressive armouring and embeddedness expected with regulated flow and sediment supply. This parameter was used to calculate critical shear stress values for different D50 sizes as determined by the automated grain size determination methods. By comparing calculated thresholds to modelled shear stress outputs from River2D simulations, potential entrainment of existing sediment in each location was assessed. To evaluate restoration alternatives, the Shields model was also applied to proposed zones of placed ideal White Sturgeon substrate based on the D50 of the mixture, and to existing substrate points with fines removed to reflect substrate cleaning. For these applications where bed sediments were expected to be looser and less embedded, a Shields parameter of 0.038 was used, which reflects the fact that these disturbed or freshly laid sediments are likely mobilized more easily.

4.4.2. Multi-Grain Size (Wilcock and Crowe 2003)

Although the single grain size approach of Shields (1936) provides a useful first approximation of potential transport patterns, the potential exists in mixed-size sediments for grain-to-grain interactions that mediate the entrainment and transport processes. For this reason, a second transport model (Wilcock and Crowe 2003) was applied to examine the relationships between grain size distribution properties and entrainment thresholds for different size classes. The Wilcock and Crowe model is a surface-based transport model for mixed-size sediments that incorporates a 'hiding function' that accounts for size-dependent differences in the mobility of small and large grains. The hiding function aims to model the fact that smaller grains tend to get lodged in the interstices of large grains and therefore are less mobile than a single-size assessment of mobility would predict, and that large grains protrude more into the flow and are exposed to higher forces and are therefore more mobile than otherwise. The Wilcock and Crowe model incorporates this hiding function so that grain size fractions coarser than the mean grain size have their entrainment thresholds reduced, and sizes finer than the mean grain size have their thresholds increased. The Wilcock and Crowe model also accounts for the importance of sand content on mixture mobility, as sand content in a sand/gravel mixture increases, overall mobility of the mixture increases as well. Thresholds for entrainment in the model are based on the concept of a reference shear stress, defined as the shear stress value at which a small but measurable rate of transport begins to occur. These thresholds are based on experimental observations and depend directly on sand content. This definition for incipient motion differs slightly from the critical shear stress approach used in the Shields model, where a more substantial rate of transport is used to define incipient motion. The Wilcock and Crowe model therefore predicts sediment movement at slightly lower shear stress values than the Shields approach. For unimodal sediments that are well-sorted, most grain size fractions tend to move at similar shear stress values, meaning results from Shields and Wilcock and Crowe are generally similar. For more poorly-sorted or bimodal sediment mixtures, departures between the two models are more evident and reference/critical shear stress values predicted by the two models diverge (Figure 15).

Figure 15. Difference in reference/critical Shields shear stress using Wilcock and Crowe approach vs. Shields approach (copied from Wilcock and Crowe 2003).



To apply the Wilcock and Crowe model to predict entrainment thresholds for existing bed conditions, an R code framework was developed that built off of the automated grain size determination from the wavelet method (Section 4.2.8). Because the wavelet method is most reliable for gravel/cobble sizes and has difficulty discerning sand content, each calculated grain size distribution was modified with the addition of a visually determined sand fraction from the image. Reference shear stress values for the mean grain size of each distribution were calculated based on this sand fraction and the empirical Wilcock and Crowe equations. Fractional reference shear stress values for each grain size class were then determined relative to this mean value based on the hiding function. Thresholds for chosen size classes (e.g., fine sand, D50, D90) at each bed image point location were then compared to River2D outputs of shear stress for modelled flow scenarios, allowing for the determination of which size classes would be potentially mobile at each location throughout the study area. A similar approach was used to predict thresholds for various restoration placement material mixtures; fractional reference shear stress values were calculated from the chosen placement material grain size distributions and then compared to River2D outputs within each potential restoration zone for a spatially continuous determination of where entrainment could occur if the restoration material were placed evenly throughout each zone. To assess the effects of cleaning existing sediment in place, the Wilcock and Crowe calculations were repeated for the bed image sediment mixtures with the fines fraction removed under the assumption that fines would be liberated and transported away during cleaning.

4.4.3. Sediment Supply (Secondary Flows Transport and Upstream Supply)

Sediment supply rate for each of the restoration areas was considered using qualitative inferences based on upstream sources, existing substrate conditions, and secondary circulations. Supply of coarse (bedload) and fine sediment (suspended load) were considered separately since coarse supply is expected to benefit rearing habitat while fines supply will have a negative impact. At each of the areas, the length of upstream erodible banks, stream bed, and tributaries were considered to provide a general indication of supply rate that could be compared between the restoration areas. Existing substrate character, including embeddedness, size range, evidence of recent transport, and fines percentage were also considered as an indicator of supply. Circulation of fine sediment from back eddies into the restoration areas was evaluated using the location and strength of back eddies from each of the flow simulations, and consideration of the frequency of the flows required to move sediment from mainstem currents into settling areas or from lateral and downstream fines deposits into the restoration areas. Previous measurements and estimates of suspended sediment loading (e.g., NHC 2007) were also reviewed and support the assumption that suspended sediment loading is correlated with the length of erodible banks from the restoration areas up to the next reservoir.

The supply of sediment to the Keenleyside sites is lower than Kinnaird and Waneta due to the dam and large reservoir immediately upstream of the site. However, the fines percentage in the Keenleyside spawning area, especially near the downstream extent, is high enough to affect rearing habitat quality. The most likely mechanism for supply of fines to the Keenleyside spawning area is expected to be through transport of fines from two large fines deposits that are subject to secondary circulation. The two locations are an approximately 250 m diameter eddy on the river right side (the HLK Eddy), and a series of persistent eddies near the downstream extent of the spawning area on river right. Assessment of the frequency and magnitude of transport from these areas was considered by examining the proportion of the area with shear force greater than the threshold for fines transport for each of the River 2D flow simulations, and assessing if a path from fines deposit to restoration area existed through the deposit where the transport threshold was consistently exceeded.

At the Waneta restoration area, fines supply was considered by examining the magnitude and frequency of the eddy that forms along the river left side upstream of the PDO confluence (the Waneta Eddy). It was assumed that the majority of fines supplied to this area would come from upstream sources on Columbia River, and that the Waneta Eddy would be responsible for delivering these fines to the restoration area under certain flow conditions (see Fissel *et al.* 2017) .

Sediment supply at the Kinnaird restoration area was considered in terms of upstream supply. Secondary circulation was not considered given that there were no Tier 1 (high priority) Kinnaird restoration alternatives identified during Workshop One.

4.4.4. Comparison of Observed vs. Modelled Sediment Transport

Sediment transport observations using tracer stones and qualitative observations of recent transport (Section 4.1.6) were compared to model predictions of sediment transport. For the tracer stones, the flow that occurred during the deployment period that was expected to create highest shear conditions at the tracer stone locations was simulated for the comparison. For the qualitative observations of transport, the highest shear conditions that occurred during 2018 freshet were used. For Keenleyside, the maximum shear stress in the EDZ was assumed to correspond with the condition of maximum ALH flow and minimum HLK flow, while at Waneta it was assumed to correspond to maximum PDO flow.

4.4.5. Sensitivity to Changes in Bathymetry

One of the assumptions for modelling restoration alternatives was that raising the stream bed with the 0.6 m thick treatments would have a negligible effect on shear stress and water surface elevation, considering the depths of water (> 10 m). However, it was important to confirm that changes in water surface elevation would not occur that could affect ALH power generation. It was expected that this increase in stream bed elevation would result in slightly higher velocities and a minimal change to water surface elevation, such that shear stress should remain similar. The sensitivity of flow to changes in bed bathymetry was tested by simulating a raised bed surface in a patch immediately below the ALH tailrace. This patch was approximately 150 m long and 50 m wide. The bed was raised by up to 1.5 m near the center of this patch with the total added volume (fill) of 6,500 m^3. Flow simulations K02 (FT3) , K04 (FT1) and K08 (1997 peak flows) were then rerun to evaluate changes in the WSE and shear velocities and to check for any evidence of backwatering of the ALH tailrace.

4.4.6. Bathymetric Change at Waneta (2004 to 2018)

Historic bathymetric data at the Waneta reach collected from 2001-2004 (Fissel and Jiang 2008) was compared to the 2018 data collected for this study to evaluate long-term changes in the river morphology. This assessment helped to validate the bed material transport and scour predictions. Bathymetric survey data was only available for the Waneta reach, so this comparison was not completed for Keenleyside or Kinnard.

The intent of this change detection assessment was to identify areas with a high degree of bed material scouring or deposition. Benchmarks were not re-surveyed between periods and therefore absolute elevation changes should be treated as approximate. Historic bathymetric data from Fissel and Jiang (2008) was only available as the mean depth above the chart datum over multiple survey dates. When combined with bathymetric data from 2018 (River2D, simulation W15), depths were within 0.04 m of each other across bedrock and boulder fields, after applying a global offset of 1.81 m.

4.4.7. Longevity of Each Alternative

Predicting the longevity of restoration alternatives requires consideration of multiple processes that are interrelated and sometimes conflicting. Alternatives were given a composite low, medium, or high longevity score that takes each process into account. Multiple lines of evidence were considered when estimating longevity, including:

- Observed sediment conditions during the 2018 and 2019 field trips;
- Observed sediment transport;
- Model predictions of sediment transport;

- Long-term bathymetric change; and
- Estimates of sediment supply.

It is expected that for treatments to remain functional, two sediment transport conditions must be met, including (1) coarse material will not be transported completely out of the restoration area, (2) if fines are supplied, they will either not settle, or will be flushed frequently. Since adjustments to sediment supply and hydraulics are not included in any of the alternatives, it is expected that, overall, there will be a tendency for conditions to revert back to existing over time

Longevity was considered in the context of sediment transport, with an assumption about what level of transport is required to maintain suitable rearing habitat. In general, the Ecofish team assumes that in most locations a short transport distance of coarse material (on the order of a few centimeters to a few meters) will be required to flush fines. The Wilcock and Crowe model predicts locations where fines can be flushed without mobilizing D50; however, it is expected these estimates have a high degree of uncertainty and should be treated with caution.

Each of the lines of evidence used to assess longevity include a moderate degree of uncertainty. Additionally, hydraulic and existing substrate conditions within the treatment areas are variable, which will likely result in fractions of the areas remaining suitable while other areas deteriorate. At Waneta, annual peak shear conditions vary enough to allow for a quantitative estimate of longevity (i.e., a certain return period is expected to deteriorate the restoration). At Keenleyside, peak shear conditions in the restoration area are similar each year, meaning that longevity is difficult to quantify.

4.4.8. Footprint Optimization

Following modelling of the initial treatment alternatives for the restoration areas defined in Workshop One, restoration areas were re-assessed based on outputs from sediment transport modelling to determine if treatment footprints could be refined to optimize function and longevity. Refinements included adjusting areas, sediment mixture sizes, or orientation to optimize habitat conditions, and limit risks of substrate scour or infilling. These refinements were completed iteratively during the sediment transport modelling process and presented as in-progress designs during Workshop Two. Discussion during Workshop Two (see Section 5.8) confirmed the general utility of the optimization analysis and led to a clarified approach based on the placement of multiple substrate mixtures that would be expected to remain stable and clear of fines under the range of shear stress conditions at each study area. In addition to the two substrate mixtures identified during Workshop One (ideal sturgeon substrate (GSD5) and gravel mixture (GSD1)), four additional mixtures were defined with a range of grain size distributions and D50 sizes. The six mixtures are detailed in Figure 16 and Table 7. The mixtures chosen are similar in size range to sediments present downstream of the Bonneville Dam, where egg incubation and hiding phase and feeding larvae have been detected (van der Leeuw *et al.* 2006).

Figure 16. Substrate placement mixture grain size distributions. Vertical dashed lines indicate D50 size for each mixture.

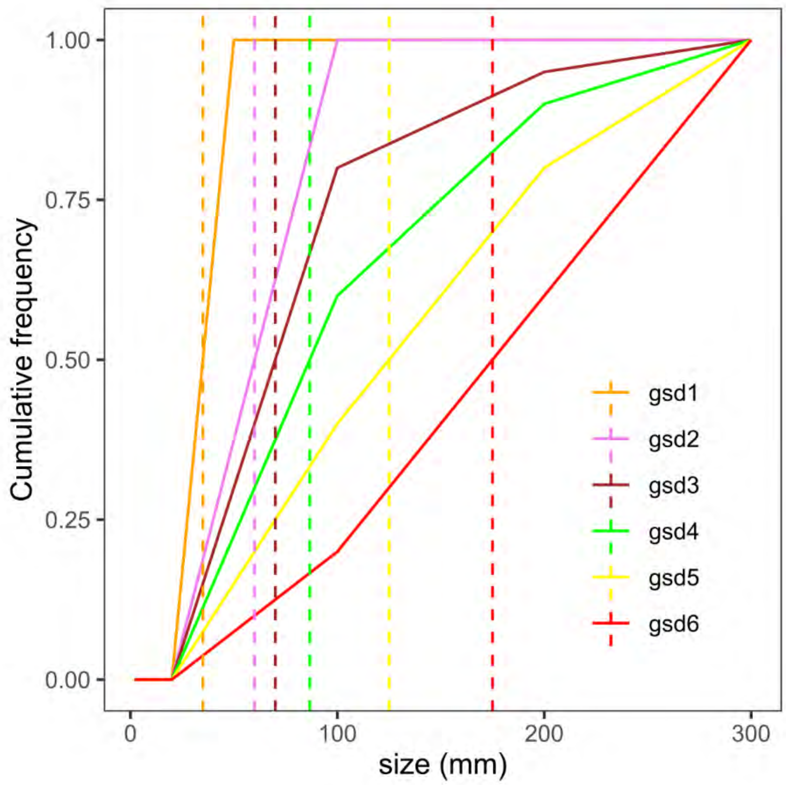


Table 7. Substrate placement mixture descriptions, sizes, and transport thresholds.

Description	D50 size (mm)	Name	Size fraction proportions	20 mm threshold W&C (Pa)	D50 threshold W&C (Pa)	D50 threshold Shields (Pa)
GSD 1 (Gravel)	35	D50-35	100% 20-50 mm	16.5	18.4	21.5
GSD 2	60	D50-60	100% 20-100 mm	21.5	26.1	36.9
GSD 3	70	D50-70	80% 20-100 mm 15% 100-200 mm 5% 200-300 mm	27.6	33.7	43.1
GSD 4	86	D50-86	60% 20-100 mm 30% 100-200 mm 10% 200-300 mm	35.0	43.6	53.3
GSD 5 (Ideal sturgeon substrate)	125	D50-125	40% 20-100 mm 40% 100-200 mm 20% 200-300 mm	44.6	58.0	76.9
GSD 6	175	D50-175	20% 20-100 mm 40% 100-200 mm 40% 200-300 mm	60.6	98.2 [1]	107.6

[1] D90 threshold is shown for GSD6 to highlight upper bounds of stability

To optimize placement footprints, River2D model results from multiple scenarios were combined into composite flow rasters representing the peak shear stress conditions that each section of the study areas would experience under a variety of modeled flow conditions. For Keenleyside, a composite of maximum shear stresses from simulations K06, K09, K10, K19, and K20 was created to focus on coarse bed material stability under a range of moderate to high flows. Although this includes an extreme condition (year 2012), it should be noted that shear stress in the ALH tailrace jet generally reaches this level on an annual basis. For Waneta, two cases were modeled to focus on the risk of fines infilling: a high freshet case representing the composite of W08 and W10 (5-year return peak freshets for PDO and LCR, respectively), and a low freshet case using simulation W03 (5-year return low freshet at PDO). These two cases served to bracket potential conditions experienced in the Waneta spawning area to assess likelihood of fines infilling while maintaining coarse material stability.

Working toward the goal of maintaining some level of coarse material stability (so material will not be transported away immediately) while also staying above thresholds for fine material infilling, the Wilcock and Crowe model was applied to the six placement mixtures to determine shear stress thresholds for 20 mm particles (lowest acceptable size of sediment to infill) and each mixture's D50 (Table 7). The shear stress rasters for each case were then classified by these thresholds, resulting in a map of zones where each placement mixture would be suitable (shear stress > 20 mm threshold and < D50 threshold). Grain size distributions were then adjusted iteratively to maximize the total area covered by each mixture for the final optimized footprint. At Keenleyside, all six mixtures were used, with upper bound of stability for GSD6 being assigned as the D90 threshold (rather than D50 as for other mixtures) in order to maintain overall stability in the very high shear stress zones directly downstream of ALH. At Waneta only GSDs 1-5 were used. An optimization based on Shields transport model was also applied, where the lower bound was still defined by the Wilcock and Crowe 20 mm threshold (given the lack of fractional size threshold calculations in Shields) and the upper bound was defined by each mixture's median grain size (D50) threshold according to Shields.

Following calculation of total optimized areas if the substrate mixtures were placed throughout the study areas, further refinement was performed to ensure that material placed at Keenleyside would remain within the areas where White Sturgeon eggs and larvae are expected to drift (under spawning conditions) and to outline the general predicted sediment transport path at Waneta if material were dumped from shore at one location near the upstream end of the egg deposition zone and allowed to be distributed by freshet flows (W08). To achieve this for Keenleyside, locations of known egg collection points were digitized and used as starting points for drift paths calculated from River2D flow data. Substrate mixture stability zones were then masked to within the paths of egg drift to create the final optimized footprint. At Waneta, a sediment input zone was chosen and paths from five points within this zone were predicted with River2D flow data as a prediction of the general dominant direction of downstream sediment transport. Substrate mixture stability zones were then masked to within these sediment transport paths for the optimized footprint at Waneta.

4.5. Biological Modelling (Habitat Suitability)

Detailed habitat suitability modelling was undertaken for Keenleyside, Kinnaird and Waneta to generate spatial predictions of recruitment and spawning suitability and identify locations that are likely to have low or high spawning habitat potential for White Surgeon. Previous habitat suitability assessments in the LCR have primarily focused on differences between the major reaches, population trends and impact mechanisms. The objective of habitat suitability modelling for this project was to use spatial variables (i.e., hydraulics and substrate) to generate detailed predictions of the relative recruitment and spawning suitability within each study area. Although criteria for suitable habitat is well characterized at a large scale, representing these predictions spatially can be challenging when considering components of spawning and other early life stages, with downstream drift and upstream sources. Additionally, sufficient spatially explicit survey data of early life stages was unavailable in the LCR to calibrate a habitat model.

To help circumvent limited availability of local survey data, an existing White Sturgeon recruitment suitability model (Hatten *et al.* 2018) was used to generate predictions of recruitment suitability for Keenleyside, Kinnaird and Waneta. This model consisted of a regression equation that predicts suitability for White Sturgeon recruitment to age-0 (spawning success: a critical demographic bottleneck) based on substrate, embeddedness and Froude number (hydrodynamics). The initial parametrization of this model was based on correlative methods with known spawning areas (Hatten *et al.* 2018). Suitable habitat for recruitment from these models is characterized as a location having a dominant substrate composition of gravel/cobble, low substrate embeddedness and a high Froude number (indicator of riffle habitat). Habitat suitability was calculated for existing conditions at the Keenleyside and Waneta study areas and a portion of Kinnaird. Suitability was also calculated following potential treatment with the assumption that substrate suitability would be 100%. This analysis provided a common approach for rating the improvements that could be gained from treatments.

Suitable habitat for White Sturgeon recruitment described by Hatten *et al.* (2018) are similar to characterizations of optimal spawning habitat described by other sources. Suitable spawning potential for U.S. Columbia River populations are broadly defined as locations with velocities between 0.8 and 1.7 m/s (Parsley *et al.* 1993; Parsley and Beckman 1994 as cited in Hildebrand and Parsley 2013). To help assess White Sturgeon habitat suitability across the LCR, areas with velocities within this target range (0.8 – 1.7 m/s) during the average spawning period flows were also identified. The overlap of areas with suitable velocity and those identified as suitable from the Hatten *et al.* (2018) model were then compared. Finally, downstream flow trajectories from the spawning period, late summer (FT4) and fall (FT3) were overlaid to predict environments that larvae are likely to encounter during downstream drift.

4.6. Restoration Alternative Prioritization (Task 4)

4.6.1. Preliminary Evaluation Metric Selection During Workshop One

Following the presentation of initial analysis results during Workshop One, the participants drafted a table of performance measures (PMs) for evaluating habitat restoration alternatives. PMs described spawning and incubation suitability and limiting factors at each location, such as depth, velocity, area (geometry), stability, substrate size and character, and proximity to habitats for subsequent life stages. A suite of PMs was sought that would describe the most important factors that should be considered when assessing (judging) different restoration alternatives. Quantitative PMs were sought where possible, though qualitative PMs were also considered. The participants noted the importance of determining how metrics will be measured, what can be practically sampled, and the detailing of magnitude of benefits to specific life stages. PMs were considered for biological benefits, feasibility, and physical habitat conditions.

PMs for each of the restoration alternatives identified during Workshop One were summarized using field data, initial model output, or professional judgement and transferred to a draft prioritization table. The draft prioritization table was then used to evaluate the alternatives as part of Task 4. During the workshop the group discussed the initial biological response scores and there was general discussion of feasibility to provide preliminary comments on the potential for each project. A stated concern from the dam managers was to ensure that restoration alternatives do not reduce power production capacity by backwatering tailraces, especially for ALH.

4.6.2. Restoration Alternative Performance Measure Refinement

The PMs identified during Workshop One were subsequently revised by the Ecofish team to clarify and formalize scoring and calculation methods, with a goal of using quantitative metrics wherever possible. A total of 81 PMs was selected. PMs were also categorized to allow for weighting of PMs based on varying objectives should this be required. The objectives included substrate mobility, substrate condition, habitat suitability, expected biological response, and technical feasibility.

The purpose of this stage was to create a longlist of PMs that characterize the relevant processes and conditions before and after treatment, as well as feasibility criteria. Most of the PMs were quantifiable using percentage of the treatment area that is above or below a threshold (e.g., sediment transport during various flow conditions), or an index that represents average habitat or substrate quality. Some of the PMs were assigned a low, medium, or high score rather than a quantitative metric to account for more subjective or difficult- to- quantify processes and conditions. This assignment was completed either during Workshop One or by the Ecofish team after the workshop using professional judgement.

4.6.3. Flags and Information Metrics

Additional details about the restoration sites for the alternatives were compiled as either flag or information metrics. Flag metrics are binary yes or no responses to questions about various criteria including feasibility, site characteristics, and monitoring. The flags provide information that can help rank projects but were not on the low/medium/high scale and thus could not be tallied along with the performance measures. These metrics are meant to serve as a secondary set of information that should be reviewed in conjunction with the PMs. None of the flag metrics were considered as necessities that would result in an alternative being feasible or unfeasible. Information metrics consist of useful statistics about the restoration sites that do not have a clear positive or negative effect on ranking. These metrics include information about hydraulics, substrate condition, biological response, and treatment geometry (size). It was not assumed that larger would be better given the uncertainty associated with rearing location and sediment transport, so geometry was expressed as an information metric.

Flag and information metrics were presented at the workshop for both Tier 1 and Tier 2 alternatives, since many were previously assigned or calculated during Task 2.

4.6.4. Normalized Performance Measure Scores (LMH)

To create scores for alternatives using the PMs, they needed to be converted to a consistent scale that would allow summation. A low, medium, and high (LMH) assignment was used to normalize the scores for each PM. Converting PM quantitative scores to LMH ranking involved choosing target ranges that would receive a high score, and bins situated either above or below the target for medium and low. Selection of the targets and bins was completed by the Ecofish team using professional judgement. For some PMs, targets would be as high or low as possible, while others had a specific target. To calculate scores for the alternatives, a scoring system was used consisting of 1 point for low, 2 points for medium, and 3 points for high.

For biological response PMs, scores were assigned during Workshop One based on input from White Sturgeon experts. Four additional PMs were identified that were discussed but not assigned in the workshop, including food availability, proximity to larval habitat, permitting challenges, and possibility of spawning monitoring. These four PMs were assessed as described in the following subsections.

4.6.4.1. Food Availability

The importance of food availability was discussed during the workshop and included food items present within the interstitial spaces within the spawning site and in larval rearing habitats downstream. While more information is needed to determine the importance of interstitial food, scores (LMH) for this PM were based on presumed food availability for first feeding larvae and young of year (YOY) based on the available literature. For example, Muir *et al.* (2000) indicated that near Bonneville Dam first feeding larvae and YOY White Sturgeon fed primarily on gammarid amphipods (*Corophium spp.*) and other prey items such as Copepods (Cyclopoida), Ceratopogonidae larvae and Diptera pupae and larvae (primarily chironomids) were also consumed; other food items were eaten but less frequently. With specific ELS diets being unknown in the LCR, PM classifications were based on the range of conditions throughout the spawning areas rather than an absolute indicator of food availability.

4.6.4.2. Proximity to Larval Habitat

Alternatives were assigned 'Yes' if one or more of the following suitability characteristics are located within a reasonable distance (< 20 km) downstream of the spawning sites: fluvial habitat and/or low velocity habitats such as river margins, open bottom, and side channels (DFO 2014). In addition, suitable habitat would include fine sediments with food of the appropriate size and type. Alternatives were assigned 'No' if these characteristics are not present or if too much uncertainty exists.

4.6.4.3. Permitting Challenges

Alternatives were assigned 'Yes' if the restoration site is located directly in designated SARA critical habitat (DFO 2014). Alternatives were assigned 'No' if outside of critical habitat.

4.6.4.4. Monitoring of Spawning Activity

Monitoring of spawning activity is deemed as a critical PM to evaluate effectiveness. Spawn monitoring has been conducted at all sites since 2010 and is planned to continue at all sites for the next several years. Specific spawn monitoring design will be considered as part of phase 2 should the project proceed.

4.6.5. Final Shortlist of Performance Measures

PMs were winnowed to produce a shortlist of PMs that could be used for effective decision-making, recognizing that it is difficult to evaluate trade-offs among a large number of PMs. The PMs were short-listed based on the two steps described below to examine sensitivity and redundancy. Given the small number of alternatives under consideration, this process was completed using professional judgement.

PMs were first reviewed to identify those that are insensitive to the alternatives under consideration. Sensitivity was assessed by considering the range in calculated PM values as either a percentage of the maximum value when the PM measurement unit was not percentage, and the difference between highest and lowest when the PM measurement unit was percentage. PMs were screened out from further consideration if their sensitivity was lower than 20%. This step resulted in the exclusion of 20 PMs, including, for example, mobile fines fraction during low flows, since each of the sites had low mobility during low flows.

The remaining PMs were then reviewed to identify PMs that were redundant because they were highly correlated with other PMs, meaning that it was reasonable to retain only one of the correlated PMs for decision-making. Correlated PMs were identified by reviewing results in the prioritization table. For example, PMs that involved sediment transport conditions using the Shields model were removed in favour of the Wilcock and Crowe model since they provide similar information and the latter is expected to be more reliable. Decisions regarding which PMs to retain or screen out were constrained to ensure that the final shortlist adequately encompassed the range of biological, feasibility and physical habitat factors that were considered important.

Redundant PMs were those that provided similar information (e.g., embeddedness vs. fines percentage); in these cases, the most relevant PM was retained. For the substrate mobility PMs, we retained the most important flow simulation that highlighted differences between the alternatives or was closest to a threshold of interest. For all substrate, substrate mobility, and habitat suitability PMs, the importance of assessing conditions before and after treatment and the associated change was considered. An effort was also made to include PMs from each of the objective categories.

4.6.6. Final Scores for each Alternative

Once the shortlist of PMs was completed, the scores for each PM were tallied for each alternative. A total score was calculated, as well as scores based on substrate mobility and combined substrate condition and expected biological response. A weighting system to allow higher weights for some PMs or objectives was considered but has not been pursued at this time.

5. RESULTS

5.1. Field Data Collection

5.1.1. Bathymetry

Maps of the raw bathymetric survey coverage across Keenleyside, Kinnaird and Waneta are provided in Appendix B.

5.1.2. Hydraulic Sampling

Obtaining accurate estimates of discharge was required for the calibration and validation of the hydrodynamic models. Overall, ADCP discharge measurements were within 7% of discharge measurements recorded at the external reference gauging stations across field trips (Table 8). During lower flows it was difficult to estimate discharge across ADCP transects located in deeper slow-moving water. Therefore, external reference gauges were relied upon (where possible) to parametrize hydrodynamic model inflow conditions. Hydraulic transects of depth and velocity were not presented in this report and can be provided upon request. Detailed velocity plots are provided in Appendix E for the calibration and validation transects. The strong agreement between ADCP measured and gauged discharge for field trips 1, 2, and 4 provides confidence that velocities and depths from these measurements can provide the basis for hydrodynamic model calibration and validation.

Table 8. Discharge measured during each field trip and comparison to external reference gauges.

Sampling Reach	Field Trip	Date	Survey Time (local)	ADCP Transects (n)	Measured Q (m^3/s)	Reference Gauge Name	Reference Gauge Q (m^3/s)	Ratio Measured: Reference
Keenleyside	FT1	5-Jul-18	13:08 - 16:23	18	**1,559.0**	HLK + ALH	1,613.8	0.97
	FT2	14-Aug-18	9:23 - 10:52	2	**2,026.2**	HLK + ALH	1,980.8	1.02
	FT3	31-Oct-18	9:20 - 9:37	5	741.9	HLK + ALH	**779.2**	0.95
	FT4	27-Aug-19	14:16 - 15:29	7	1,226.8	HLK + ALH	**1,303.7**	0.94
Kinnaird	FT1	6-Jul-2018	9:11 - 12:52	18	**2,688.4**	WSC-08NE049[1]	2,790.0	0.96
	FT2	15-Aug-2018	8:45 - 9:55	2	**2,614.3**	WSC-08NE049[1]	2,570.0	1.02
	FT3	3-Nov-2018	7:47 - 9:01	8	1,066.1	WSC-08NE049[1]	**1,370.0**	0.78
Waneta US[2]	FT1	7-Jul-18	9:50 - 10:30	5	**2,699.2**	USGS - Waneta Dam	2,752.8	0.98
	FT2	16-Aug-18	9:54 - 10:10	2	**2,570.6**	USGS - Waneta Dam	2,674.7	0.96
	FT3	2-Nov-2018	9:50 - 9:56	2	840.8	USGS - Waneta Dam	**1,260.8**	0.67
Waneta DS[3]	FT1	7-Jul-2018	11:29 - 12:43	9	**3,873.6**	USGS-12399500[4]	3,936.0	0.98
	FT2	16-Aug-2018	10:27 - 10:44	2	3,078.4	USGS-12399500[4]	**2,888.3**	1.07
	FT3	2-Nov-2018	10:33 - 10:37	2	1,404.9	USGS-12399500[4]	**2,024.7**	0.69
	FT4	28-Aug-19	10:18 - 11:36	13	1,846.6	USGS-12399500[4]	**1,863.2**	0.99

[1] WSC Real-Time Hydrometric data graph for Columbia River at Birchbank (08NE049) [BC] (49° 10' 40", 117° 43' 03").
[2] Columbia River at Waneta upstream of confluence with Pend Oreille River.
[3] Columbia River at Waneta downstream of confluence with Pend Oreille River.
[4] USGS 12399500 Columbia River at International Boundary (49°00'03", -117°37'42").
* Bold values indicate most reliable discharge measurement for each field day.

5.1.3. Substrate Surveys

Substrate survey data were incorporated into the components of the following sections. Detailed maps of the dominant and sub-dominant substrate type and substrate embeddedness are provided in Appendix C and Appendix D.

Exploratory analyses attempted to detect and map change in embeddedness between each of the survey periods. Embeddedness patterns were similar between surveys at a coarse scale (i.e., within reach segments, under eddies and around major bathymetric features); however, detecting subtle change was difficult due to the incomplete coverage between surveys and the high variability in embeddedness between neighbouring locations. Multiple methods were undertaken that compared neighbouring annotated points between surveys (e.g., within 10 m), but upon review it was determined that any differences in embeddedness scores were the result of microsite features rather than temporal change at a scale on the order of 20-50 m. Efforts were also made to produce interpolated surfaces of embeddedness for each survey, but large gaps in coverage for a single survey period reduced the reliability of these outputs. Qualitative descriptions of changes that were observed are detailed in the following sections.

5.1.4. Ground-Based Sampling

Results from the ground-based sampling of grain size distribution are provided in Appendix A.

5.1.5. Sediment Transport Observations

Results of sediment transport observations are provided in Section 5.4.5 along with comparison to model predictions.

5.2. Substrate Classification

Sample images of each approximate substrate patch are shown for Keenleyside in Map 2 and Waneta in Map 3. Descriptions of substrate conditions in each spawning area are provided below.

5.2.1. Dominant and Subdominant Substrate

Cobble and boulder were identified as the leading substrate class across Keenleyside, Kinnaird and Waneta followed by coarse gravel and fines (Table 9). There was a large difference in the composition and extent of the substrate classes both between and within each of the three study areas (detailed maps are provided in Appendix C).

5.2.1.1. Keenleyside

The dominant substrate composition of Keenleyside consisted largely of cobble, gravel and boulders within the spawning and restoration areas. Fines accounted for almost half of the substrate composition outside of the focal areas, especially downstream of the restoration area and within the HLK Eddy.

5.2.1.2. Kinnaird

The dominant substrate composition of Kinnard consisted largely of boulder and cobble. Pockets of fines were still present throughout, however these areas were much smaller and more localized in comparison to Keenleyside and Waneta.

5.2.1.3. Waneta

The dominant substrate composition at Waneta also consisted largely of cobble, but with a greater portion of boulders. The substrate composition within the proposed restoration area and the EDZ area consisted almost exclusively of either cobble or boulder. Pockets of fines were still present at Waneta, but were limited to areas under the Waneta Eddy, immediately upstream on river left of the PDO confluence, and along the river right margin.

Table 9. Dominant substrate class distribution at Keenleyside, Kinnaird, and Waneta based on substrate image annotations (n = 5,638). Summaries are provided for the entire study area and separately for image annotations within the restoration and spawning areas.

Study Area	Location	Dominant Substrate by Area Coverage (%)[1]						
		Bedrock (mm)	Boulder >256	Cobble 64-256	Coarse Gr. 16-64	Med. Gr. 4-16	Fine Gr. 2-4	Fines <2
Keenleyside	Overall	0 - 1	5 - 6	27 - 35	15 - 16	5 - 7	4 - 5	33 - 41
Kinnaird	Overall	0 - 1	14 - 34	51 - 73	7 - 9	1	1	1 - 6
Waneta	Overall	1	34 - 35	49 - 51	5 - 7	1	1	6 - 9
Keenleyside	Restoration Area (Inside)	0 - 2	6 - 9	30 - 47	23 - 35	3 - 7	3 - 4	13 - 18
	Restoration Area (Outside)	0	4	36	10	4	4	43
Waneta	Restoration Area (Inside)	0	50 - 64	36 - 50	0	0	0	0
	Restoration Area (Outside)	1	36	48	6	1	1	7
Keenleyside	Spawning Area (Inside)	1 - 2	5 - 8	28 - 47	20 - 31	4 - 10	3 - 5	17 - 20
	Spawning Area (Outside)	0	5	36	12	4	4	41
Waneta	Spawning Area (Inside)	0 - 1	49 - 55	40 - 45	2	2	0	1 - 2
	Spawning Area (Outside)	1	17	54	11	0	3	13

[1] Percent estimates show the proportional total area coverage based on three different spatial summary methods including count of annotations, area estimates with Voronoi Polygons and area estimates with a 10m grid. Ranges reflect uncertainty between spatial summary methods.

5.2.2. Substrate Embeddedness

The average overall embeddedness scores were lowest at Waneta and highest at Keenleyside (Table 10 and Table 11). However, there was a large difference in the embeddedness within each study area (detailed maps are provided in Appendix D). Embeddedness was correlated with the dominant substrate type at a coarse scale; however, site-specific embeddedness scores were highly variable with large changes over short distances.

5.2.2.1. Keenleyside

The downstream portion of the Keenleyside spawning area (on river-left) was highly embedded approximately 300 m downstream of the ALH tailrace despite having a dominant/subdominant cobble substrate. The restoration area had generally low embeddedness with an average embeddedness score of approximately 2.

5.2.2.2. Kinnaird

Embeddedness within Kinnaird was generally low, but highly variable throughout. Some areas of high embeddedness at Kinnaird were more directly associated with substrate compaction rather than the deposition of fines.

5.2.2.3. Waneta

Embeddedness at Waneta was generally low to moderate throughout, especially in the vicinity of the EDZ zone and proposed restoration area. Larger pockets of highly embedded substrates tended to correlate with the distribution of fines across the larger Waneta study area.

5.2.3. Detailed Substrate Characteristics

Substrate summaries indicate that current conditions of the Waneta EDZ and proposed restoration area are more favorable than conditions at Keenleyside for early life stages of White Sturgeon (Table 10, Figure 17 and Figure 18). The EDZ and proposed restoration area at Waneta were characterized as having lower embeddedness, lower percentages of fines, a lower degree of substrate armoring and higher roughness than target areas at Keenleyside.

The spatial distribution of substrate characteristics revealed general correlations between locations with high recruitment habitat suitability, low embeddedness, and a low percentage of fines (Figure 17 and Figure 18). The high degree of armoring/compaction observed across both Keenleyside and Waneta was largely the result of boulder fields interlocked with cobble, which are generally regarded as suitable habitat for early life stages of White Sturgeon. Although the spatial resolution of the detailed substrate characteristic dataset is limited, current substrate conditions appear more favorable on the far river right side of Keenleyside, within 300 m from the tailrace. Spatial trends are less obvious for Waneta.

Changes in substrate character between field trips were not observed at Keenleyside. The only qualitative observation of change in substrate character between field trips was an apparent shift towards greater fouling from algae growth and an increase in fines thickness on top of boulders at the Waneta restoration area between 2018 and 2019 field trips. This observation aligns with the expectation that fines deposition and fouling in this area would occur during average flow years but may be scoured away during some freshet conditions (Fissel *et al.* 2017), such as the 25-50 year return event that occurred during May 2018, prior to FT1 (July 2018). Example images from the Waneta restoration area from FT2 (August 2018) and FT4 (August 2019) are shown in Figure 19.

Table 10. **Substrate attributes for the proposed Keenleyside and Waneta restoration and EDZ areas as assessed qualitatively from substrate image annotations (n = 229).**

Substrate Characteristics	Level	Area Coverage (%)[1]	
		Keenleyside	Waneta
General Rearing Suitability	Low	20 - 32	6 - 10
	Medium	20 - 25	25 - 27
	High	46 - 58	65 - 68
Embeddedness[2]	<5%	24 - 26	39 - 44
	6-25%	34 - 39	22 - 23
	26-50%	24 - 27	27 - 30
	51-75%	12 - 13	6 - 8
	>75%	1 - 2	0 - 0
Fines Percentage	0%	27 - 28	48 - 58
	10%	44 - 58	30 - 39
	50%	14 - 29	13 - 16
Armoring Evidence	No	24 - 26	34 - 36
	Yes	74 - 76	64 - 66
Evidence of Recent Transport	No	33 - 40	26 - 33
	Yes	60 - 67	67 - 74
Roughness	Low	36 - 48	10 - 15
	Medium	19 - 26	23 - 25
	High	27 - 44	61 - 65

[1] Percent estimates show the proportional total area coverage based on three different spatial summary methods including count of annotations, area estimates with Voronoi Polygons and area estimates with a 10m grid. Ranges reflect uncertainty between spatial summary methods.

[2] Embeddedness estimates redeveloped for this imagery subset with a focus on rearing habitat suitability.

Table 11. Substrate embeddedness class distribution across Keenleyside, Kinnaird and Waneta based on substrate image annotations (n = 5,638). Summaries are provided for the entire study area and separately for image annotations within the restoration and spawning areas.

Study Area	Location	Embeddedness Class by Area Coverage (%)[1]					
		0. Neg. <5%	1. Low 6-25%	2. Mod 26-50%	3. High 51-75%	4. V. High >75%	5. Fines -
Keenleyside	Overall	0 - 1	6 - 9	12 - 16	13 - 18	23 - 25	34 - 44
Kinnaird	Overall	1 - 2	8 - 10	19 - 21	27 - 29	37 - 40	2 - 4
Waneta	Overall	1 - 2	24 - 27	28 - 30	19 - 22	15	7 - 10
Keenleyside	Inside Restoration Area	1 - 3	11 - 13	16 - 18	20 - 25	29 - 33	13 - 20
	Outside Restoration Area	0	9	16	15	15	45
Waneta	Inside Restoration Area	0	26 - 36	17 - 26	34 - 35	10 - 17	0
	Outside Restoration Area	2	25	29	21	14	8
Keenleyside	Inside Spawning Area	1 - 2	13 - 15	15 - 16	17 - 22	28 - 30	16 - 26
	Outside Spawning Area	1	6	17	18	16	44
Waneta	Inside Spawning Area	1 - 3	29 - 33	30 - 33	21 - 25	9 - 11	1 - 2
	Outside Spawning Area	1	16	28	18	21	16

[1] Percent estimates show the proportional total area coverage based on three different spatial summary methods including count of annotations, area estimates with Voronoi Polygons and area estimates with a 10m grid. Ranges reflect uncertainty between spatial summary methods.

Figure 17. Distribution of substrate characteristics at the proposed restoration area of the Keenleyside reach immediately below the ALH tailrace, as derived from annotated imagery and summarized within 10 m X 10 m grid cells (pixels). See Map 2 for location context.

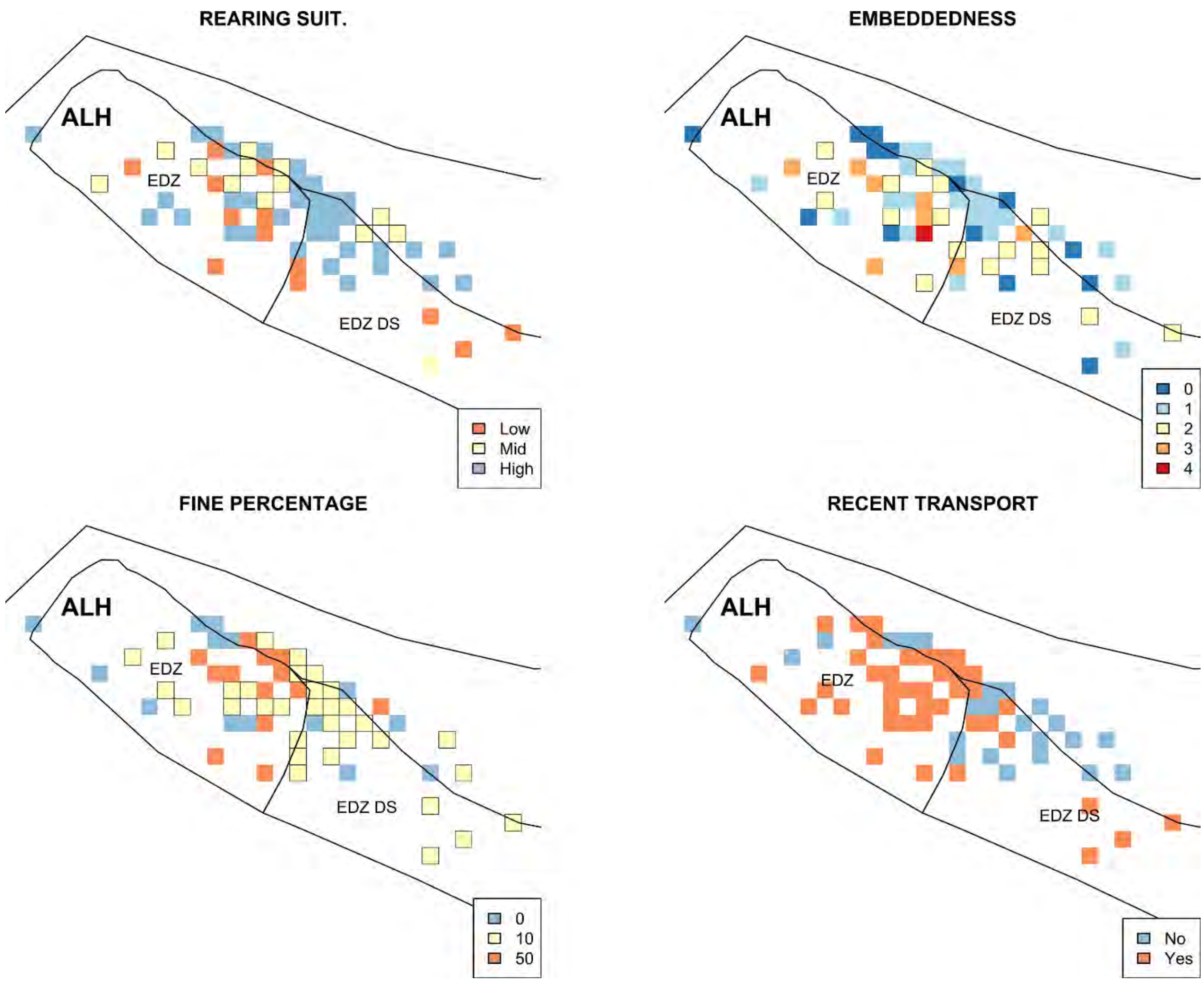


Figure 18. Distribution of substrate characteristics at the proposed restoration area and EDZ at Waneta, as derived from annotated imagery and summarized within 10 m X 10 m grid cells (pixels). See Map 3 for location context.

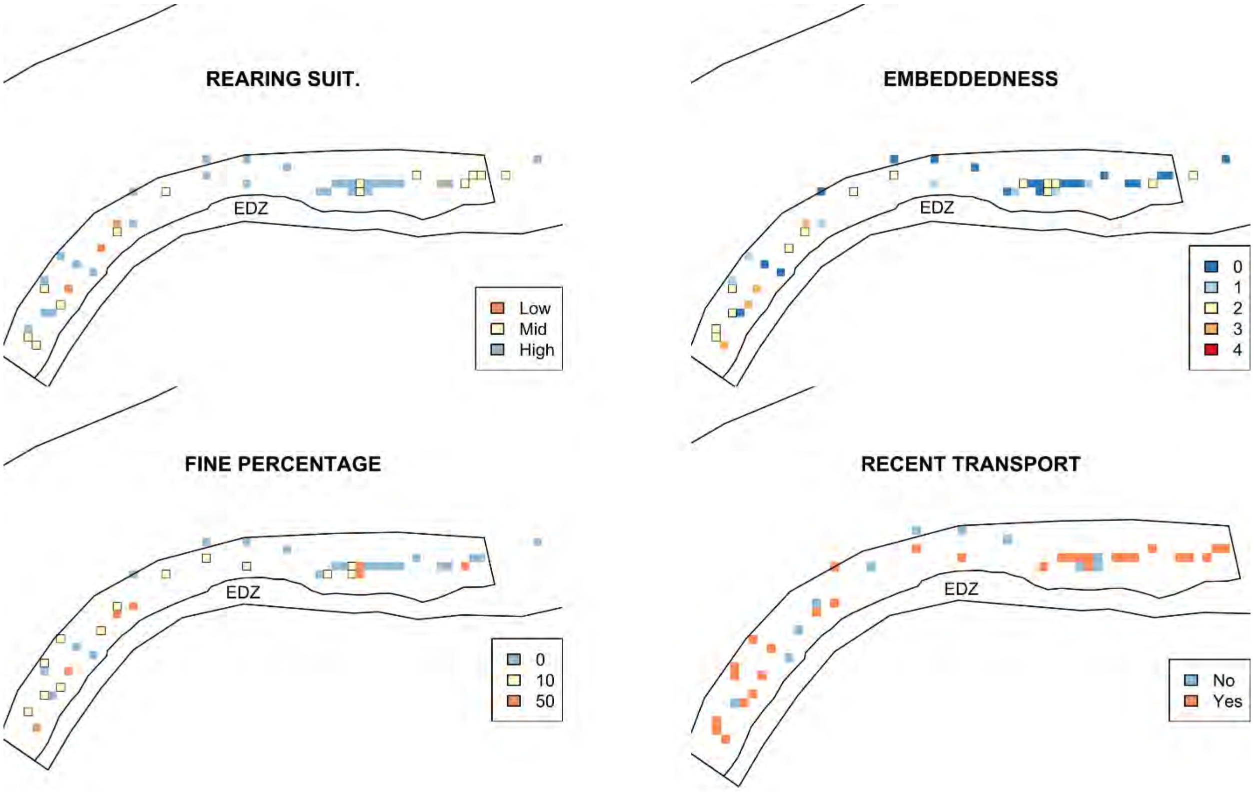
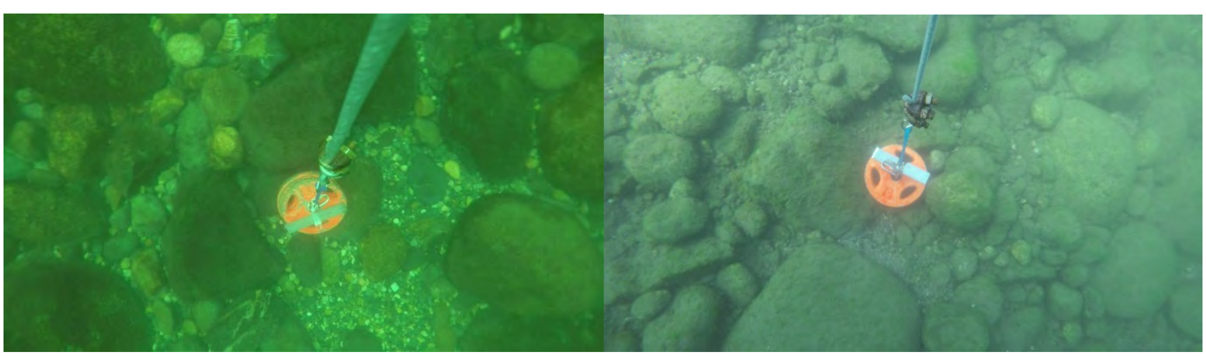


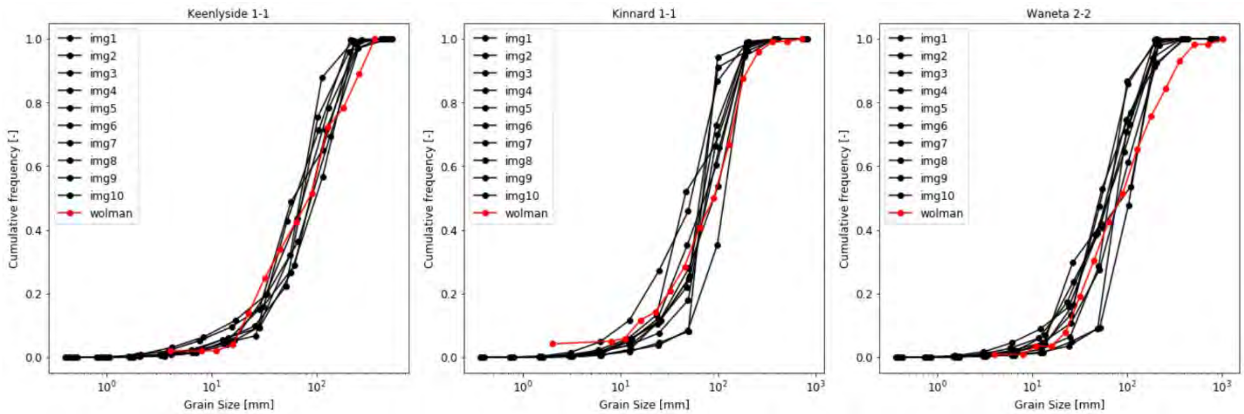
Figure 19. Example of changes in fouling and fines aggradation level at Waneta. Left photo was taken during August 2018, and right photo was taken during August 2019. Photos were taken within 100 m of each other.



5.2.4. Grain Size Distribution

Results from the calibration test with wavelet analysis of images from dry bank areas and the Wolman count data allowed for assessment of method applicability in the Columbia River conditions. Computed grain size distributions from the wavelet method for each image were qualitatively similar to those determined through Wolman counts, with Wolman distributions generally falling in the middle of the range of variability of the ten wavelet distributions (Figure 20). Wavelet distributions were also consistent among themselves for a given reach, providing confidence in the reproducibility of the method. There is some uncertainty at the tail ends of each distribution, as wavelet and Wolman methods may characterize the proportions of fines differently, and the wavelet method becomes less reliable with very large grain sizes (e.g., mid-sized boulders) as they take up more and more of each image and may be only partially visible. However, in the context of spatial variability in sediment sizes and the uncertainty inherent in any method of sediment sampling, the conclusion from the dry land calibration process was that the wavelet method was accurate and applicable to the types of bed sediments found throughout the study reaches.

Figure 20. Comparison of Wolman count grain size distribution and grain size distributions determined with wavelet method. Black series represent individual images processed with wavelet method; red series represents Wolman data for the same area.



Automated grain size calculations for selected underwater bed substrate images revealed the general patterns for each study area and the within-zone variability in substrate conditions. Grain size distributions are presented as cumulative frequencies for individual bed images and averages within the EDZ and within the greater study area for Keenleyside in Figure 21 and for Waneta in Figure 22; maps of measured D50 sizes in the vicinity of the restoration zones are also included. Overall, results of the automated grain size calculations confirm the qualitative assessment results that average sediment sizes were smaller in the Keenleyside study area (D50 = 46.9 mm, D84 = 89.5 mm) than in the Waneta study area (D50 = 83.8 mm, D84 = 142.9 mm). The Keenleyside EDZ (average D50 = 34.1 mm) was finer than the surrounding areas, but likely due to the inclusion of rip-rap at the channel margins. At Waneta, the EDZ (average D50 = 86.9 mm) was similar to its surroundings but slightly coarser. Grain size sorting as characterized by the graphic standard deviation (Folk 1966) was similar between the two study reaches, with an average value of 1.26 for both Keenleyside and Waneta, corresponding to a poorly sorted sediment mixture.

Figure 21. Grain size distributions from wavelet method presented as cumulative frequencies for Keenleyside study area. Black series represent distributions for individual images; red series show average distribution within each zone. Determined D50 values at each image point are shown in the lower panel. Polygon labels for the lower panel are shown in Map 2.

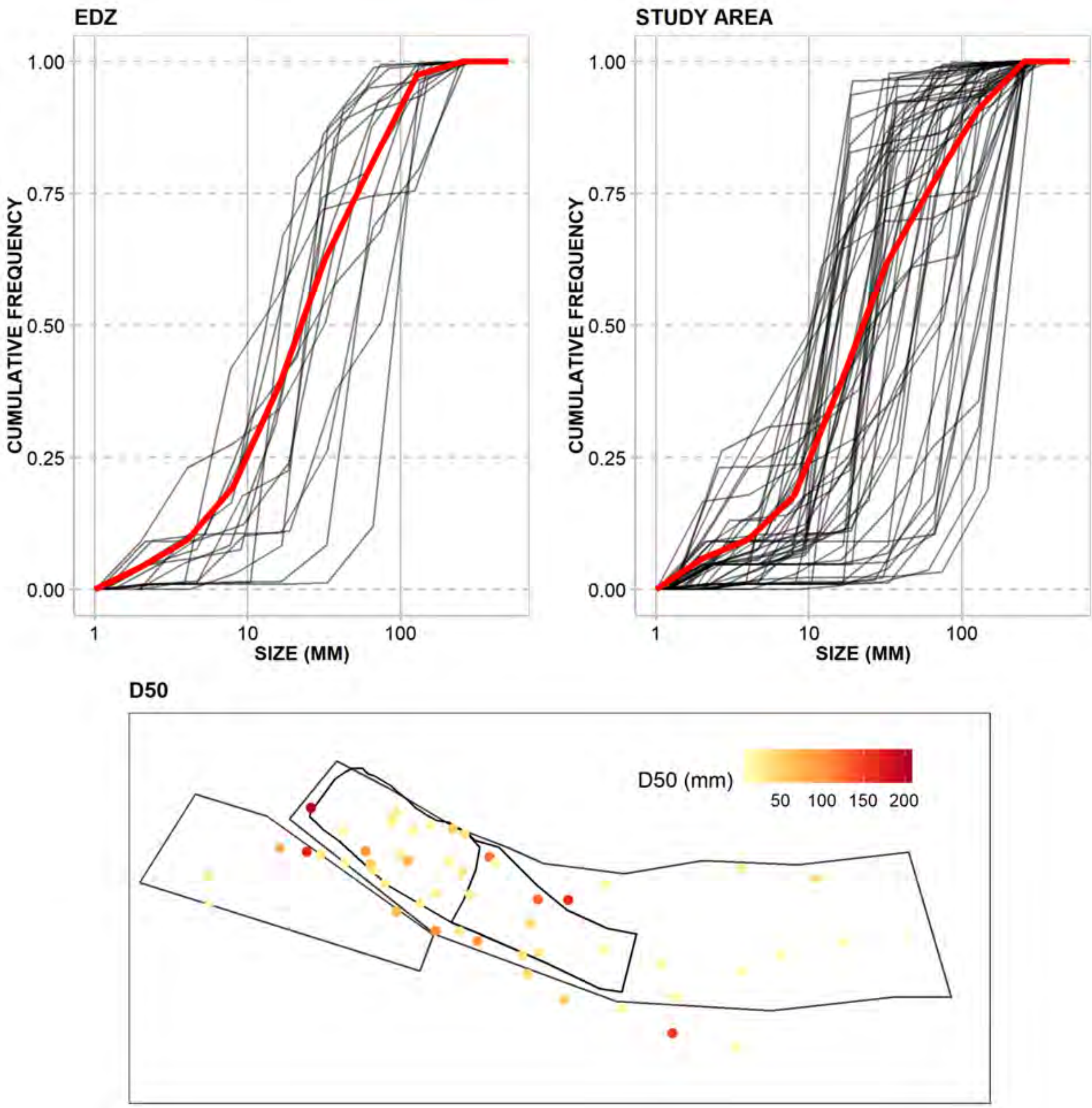
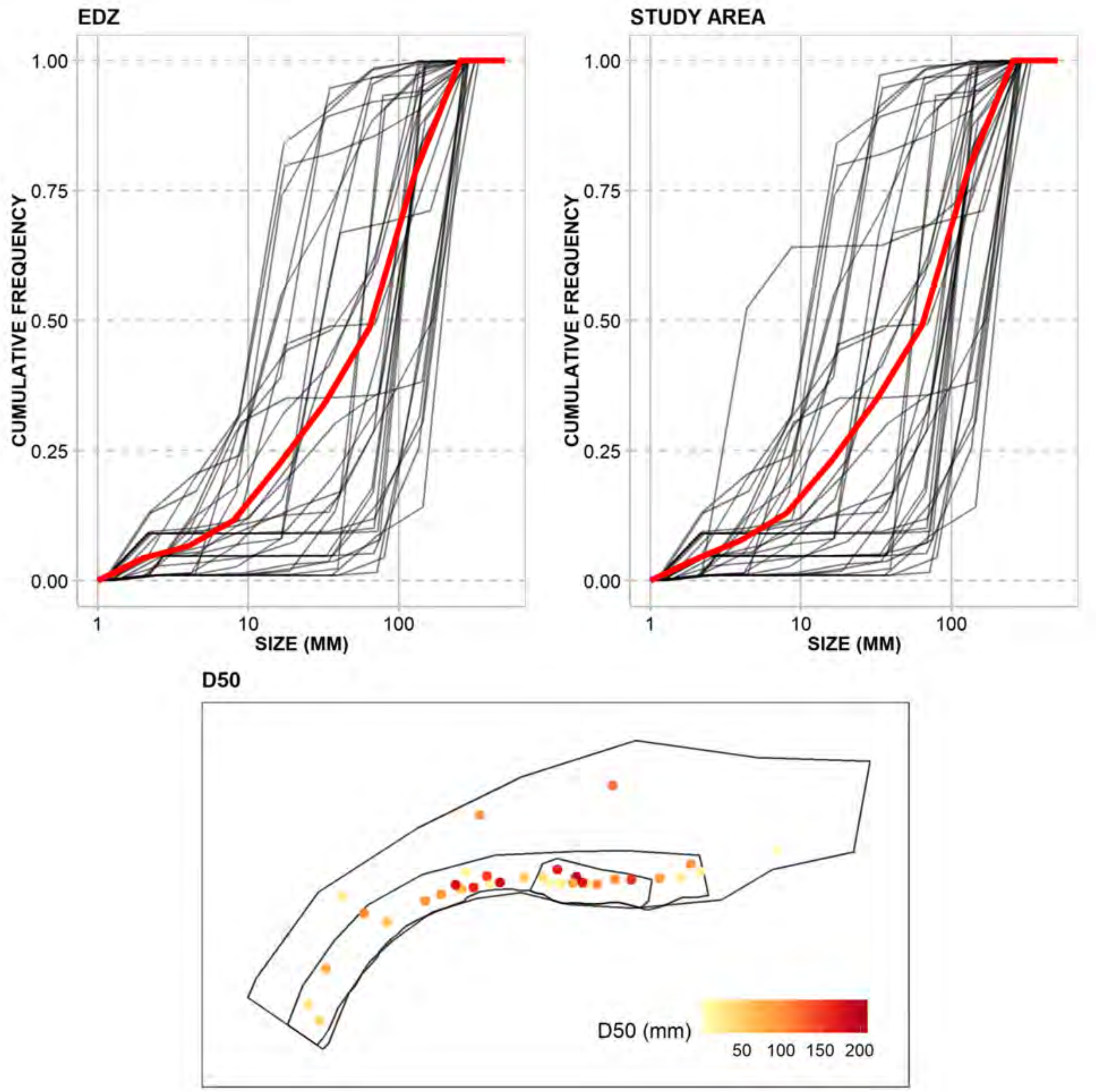


Figure 22. Grain size distributions from wavelet method presented as cumulative frequencies for Waneta study area. Black series represent distributions for individual images; red series show average distribution within each zone. Determined D50 values at each image point are shown in the lower panel. Polygon labels for the lower panel shown in Map 3.



5.3. Hydrodynamic Modelling

5.3.1. Surface Topography

Digital elevation models were produced for each of the study areas as raster datasets with a 1 m by 1 m pixel resolution. Thin-plate spline interpolation from the raw bathymetric survey points provided an accurate representation of the riverbed topography. Error from thin plate spline interpolation was usually within 0.01 to 0.03 m from hold-out portions of the raw bathymetry survey points. Rarely did the surface topography error exceed 0.10 m.

5.3.2. Boundary Water Surface Elevations

Boundary WSE measurements collected from the ADCP closely aligned with stage from reference gauges near to the ADCP transects (Table 12). The difference between WSE values was within the combined measurement error of the corresponding input data sources (approximately 0.10 m). HEC-RAS WSE predictions were also similar to ADCP measured WSEs, but only for Keenleyside and sub-sections of Kinnaird. The HEC-RAS WSE predictions did not align with ADCP observations during any of the field trips (offset > 3 m) at Waneta. This large discrepancy was believed to be the result of a localized issue with the HEC-RAS model since close alignment was observed between the ADCP WSE estimates and stage measurements from the nearby hydrometric station.

River2D requires an estimate of the outlet WSE for each flow simulation. It is important that these values are as accurate as possible, because error in the boundary conditions will result in inaccurate model results near the boundary. Given the location-specific availability and reliability of each WSE data source (Table 12), we chose to use WSE values from reference gauges for Keenleyside and Waneta, and HEC-RAS (HEC1) estimates for Kinnaird. During each of the field trips at Keenleyside the WSE across the study area was topographically flat and showed no downward trend with distance downstream due to the low gradient morphology of the reach. Therefore, the BC Hydro gauge at the ALH/HLK tailrace could be used as an adequate estimate of the outlet WSE for Keenleyside. At Waneta the reference USGS gauge (1239950) was used to estimate WSEs for flow simulations since it closely aligned with the downstream extent of the study area and was similar to ADCP WSE estimates. For each flow simulation at Keenleyside and Waneta, outlet WSE estimates were obtained directly from historical gauge measurements (if available) or estimated with custom range-specific rating curves. At Kinnaird a 500 m overlap zone was created between the two subsections and the bottom lower 500 m was discarded (as potential boundary affected areas) due to the inability to adequately validate WSE estimates for unobserved flows.

Table 12. Water surface elevation for ADCP and reference gauge measurements compared with HEC-RAS model estimates for Keenleyside, Kinnaird and Waneta.

Sampling Reach	Field Trip	Date (YYMMDD)	Discharge (m^3/s)	Water Surface Elevation (m)			
				Observations ADCP[1]	Reference Gauge[2]	HEC-RAS (Bruce 2016)[3]	
						HEC1	HEC2
Keenleyside	FT1	180705	1613.7	420.99	420.86	421.11	420.51
	FT3	181031	779.16	419.40	419.21	419.54	419.19
	FT4	190827	1303.7	420.21	420.24	420.58	420.03
	Keenleyside mean difference from ADCP (m):				-0.12	0.21	-0.29
Kinnaird - U	FT1	180706	2688.4	416.62	-	416.32	416.21
	FT3	181103	1370	414.3	-	413.43	413.32
	Kinnaird U mean difference from ADCP (m):				-	-0.58	-0.69
Kinnaird - L	FT1	180707	2688.4	415.75	-	415.91	415.88
	FT3	181103	1370	413.73	-	413.16	413.13
	Kinnaird L mean difference from ADCP (m):				-	-0.21	-0.24
Waneta	FT1	180707	3,873.50	398.40	398.6	395.36	394.77
	FT3	181102	2,024.65	395.96	396.17	392.94	392.79
	FT4	190828	1,863.25	-	-	-	-
	Waneta mean difference from ADCP (m):				0.21	-3.03	-3.40
	Mean difference from ADCP (m):				0.04	-0.90	-1.15

[1.] Field observations from ADCP and bathymetric survey data. Georeferenced data unavailable for FT2.

[2.] Reference gauge refers to either BCH ALH/HLK gauge for Keenleyside or USGS gauge 12399500 for Waneta. No gauge data available for Kinnaird reach.

[3.] HEC-RAS WSE estimates obtained from stations and modelled discharge values in: Bruce, J.A. 2016 Fate Modeling of Air Supersaturated Waters in the Columbia River (Phase 1).

5.3.3. Bed Roughness and Calibration/Validation

An overall summary of River2D flow calibration and validation is provided in Table 13. Global bed roughness (ks) values of 0.30 to 0.60 were assigned for each study area using ADCP depth measurements from Field Trip (FT) 1 to optimize values. Bed roughness was increased incrementally from 0 to 1.50 until the predicted depth and velocity from River2D provided the closest match to the observed depth and velocity from the ADCP transects (Table 13). External validation of the roughness values from FT3 and FT4 suggest that these estimates were adequate for flow simulations. It should be noted that trial applications of distributed roughness values across the study areas had a relatively minor effect on flow simulations compared to the depths and large cross-sectional area of the Columbia River.

Supplementary 'detailed flow simulation diagnostic plots' were created for this project to show the location-specific alignment between the River2D flow simulations and the ADCP measurements

(Appendix E). Samples of these diagnostic plots are shown for the restoration areas of Keenleyside (Figure 23) and Waneta (Figure 24), which indicate good agreement between observed and modelled velocity magnitude and direction in these areas.

Table 13. River2D finalized model parameters and accuracy metrics from calibration and validation.

River2D Run Type	Field Trip	Study Area	Inflow Discharge (m^3/s)	E1	E2	E3	Mean Bottom Roughness	Error (River2D - ADCP)[1] Velcity Difference (m/s)	WSE Differenc (m)	Flow Direction Difference (°)[2]
Calibration	FT1	Keenleyside	1,103.9	0.01	0.50	0.05	0.50	-0.06	-0.04	-1.30
		Kinnaird U	2,688.4	0.00	0.50	0.00	0.30	-0.04	-0.04	-1.80
		Kinnaird L	2,688.4	0.00	0.50	0.00	0.60	-0.03	-0.06	-1.80
		Waneta	3,873.6	0.00	0.50	0.05	0.30	0.09	-0.05	-3.30
Validation	FT3	Keenleyside	779.2	0.01	0.50	0.05	0.50	0.18	0.03	3.80
		Kinnaird U	1,370.0	0.00	0.50	0.00	0.30	0.14	0.18	-5.00
		Kinnaird L	1,370.0	0.00	0.50	0.00	0.60	0.18	0.04	0.50
		Waneta	2,024.7	0.00	0.50	0.05	0.30	0.10	-0.08	-0.60
	FT4	Keenleyside	1,303.7	0.01	0.50	0.05	0.50	0.10	-0.21	-14.50
		Waneta	1,863.2	0.00	0.50	0.05	0.30	-0.01	-0.30	-3.30
Absolute mean difference between River2D predictions and ADCP observations								0.08	0.09	3.26

[1] Error is reported as the mean of River2D predictions minus ADCP observations.

[2] Flow direction was converted to absolute degrees prior to calculating the difference between values.

Figure 23. Sample hydrodynamic model calibration velocity plot for a hydraulic transect (blue line in top left panel) located in the Keenleyside restoration area (FT1). Top-middle plot is oriented looking upstream.

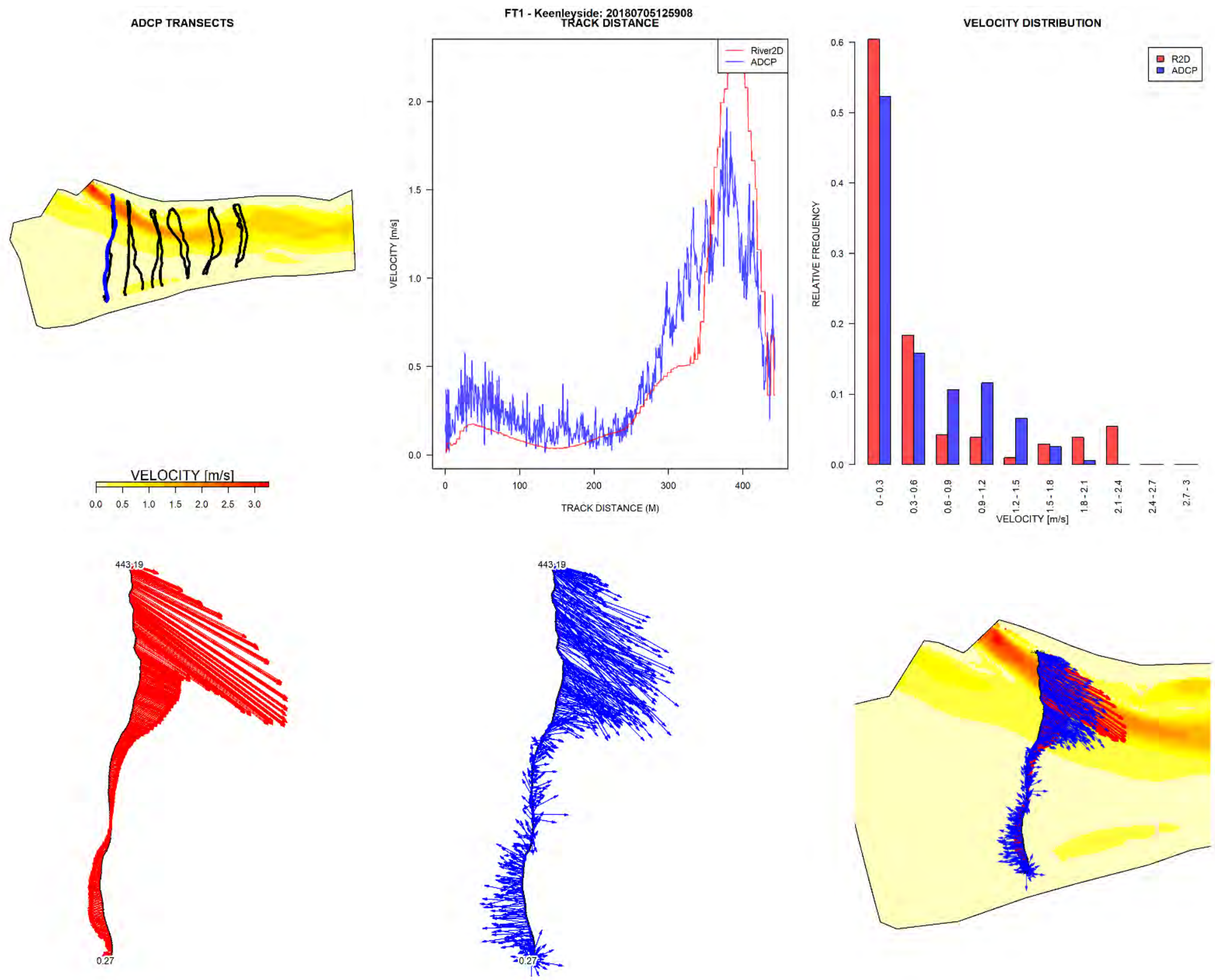
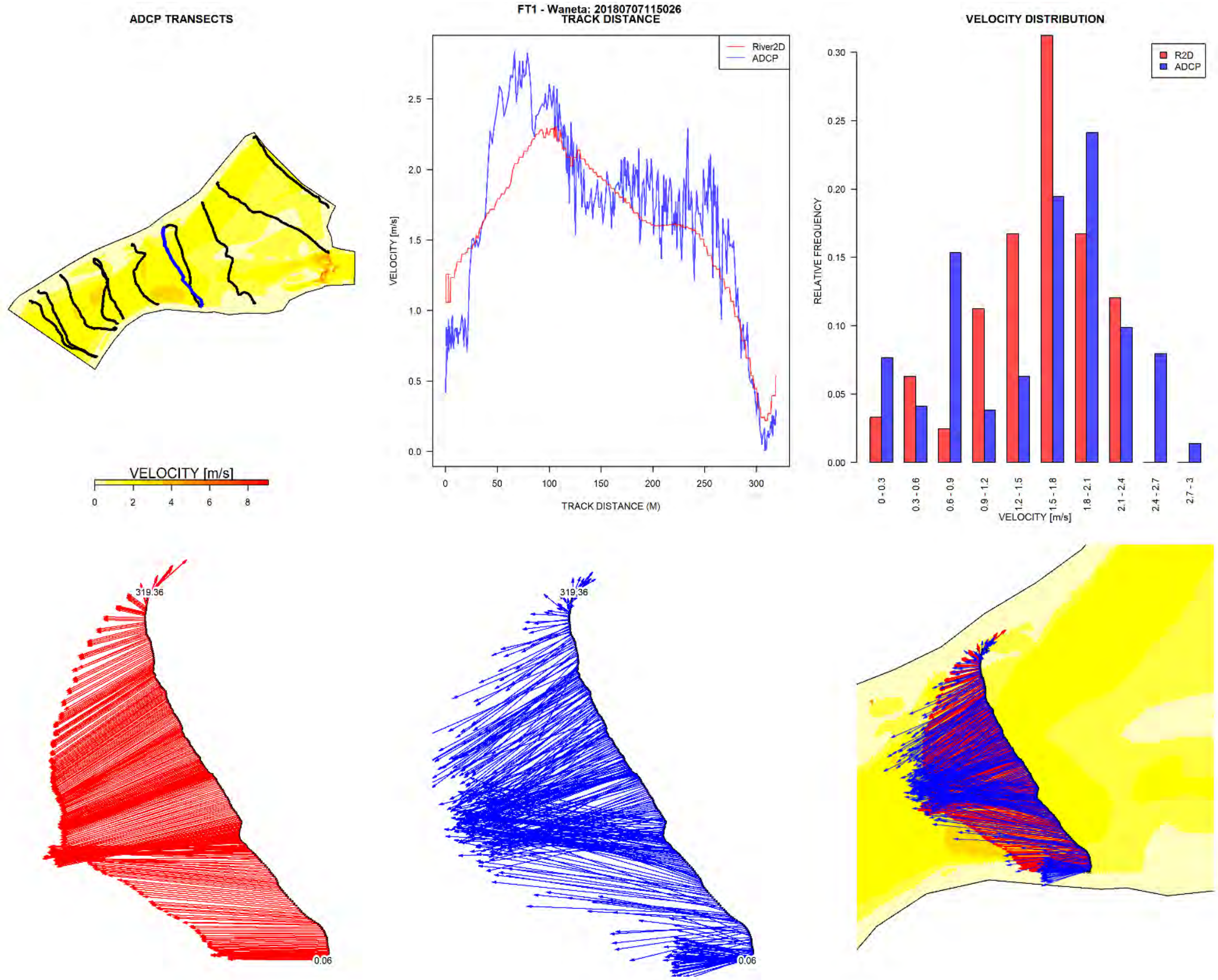


Figure 24. **Sample hydrodynamic model calibration velocity plot for a hydraulic transect (blue line in top left panel) located in the Waneta restoration area (FT1). Top-middle plot is oriented looking downstream.**



5.3.4. Simulated Flows

Flow combinations that were simulated for each spawning area are shown in Table 6, and bed shear stress distributions are shown for each simulation in Figure 25 and Figure 26. Example velocity vectors maps are provided for each spawning area in Appendix F. The following subsections include a rationale for the selection of flows for each objective described in Section 4.3.6. For each flow, the purpose of the simulation, flow distribution, calculation details, and frequency information are described.

Figure 25. River2D shear stress outputs for each Keenleyside simulation. Polygon labels are shown in Map 2.

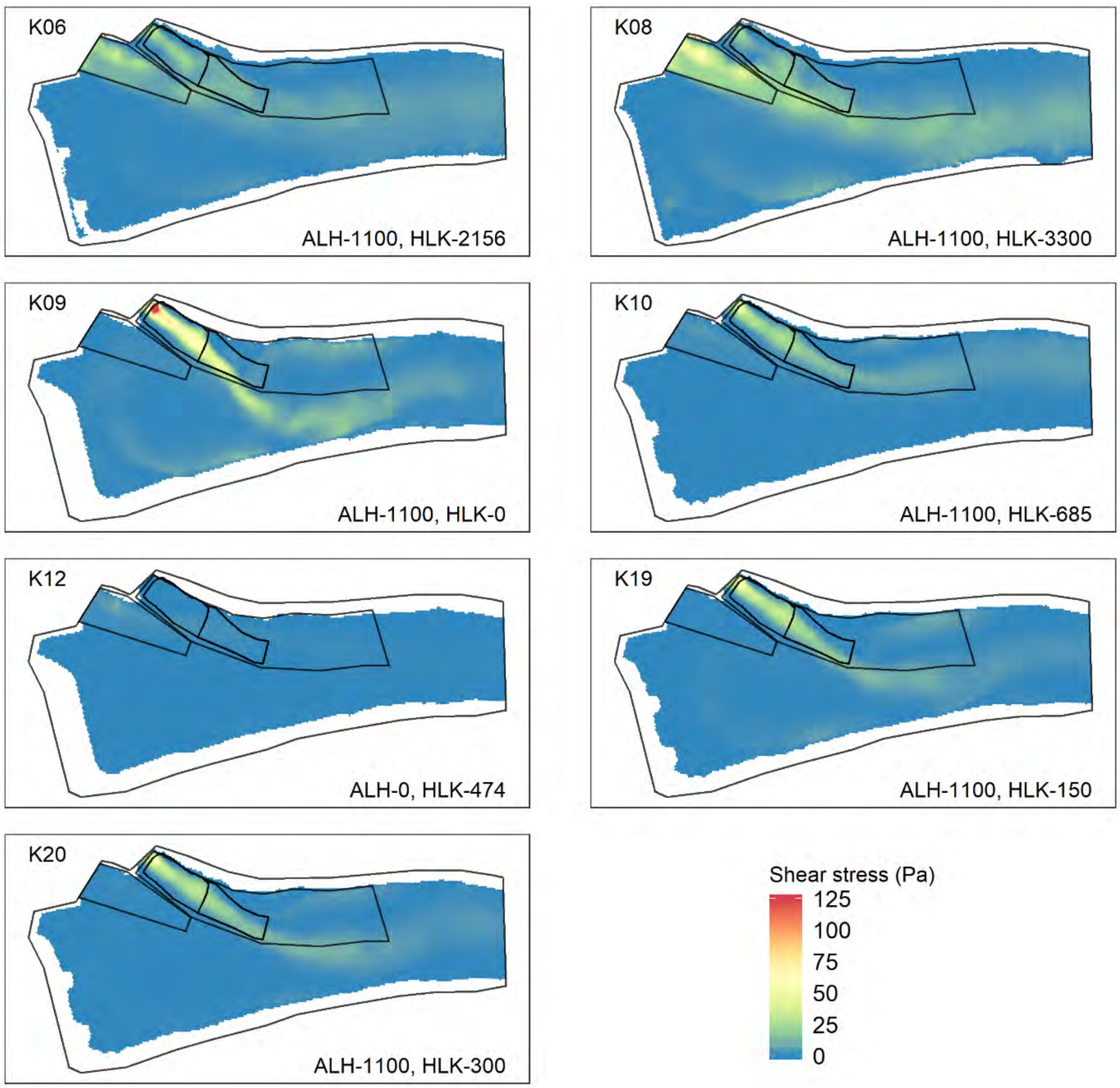
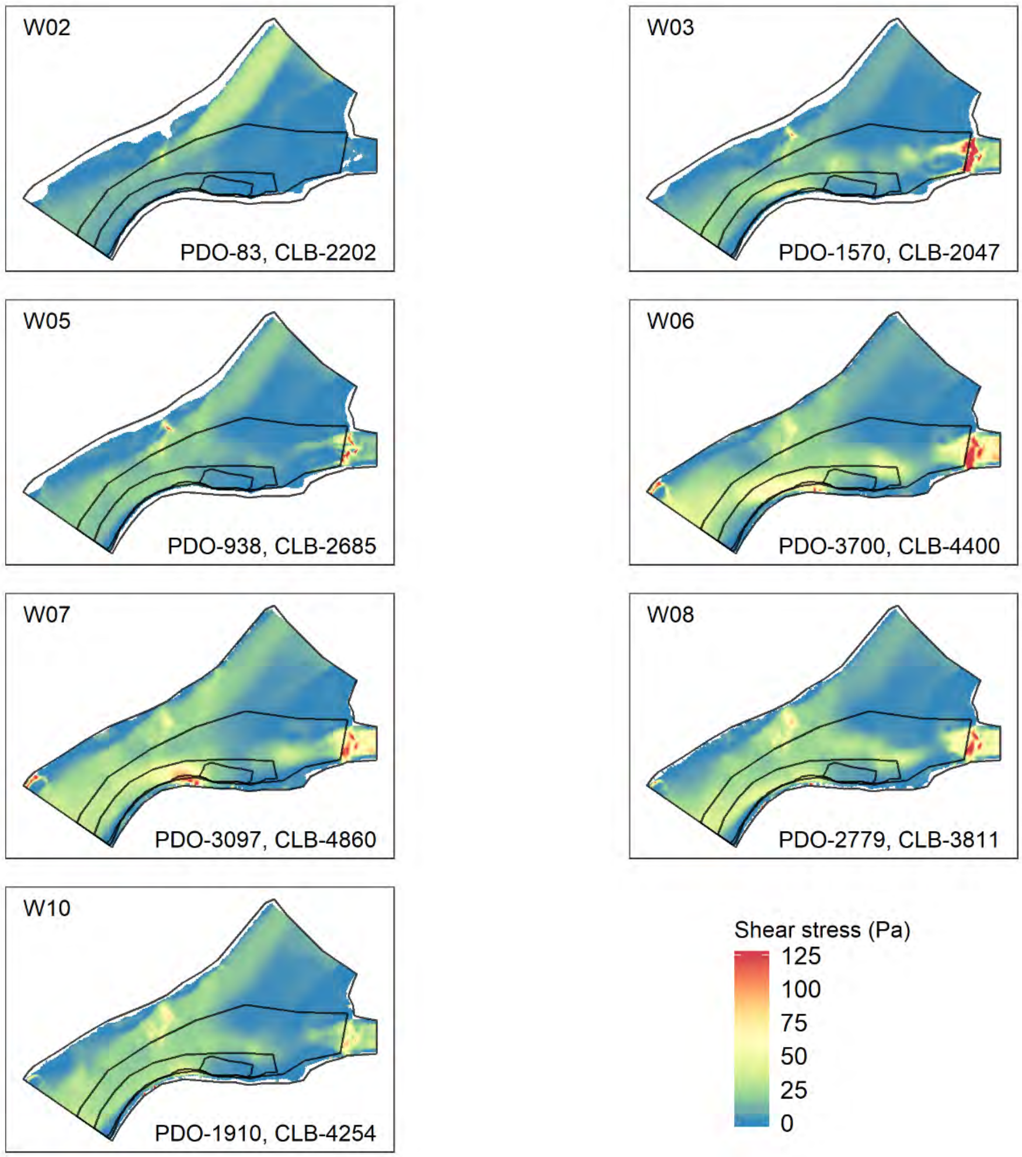


Figure 26. River2D shear stress outputs for each Waneta simulation. Polygon labels are shown in Map 3.



5.3.4.1. Peak and Low Flow Frequency Analysis

Return periods for annual low flows and peak flows were calculated for PDO and LCR (also referred to as CLB) to support selection of Waneta flow simulations. The date range assessed included 1984-2017. The most recent dam constructed on the Columbia River system was the Revelstoke Dam in 1984, therefore, only flows after 1984 were used for frequency analysis. Return periods for relevant flows are shown in Table 6. Further details of the flow frequency analysis can be provided upon request.

5.3.4.2. Calibration & Validation

The flows used for calibration and validation corresponded to field trip 1, 3, and 4 when hydraulic sampling was completed. A selection of these simulations were included in sediment transport analysis to provide an indication of transport conditions at intermediate flows between the more rare conditions that were assessed.

5.3.4.3. Highest Shear Scenario in Restoration Area (Coarse Scour)

For both Waneta and Keenleyside, an initial set of flow combinations were simulated that were expected to provide worst case (highest) scour conditions for coarse material at each of the restoration areas. Shear stress outputs (e.g., Figure 25 and Figure 26) were reviewed to determine other flow combinations that should be simulated to ensure that worst case conditions are known.

The flows selected for analysis of coarse material scour conditions at Keenleyside included the two highest HLK peak flows on record (1997 and 2012), and scenarios where ALH was at full capacity (1100 m^3/s) and HLK was low. During the preliminary analysis, it was noted that the greatest scour conditions at the ALH EDZ likely occurred when ALH was at full capacity and HLK was zero. This appears to be a result of lower water depth and backwatering conditions that occur at the EDZ. Simulations were also completed with modest amounts of flow through HLK while ALH was at capacity, to determine if some flow from HLK could increase scour in the ALH restoration area.

In the HLK tailrace and further downstream within and adjacent to the EDZ DS restoration area, high HLK flows were more influential on shear conditions, especially on the river right side of EDZ DS. Therefore, the 1997 and 2012 simulations were also reviewed to assess the scour conditions in these areas.

At Waneta, it was assumed that the greatest scour conditions would occur with high peak flows from PDO. This assumption was based on review of the velocity vectors and shear patterns in preliminary results and based on Fissel *et al.* (2017) analysis. Peak PDO flows that were modelled consisted of the 1997 and 2012 extreme flow years, as well as a 5-year return period peak flow with corresponding mean flow from Columbia while flows are higher than the PDO 5-year return flow. To confirm that PDO was the dominant control of shear conditions in the spawning area, a simulation was also completed with 5-year return period peak flow in Columbia river, with corresponding mean flow from PDO while flows are higher than the Columbia 5-year return flow.

At Kinnaird, the 2012 peak flow was used to develop a general sense of worst-case scour conditions. Further analysis was not completed given that there were no Tier 1 Kinnaird restoration alternatives.

5.3.4.4. Fines Settling Risk (Fines Settling)

Assessment of fines settling risk was assessed by simulating low flow conditions of various frequency. It was assumed that fines could be supplied to each restoration area either through upstream sources or due to secondary circulation. Discussion of the supply rate of fines is discussed in Section 5.4.3.

At Keenleyside, review of preliminary simulations indicated that fines deposition conditions likely occurred at the EDZ and EDZ DS when ALH was nearly zero, and at the HLK tailrace when HLK was nearly zero. To examine these conditions, three scenarios were simulated including the 5th percentile low flow at HLK while ALH is not flowing, and the mean annual flow at HLK while ALH is not flowing. A flow frequency approach was not used for HLK since the HLK tailrace restoration was a Tier 2 alternative, instead Field Trip 3 was used to assess depositional risk.

At Waneta, it was assumed that fines settling risk in the restoration area would be worst when PDO flow was low. This was based on review of preliminary results and the model work done by Fissel *et al.* (2017). Two flows were selected consisting of the 5th and 50th percentile annual low flow from PDO and the corresponding mean from Columbia River while flows are less than the PDO condition. These flows were selected to present extreme and typical annual settling conditions, respectively.

Deposition characteristics at Kinnaird were reviewed using FT3 conditions, which were relatively low. Further analysis was not completed given that there were no Tier 1 Kinnaird restoration alternatives.

5.3.4.5. Low Annual Peak Flow (Fines Flushing)

Based on previous analysis done by Fissel *et al.* (2017) and discussions in Workshop One, it was assumed that a proportion of deposited fines in the Waneta EDZ may be flushed on a nearly annual basis. The degree to which fines are flushed and the frequency was assumed to depend on the magnitude of the annual peak flow for each location. Furthermore, during years with weak freshets, it was speculated that rearing habitat could be compromised for the following year. At Keenleyside, peak flushing conditions at the EDZ and EDZ DS were assessed to occur every year when ALH was at capacity and HLK was low. At Waneta, the 5-year return low PDO freshet was simulated to determine if relatively weak freshets could flush material.

Analysis of Kinnaird flushing conditions was not completed given that there were no Tier 1 Kinnaird restoration alternatives.

5.3.4.6. Typical Spawning Flow Conditions (Habitat Suitability)

To determine the appropriate flow to use to assess habitat suitability, the typical conditions during the spawning period were assessed for Keenleyside and Waneta.

At Keenleyside, the spawning period was assessed to occur during July and August, while ALH is at full capacity. The corresponding median HLK flow was taken to be the median from July to August. The sturgeon expert team recommended removing known low flow years (1973, 1977, 1992, and 2001); however, the data set for Keenleyside flows started after these dates.

At Waneta, the spawning period was assumed to occur on the receding limb of PDO freshet. A representative value for PDO was calculated using the median flow from the peak of freshet to the beginning of August, with low flows removed as per the sturgeon expert team recommendation.

The corresponding Columbia River flow was calculated as the mean during receding limb of PDO freshet.

Habitat suitability conditions at Kinnaird were assessed using the Field Trip 1 simulation, which was assessed to be relatively close to typical spawning conditions. Further analysis was not completed given that there were no Tier 1 Kinnaird restoration alternatives.

Details of how these simulations were used to determine habitat suitability are provided in Section 4.5.

5.4. Sediment Transport Modelling

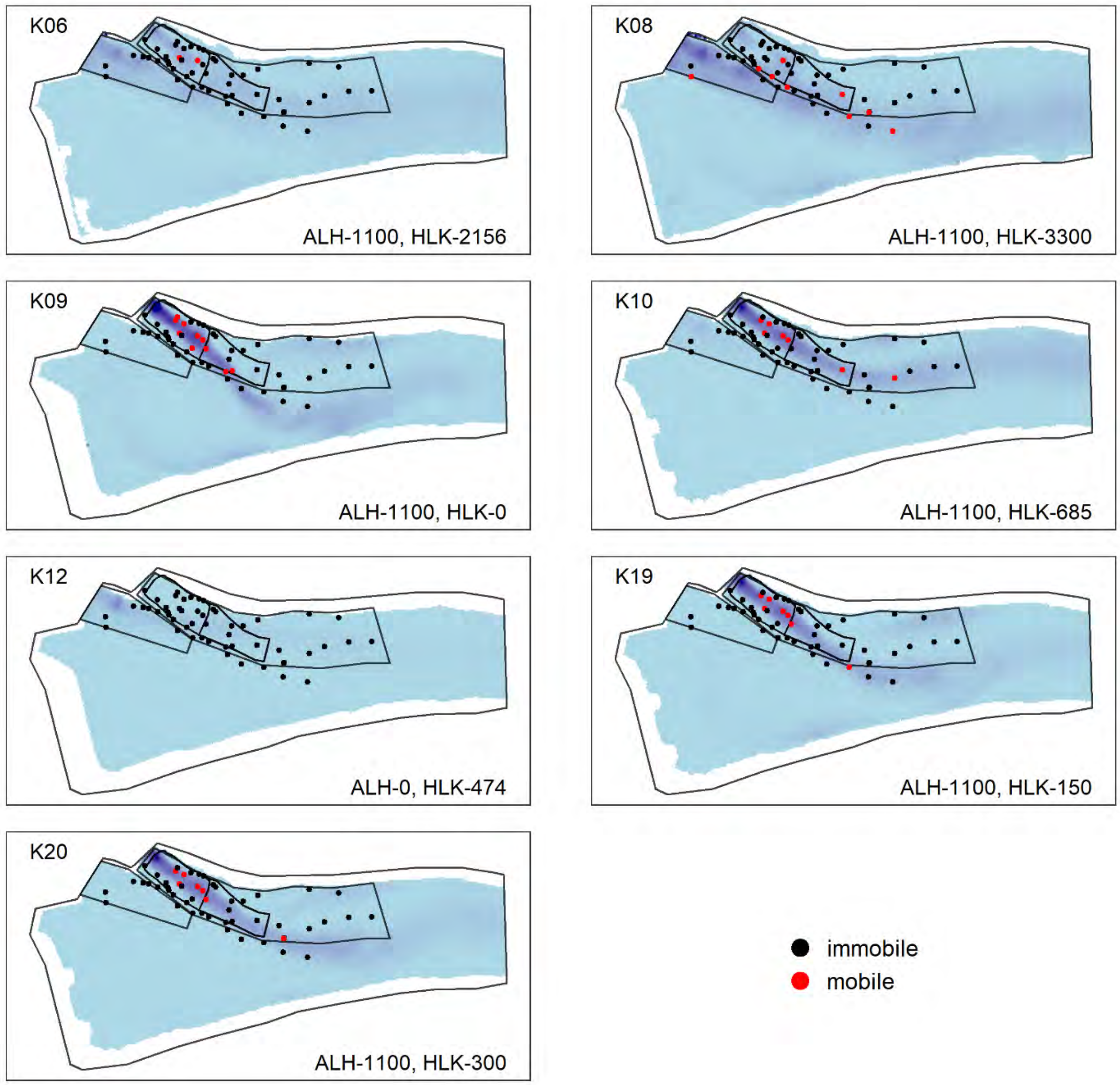
Sediment transport modelling included assessments of potential mobility of existing bed sediment for modelled flow scenarios with two distinct transport models, an analysis of fine sediment sources that could affect restoration areas through secondary circulation transport and upstream supply, and an assessment of patterns of scour and fill measured through bathymetric surveys at Waneta between 2004 and 2018 as an indicator of ongoing geomorphic change. Taken together, these multiple lines of evidence provide insight into patterns of sediment mobility under different flow conditions and support the comparison of restoration alternatives to existing conditions.

5.4.1. Single Grain Size (Shields 1936)

5.4.1.1. Keenleyside

Results from the Shields (1936) model that treats the sediment mixture as a single size represented by the D50 are shown for Keenleyside in Figure 27. Transport predictions of existing material varied based on simulation and were strongly controlled by the relative contributions of ALH/HLK. At Keenleyside, the simulation that produced the most mobility of existing material within the restoration area was K09 (HLK-0, ALH-1100), with high shear stress values downstream of the ALH tailrace leading to a predicted 56.2% mobility of points in the EDZ and 28.6% in the EDZ DS. High flows from ALH drive most of the mobility in areas of interest; as HLK flows increase with ALH at capacity (e.g., K20, K10), points directly within the EDZ and EDZ DS show reduced mobility. In general, points outside the high energy current of ALH flow show limited mobility, but the position of this jet varies based on relative flows from ALH and HLK. Under conditions when HLK flows are high (K08) more points along the seam between ALH and HLK tailraces are mobile, with reduced mobility in the EDZ and EDZ DS despite the fact that ALH is still running at capacity.

Figure 27. Predicted mobility of existing material using the Shields model at Keenleyside. Polygon labels are shown in Map 2.



Restoration alternatives were also assessed with the Shields model. Figure 28 shows the predicted mobility with placement of the ideal sturgeon substrate (D50-125) within each treatment zone polygon (EDZ, EDZ DS, and HLK) at Keenleyside. Given the large size of the D50-125 placement material and the conservative entrainment thresholds from the Shields method, the material was predicted to remain stable under all simulated flow conditions except for isolated mobility immediately downstream of ALH in the K09 simulation. For the gravel mixture alternative (D50-35; Table 7), the Shields method predicted more areas of the bed to be mobile, particularly in simulations when ALH was running at capacity and HLK flows were moderate to low.

Figure 28. Predicted mobility of placed ideal sturgeon substrate (D50-125) at Keenleyside using the Shields model. Polygon labels are shown in Map 2.

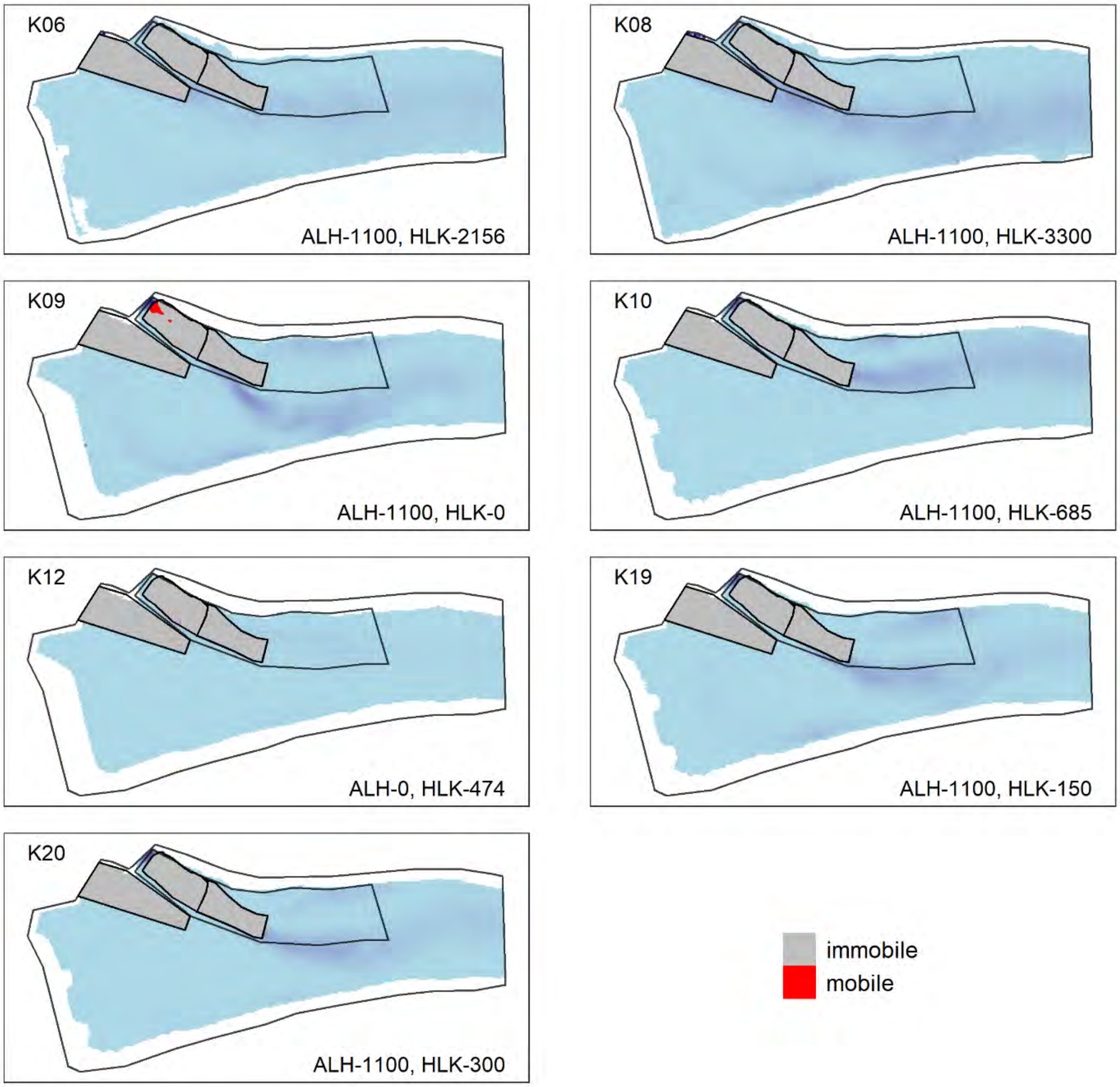
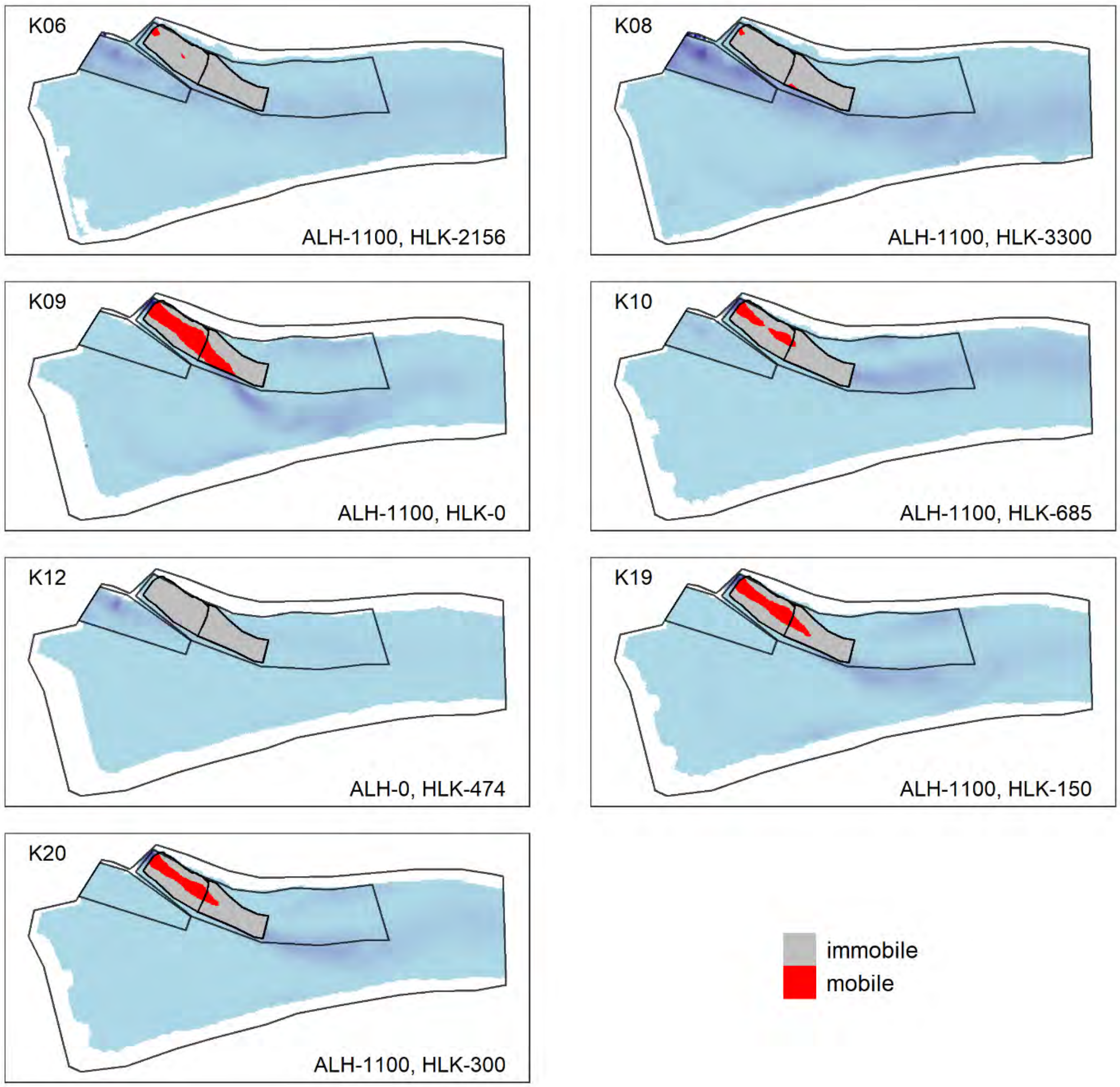
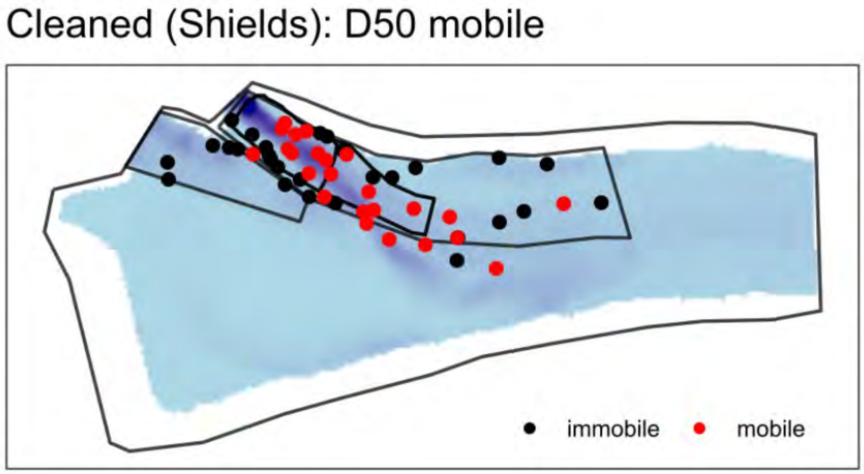


Figure 29. Predicted mobility of gravel mixture placement (D50-35) at Keenleyside using the Shields model. Polygon labels are shown in Map 2.



Effects of cleaning existing substrate were also assessed at Keenleyside by applying the Shields model with the Shields parameter (transport threshold) reduced from 0.047 to 0.038 (Figure 30). Multiple flows were used for this analysis to create a composite of the maximum shear from each flow scenario. The results show that the transport of material finer than D50 would be increased substantially, which could lead to erosion of ideal sturgeon material from this region.

Figure 30. Locations where the Shields model predicts that existing bed material would be mobilized following cleaning. Polygon labels are shown in Map 2.



5.4.1.2. Waneta

At Waneta, high flow releases from PDO appear to drive most of the potential sediment entrainment of existing material in the areas of interest as predicted by the Shields model (Figure 31). Scenario W06 (PDO-3700 m^3/s, LCR-4400 m^3/s) shows the most mobility in the EDZ (34.4% mobility of sediment measurement points) and restoration area (27.3% mobility), whereas scenario W07 (PDO-3096 m^3/s, LCR-4860 m^3/s) shows that a reduction in PDO flows and an increase in LCR flows leads to slightly lower mobility in the EDZ (28.1%). When PDO flows are low (e.g., W02), sediment mobility in the EDZ is much lower. The treatment alternative of placement of the ideal sturgeon substrate (D50-125) within the restoration area was also assessed at Waneta using the Shields approach (Figure 32); no mobility was predicted given the large size of placed material and low overall flow forces in the direct vicinity of the restoration area. It is noted that shear stresses increase substantially just downstream of the proposed restoration area.

Figure 31. Predicted mobility of existing material at Waneta using the Shields model. Polygon labels are shown in Map 3.

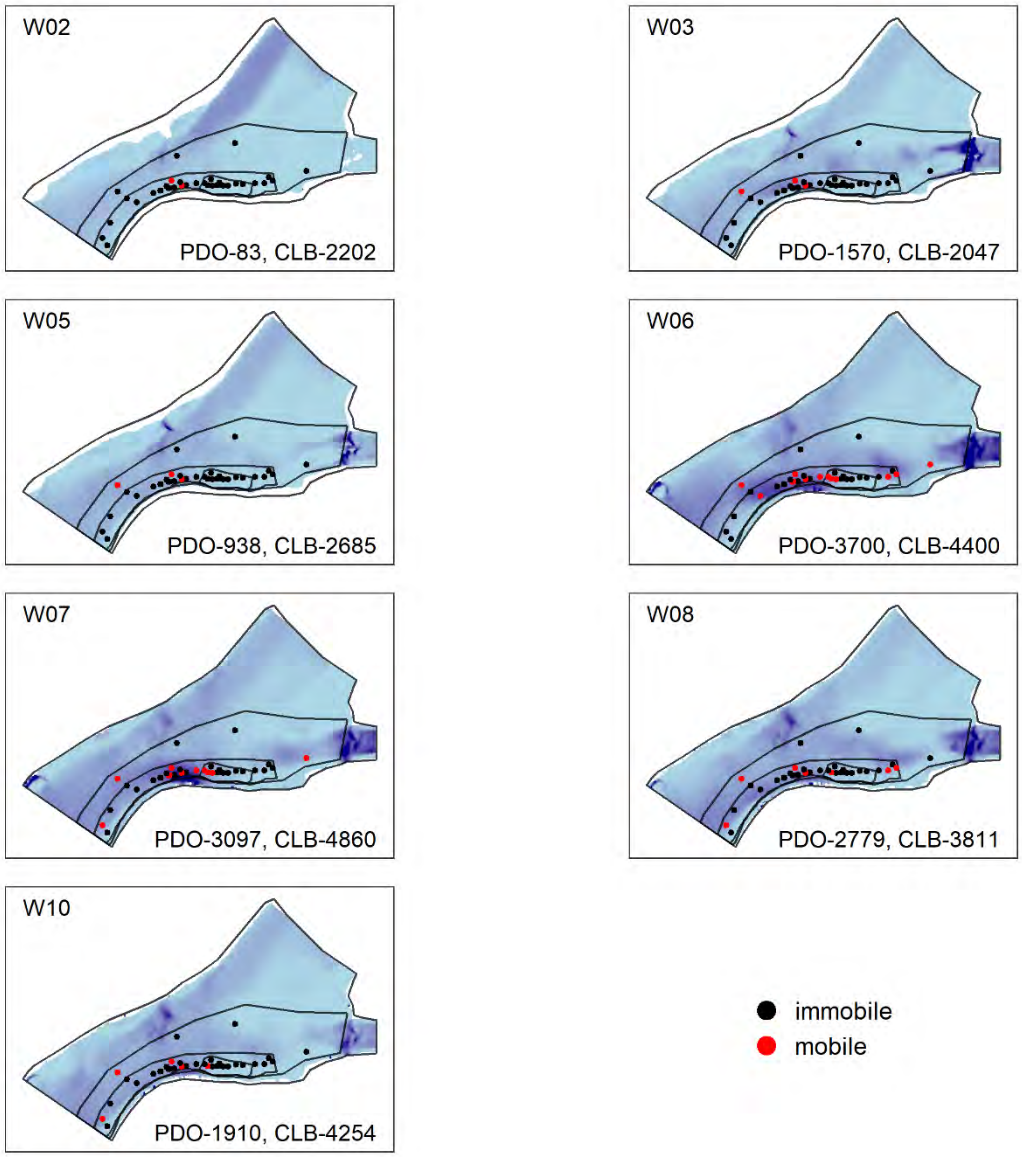
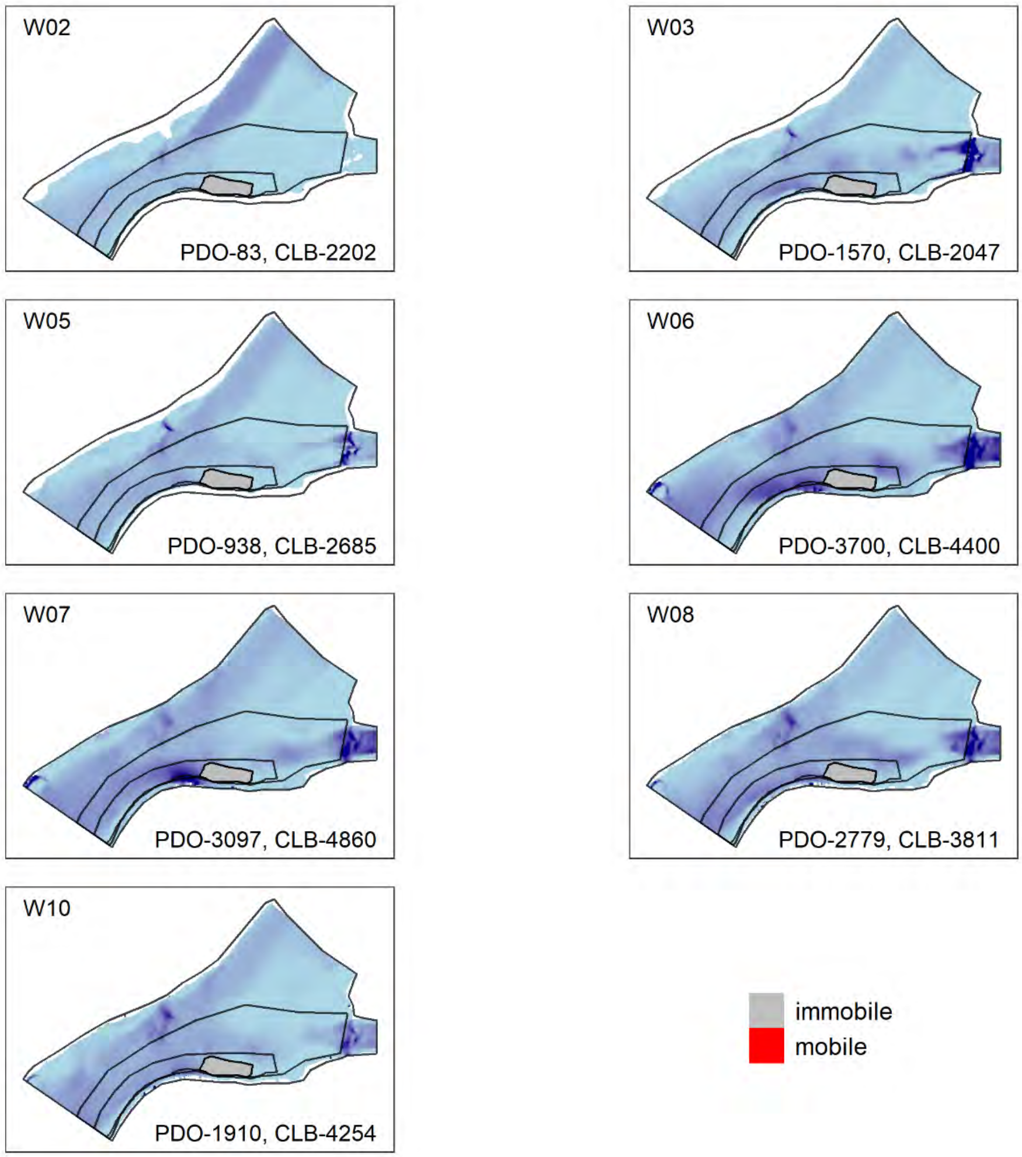


Figure 32. Predicted mobility of placement of ideal sturgeon substrate (D50-125) at Waneta using the Shields model. Polygon labels are shown in Map 3.



5.4.2. Multi-Grain Size (Wilcock and Crowe 2003)

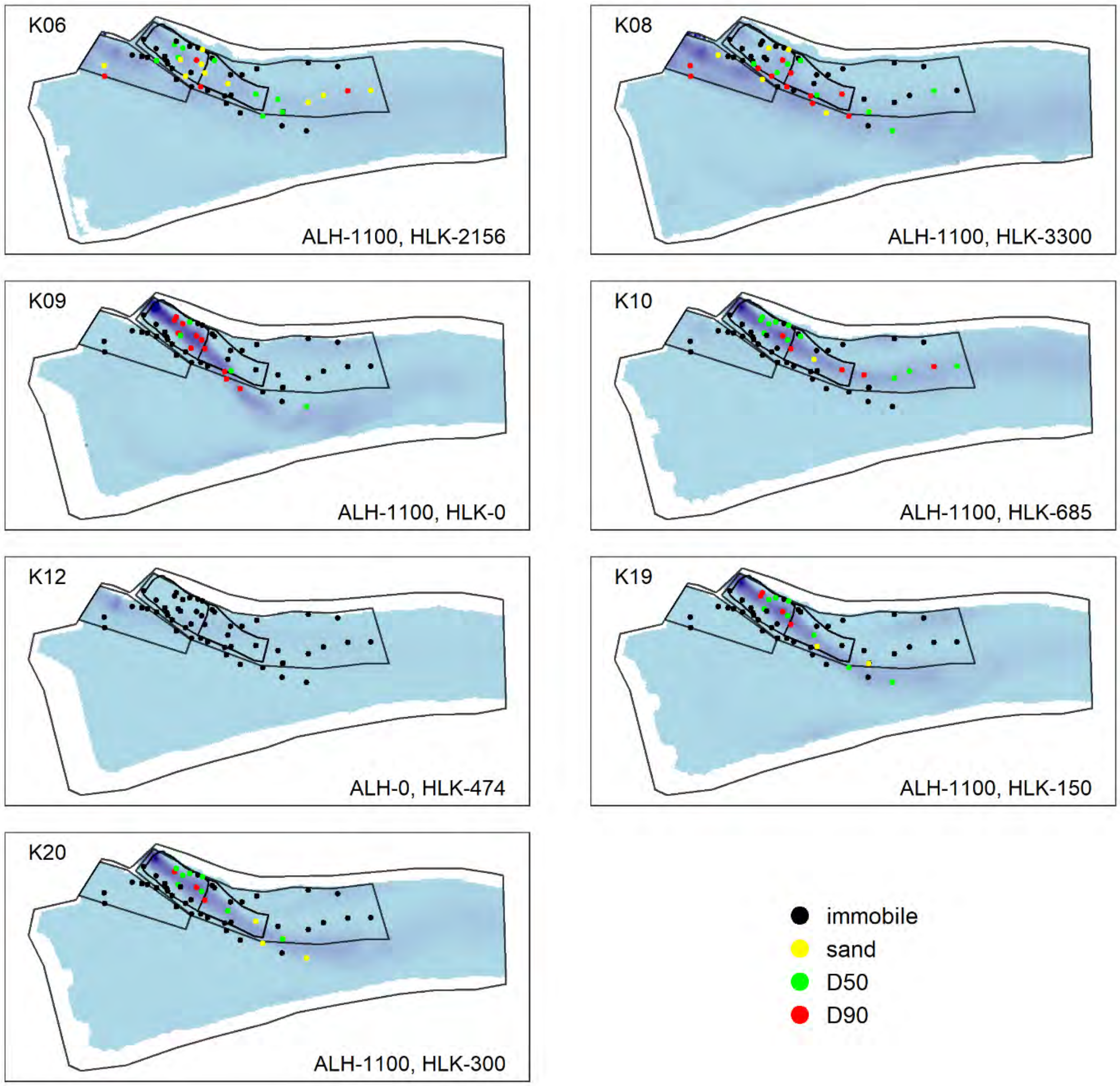
The mixed-size transport model of Wilcock and Crowe (2003) allows a more detailed investigation of differences in entrainment thresholds for different size fractions based on the characteristics of each grain size distribution and the effects of hiding between small and large grains.

5.4.2.1. Keenleyside

The Wilcock and Crowe predictions align in a general sense with those of Shields; the greatest predicted transport of existing bed material at Keenleyside is found during the K09

(ALH-1100, HLK-0) simulation conditions (Figure 33). This combination of flows, which happens at least once a year, leads to strong transport conditions and predicted mobility of the coarse fractions (D50 and D90) throughout parts of the EDZ (D50 mobility = 56.2%, D90 mobility = 43.7%) and EDZ DS (D50 mobility = 28.6%, D90 mobility = 14.3%). In fact, transport conditions under K09 are such that there are no points where sand is mobile but the D50 is immobile, suggesting that fine sediment may be trapped in the grain size matrix until the D50 size class starts to move. According to the definition of thresholds of entrainment that the Wilcock and Crowe model is built on, very small transport rates indicate mobility, so the predicted mobility in this area does not necessarily mean that material is being transported away in large quantities. Instead, the predictions could indicate that thresholds are exceeded but overall transport rates are not large and that sediment moves just enough to prevent fouling and infilling. This degree of transport is generally supported by qualitative observations of recent bed sediment transport (Section 5.2.3), despite the lack of coarse material supply to Keenleyside. As shown in the Shields analysis, the position of the jet of highest shear stress shifts with relative ALH/HLK contributions. This effect controls where entrainment of different size fractions occurs. For example, the K08 scenario (ALH-1100, HLK-3300) shows more sand and D50 mobility towards the middle of the river in the area between ALH and HLK tailraces compared to K09 where mobility is confined spatially to only below ALH but is more intense locally. While these patterns of coarse size mobility under high flow conditions are important considerations for material turnover rates and potential longevity and function of restoration alternatives, low flows and fine sediment dynamics are also important. During typical annual low flows (K12, ALH-0, HLK-474), there are no points where sand is able to be transported. This indicates that deposition of fine material can happen anywhere during these conditions, although transport of sand is low in most areas under these conditions.

Figure 33. Predicted mobility of existing material from the Wilcock and Crowe model at Keenleyside. The largest size mobile fraction is shown. Polygon labels are shown in Map 2.



Assessing Keenleyside restoration alternatives with the Wilcock and Crowe model provides more insight into potential fractional transport patterns that the Shields model is incapable of predicting. Figure 34 shows predicted mobility of placed ideal sturgeon substrate within the EDZ, EDZ DS, and HLK treatment zones. As before, K09 causes the most predicted entrainment, particularly in the EDZ where the D50 is mobile in 35.6% of the area and the D90 is mobile in 12.6%. Mobility is reduced in the EDZ and EDZ DS when HLK flows increase even when ALH remains at capacity (e.g., K10, K19, K20); mobility in these cases is mainly limited to flushing of fine sand. When HLK flows are even higher (K06, K08), fine sand is predicted to start to mobilize within the HLK treatment zone. For the gravel placement alternative where smaller material is placed in the EDZ and EDZ DS (Figure 35), mobility is enhanced and some level of fine sand or D50 transport is predicted for all simulations where ALH is running. Under the highest shear conditions (K09), the D90 is predicted to be mobile in 41.1% of the combined EDZ+EDZ DS restoration area.

Figure 34. Predicted mobility of ideal sturgeon substrate placement (D50-125) at Keenleyside using the Wilcock and Crowe model. The largest size mobile fraction is shown. Polygon labels are shown in Map 2.

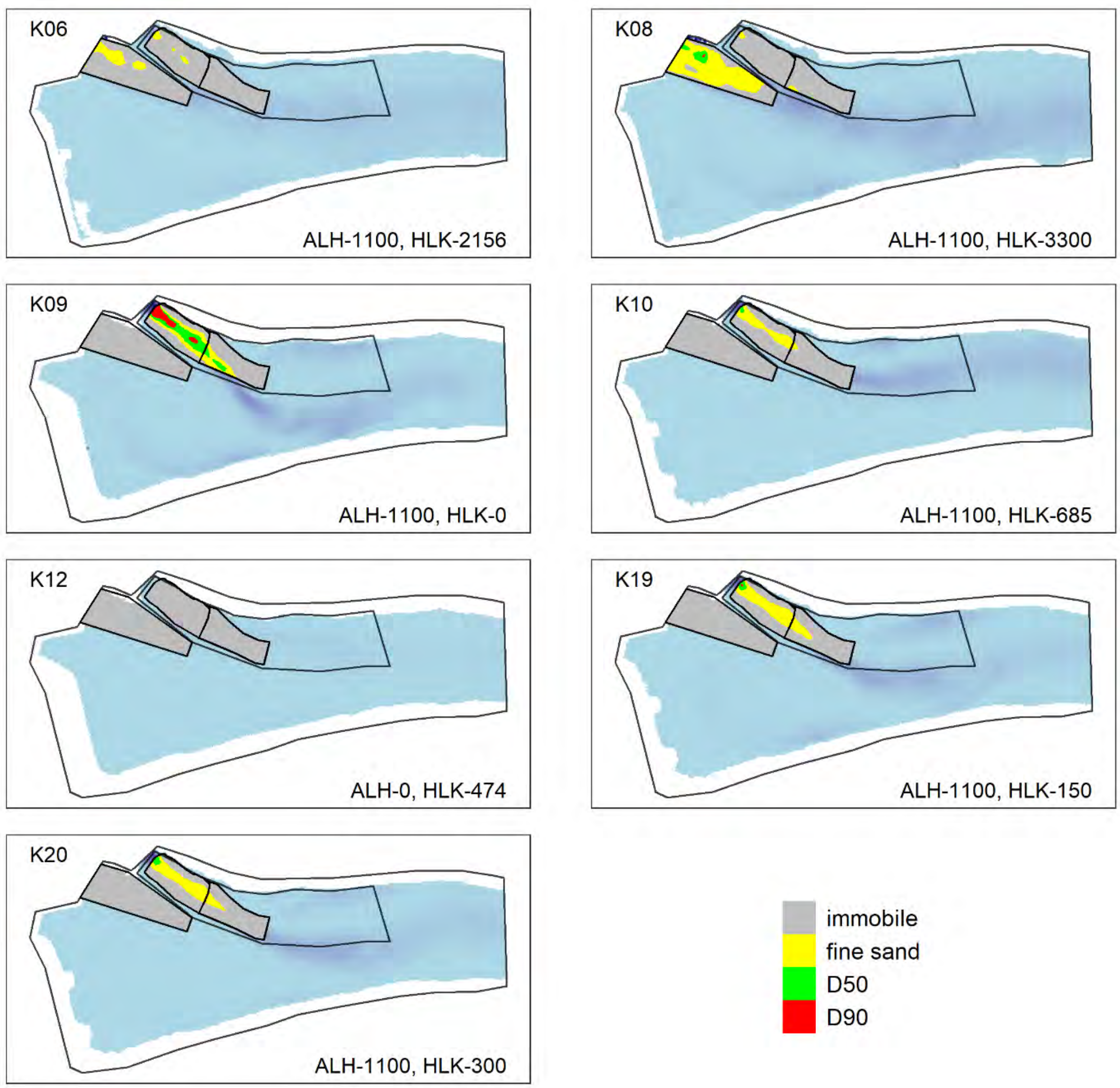
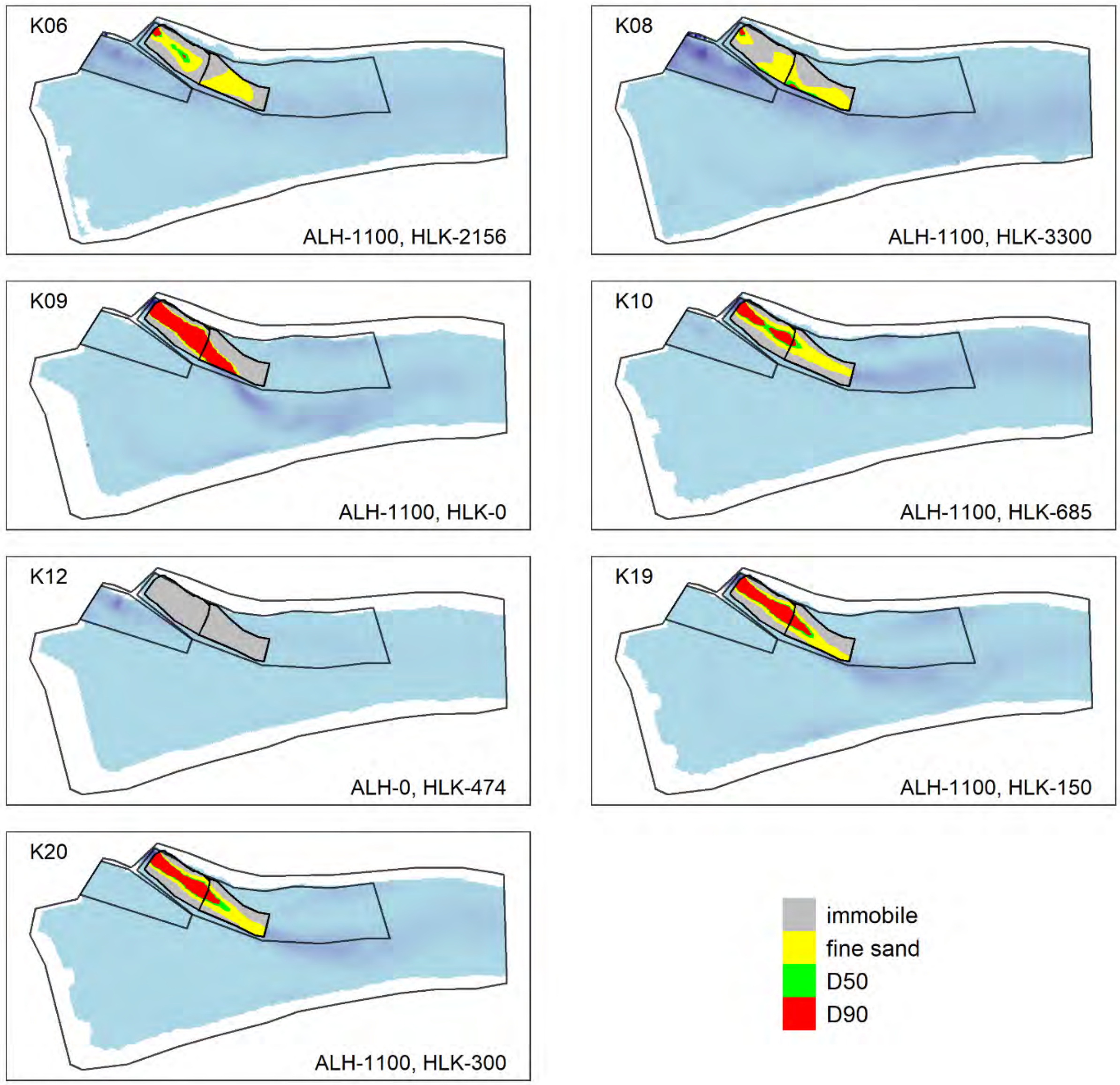


Figure 35. Predicted mobility of gravel mixture placement (D50-35) at Keenleyside using the Wilcock and Crowe model. Polygon labels are shown in Map 2.



5.4.2.2. Waneta

Results from the Wilcock and Crowe model analysis at Waneta (Figure 36) also reflect the conclusions from the Shields approach, but with shifted overall mobility rate predictions. The importance of high PDO flows is again emphasized; the greatest level of mobility is found under the W06 simulation (PDO-3700 m^3/s, LCR-4400 m^3/s). Under these flows, 37.5% of the D90 and 50% of the D50 within the EDZ are predicted to be mobile for existing conditions. Within the restoration area itself, 27.3% of both the D90 and D50 are predicted to be mobile. Similar conditions are predicted for simulation W07 (PDO-3097 m^3/s, LCR-4860 m^3/s), indicating that even with extreme flows less than one third of the restoration area would be mobilized. Some evidence of sediment movement was observed in this area during bed image review, likely associated with high flows during the 2018 freshet. This is somewhat contradictory to the findings of Fissel *et. al.* (2017) who predicted that this material would be mobilized annually. However, it is clear that this is an area of typically lower shear stress compared to adjacent regions. Field trips in 2018 identified limited fine material in this area; however, the 2018 freshet from PDO was the highest on record since 1997. Field trips in 2019 documented fines beginning to infill in this area. The same patterns are evident for the placement of ideal sturgeon substrate in the restoration zone (Figure 37), where mobility is limited to fine sand fractions on the downstream edge of the restoration zone and only when PDO flows exceed 3000 m^3/s (W06, W07).

Figure 36. Predicted mobility for existing material at Waneta using the Wilcock and Crowe model. Polygon labels are shown in Map 3.

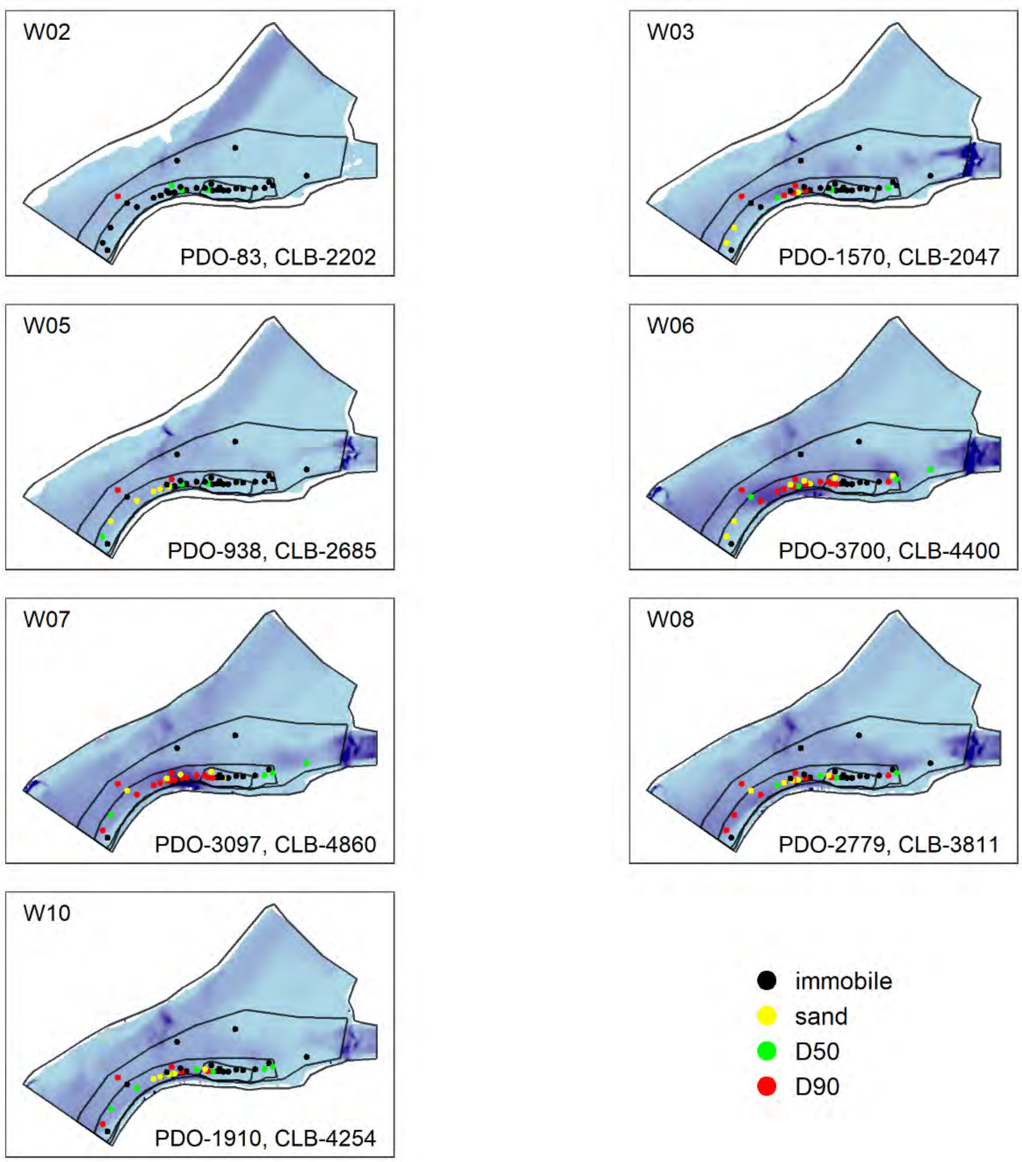
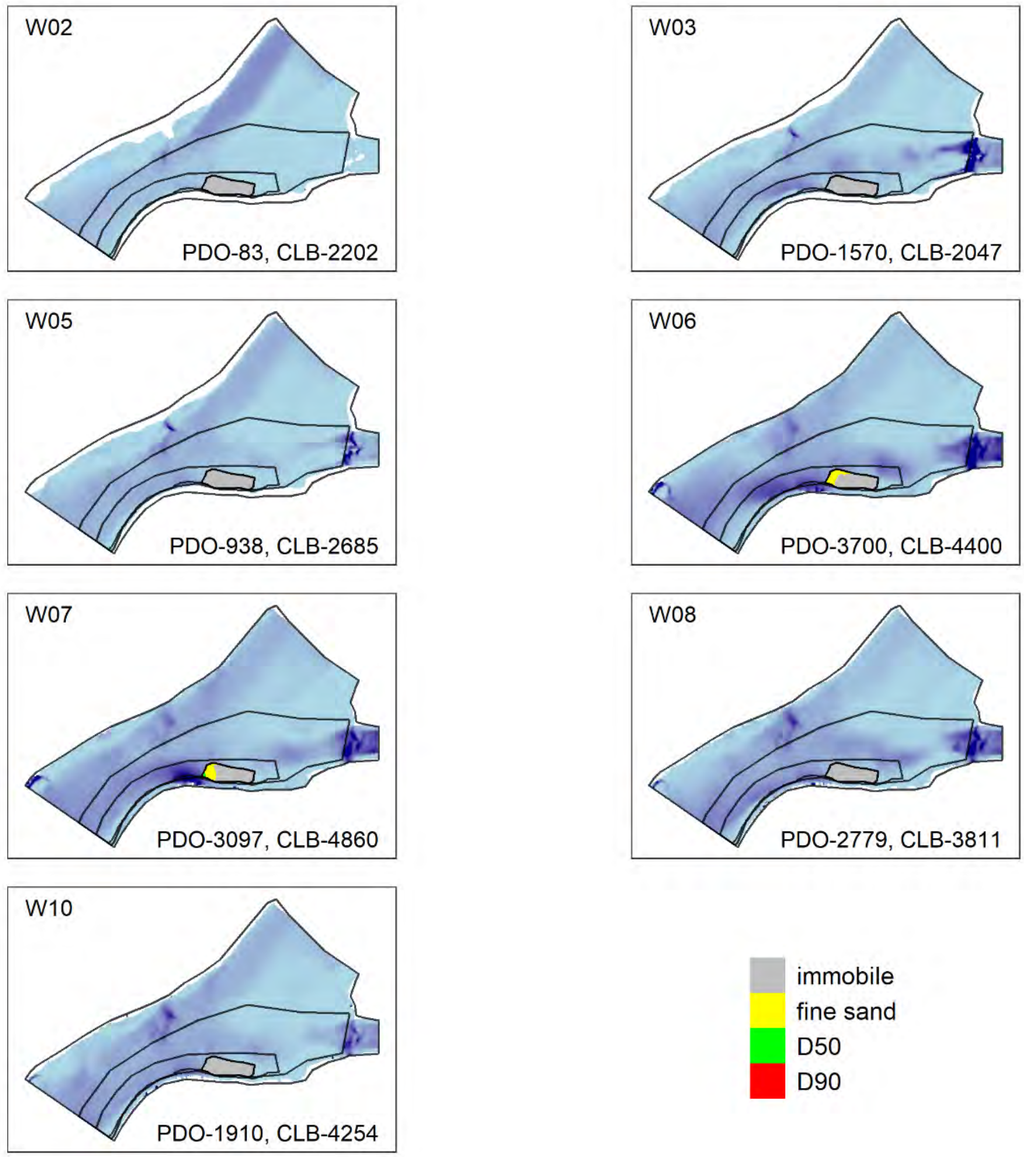


Figure 37. Predicted mobility of ideal sturgeon substrate placement (D50-125) at Waneta using the Wilcock and Crowe model. Polygon labels are shown in Map 3.



5.4.3. Sediment Supply (Secondary Flows Transport and Upstream Supply)

5.4.3.1. Keenleyside

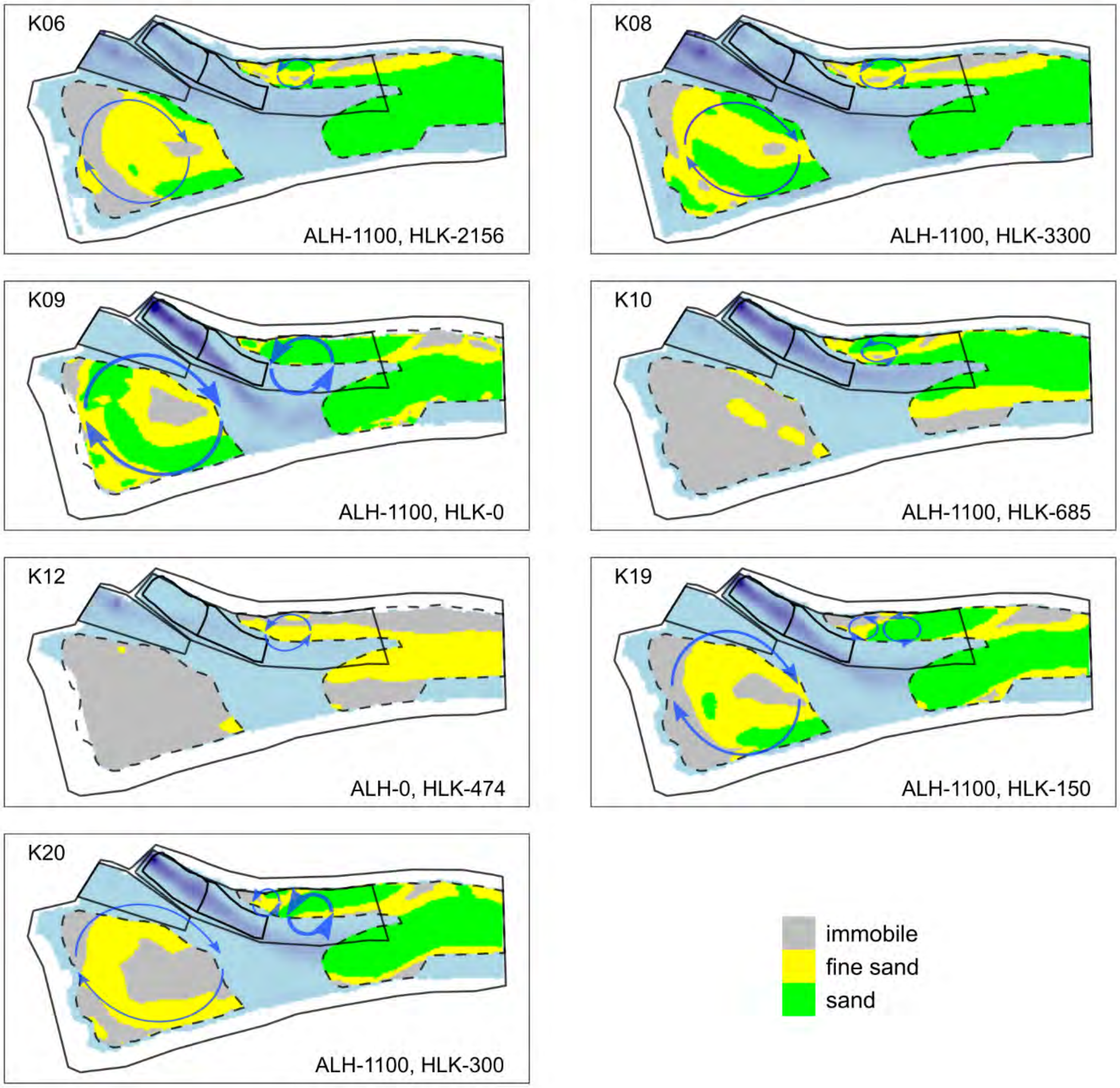
Supply of coarse material (larger than 2 mm) at Keenleyside is negligible since the site is immediately downstream of a lake and dam. Minimal suspended sediment is transported through the lake, and therefore it is expected that fines delivery (sands and fine gravels) to the restoration area is resultant of re-circulation of fine material that has been in the study area since completion of the Keenleyside dam in 1968, or that has entered from localized erosion. The condition when a flow combination similar to K09 (ALH is high and HLK is low) transitions to K12 (HLK is high and ALH is low) relatively quickly is expected to be responsible for moving fines from the HLK eddy to the upper spawning area. The HLK eddy is strongest while ALH is high and HLK is low and could transport fines to the HLK tailrace. If HLK begins to flow while ALH is reduced, then fines that had loosely deposited in the HLK tailrace could be pushed laterally to the head of the ALH tailrace (the EDZ). In the downstream portion of the spawning and restoration area (the EDZ DS), fine sediment may also be transported up from river left eddies that are present and relatively strong during all flow conditions (Figure 38).

Figure 38 indicates the mobility of fine sand or sand from the eddy areas during various flow combinations. It can be seen that sand can be transported to the HLK tailrace when ALH = 1100 m^3/s (fully capacity) and HLK = 0 m^3/s, and fine sand can be transported during modest HLK flows along with ALH at full capacity. Therefore, fines can likely be transported to the HLK tailrace, and it could be assumed that some of the fines would stay mobile (i.e., not become trapped in the interstitial spaces of the HLK tailrace substrate). Figure 34 indicates that fines could be flushed from the HLK tailrace during extreme flows that were exceeded in 1997 and 2012. However, a portion of fines may deposit above interstitial spaces occasionally and thus have a lower transport threshold.

A transition from ALH >800 m^3/s while HLK < 50 m^3/s to ALH < 50 m^3/s while HLK > 100 m^3/s within one or two days did not occur during the period of data availability (2010 to 2019). This implies that fines delivery to the top of the ALH tailrace could be extremely rare. Other lower flows were analyzed to identify a transition that has been observed. It was observed that a transition from ALH > 100 m^3/s while HLK < 50 m^3/s to ALH < 50 m^3/s while HLK > 100 m^3/s within one day did not happen, but a transition over two days happened on four separate occasions from 2010 to 2019. It is expected that these conditions are likely insufficient to mobilize material to the EDZ. However, the HLK eddy appears to be capable of delivering fines to the EDZ DS on a more regular basis, which aligns with observations of fines deposits in this area. The lower portion of the EDZ DS is also in contact with the river left eddies that likely deliver fines to the downstream extent on a more regular basis.

This analysis supports the observations of low fines percentage in the EDZ, and suggests that the furthest fines would typically migrate from the HLK eddy would be to the outer edge of the ALH tailrace jet where they were observed to have aggraded in a seam during 2018 sampling. Furthermore, this analysis suggests that progressive coarse material transport from the EDZ is unlikely to explain the lack of fines, meaning that if coarser material is placed the risk of fines infilling is low.

Figure 38. Predicted mobility of fines patches using the Shields model. Dashed lines indicate extent of digitized areas of fines sources; blue arrows indicate primary direction of eddy circulation. Polygon labels are shown in Map 2.



5.4.3.2. Waneta Restoration Area

Supply of coarse material and fines to the Waneta restoration area were both assessed to be moderately high. The upstream reach of LCR is dominated by coarse substrate in bed deposits and eroding banks. Additionally, evidence of recent transport of coarse material was observed throughout the Waneta area during summer 2018. Upstream banks and tributaries likely supply fines that could be diverted from the thalweg to the restoration area via the Waneta eddy that is present during most flow conditions, and especially when PDO flows are low (e.g., Fissel *et al.* 2017; Figure 39).

Figure 39. Variations of the Waneta eddy during different flow combinations (copied from Fissel *et al.* 2017).

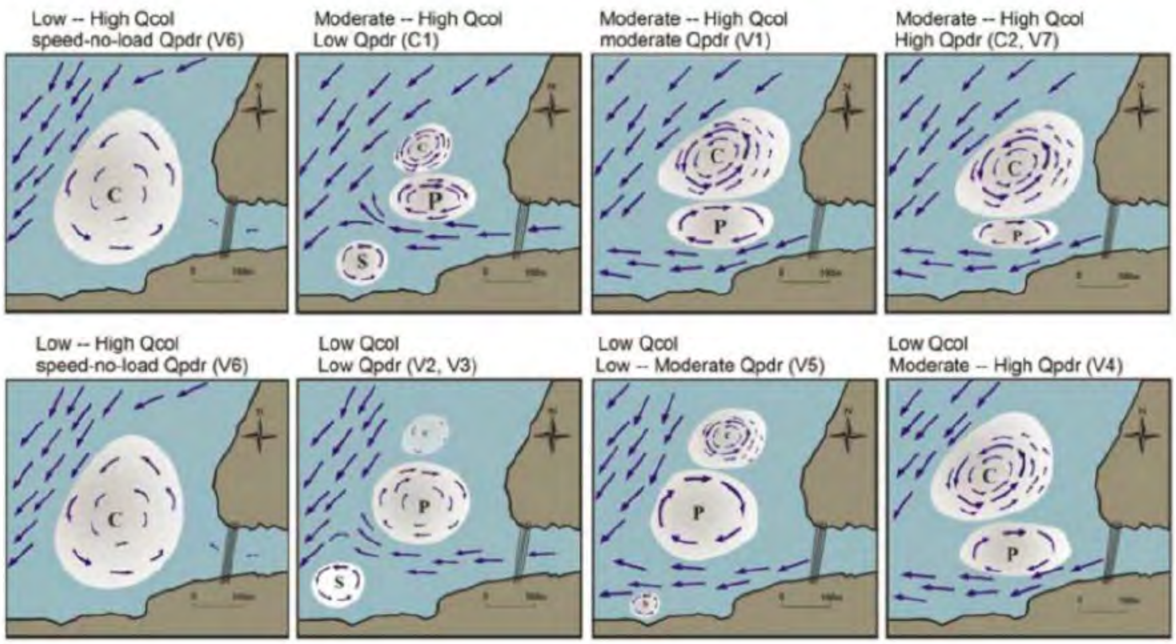
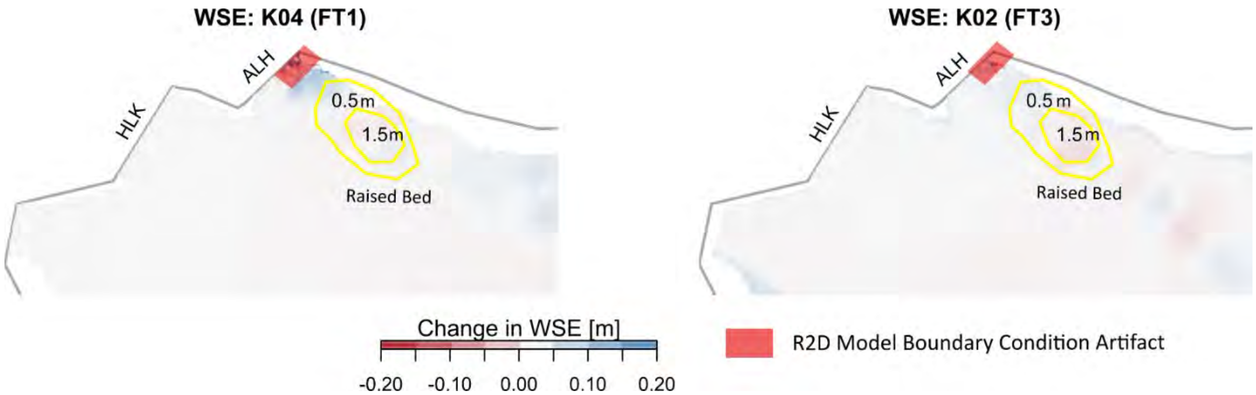


Figure 4-7: Different circulation patterns in the Waneta Eddy area in response to changes in the Columbia River (Qcol) and Pend d'Oreille River (Qpdr) flows (Fissel and Jiang, 2008).

5.4.4. Sensitivity to Changes in Bathymetry

After elevating the bed topography at the ALH tailrace, to simulate placed material associated with a theoretical restoration project, the K02 (FT3), K04 (FT1) and K08 (1997 peak flows) flow simulations showed a subtle increase in water surface elevation. Figure 40 shows the placement of a theoretical treatment geometry and changes to the water surface elevation, which were approximately 10 cm in the ALH tailrace for FT1 flows. In reality, a depth for placed material (i.e., cobble/gravel) would be unlikely to exceed 0.6 m, making this assessment a relatively conservative test. Re-assessing potential backwatering effects may be necessary during a detailed design phase to ensure that the rock placement will not affect ALH generation.

Figure 40. Changes in the WSE near the ALH tailrace after modification of surface topography (yellow areas - artificially raised bed elevation).



5.4.5. Comparison of Observed vs. Modelled Sediment Transport

5.4.5.1. Tracer Stones

Results of the tracer stone deployment are shown in Table 14. Tracer stones were recovered successfully and evidence of movement was assessed from repeat images and detailed field notes. It was determined that at Keenleyside, 100% of tracers in the 45 mm size class had moved, while 80% in the 91 mm size class (D50 at the placement area) had moved, and 0% in the 181 mm size class had moved. It should be noted that the movement distance of the mobile stones was typically less than 1 m. Predicted shear stress thresholds for entrainment were calculated using the Shields model (assuming single grain size corresponding to the tracer size), and using the Wilcock and Crowe model (where size-specific thresholds for each tracer size were calculated based on the existing bed grain size distribution at tracer locations determined through Wolman pebble counts - Appendix A). Shear stress thresholds for entrainment of each size class differed between Shields and Wilcock and Crowe model predictions, with Wilcock and Crowe predicting a slightly greater threshold than Shields for the 45 mm class and lower thresholds for the two larger classes. Interestingly, most tracers were observed to have moved in an upstream direction, highlighting the influence of eddy circulation on local sediment transport processes. As an estimate of peak shear conditions that may have occurred during the tracer deployment period, model results for the K04 simulation (ALH-1100, HLK-514) were used after examination of secondary circulation pathways in the vicinity of the tracer locations. However, shear stress at the tracer points under these conditions was only 9.5 Pa, well below predicted thresholds. Given the observed degree of mobility, it is likely that the K04 scenario does not fully capture the strength of the downstream eddy along the left bank where the tracers were located, and that a higher flow release from HLK might produce more realistic estimates of peak shear stress in this area. Flow scenarios were selected with a focus on simulating peak shear conditions in areas downstream of the ALH tailrace. Further modelling could provide more insight into local hydraulics at the tracer placement location.

At Waneta, two of the five tracers (D50 at the placement area) were observed to have moved several meters downstream. Predicted entrainment thresholds for these large size stones were 124 Pa from Wilcock and Crowe and 195 Pa from Shields. The peak PDO flow during tracer deployment at Waneta was modelled in simulation W15 (PDO-2584 m^3/s, LCR-1898 m^3/s), which was expected to represent peak shear conditions. Similar to Keenleyside, peak observed shear stress under these conditions at the tracer location (43 Pa) was much lower than predicted entrainment thresholds. Because the overall conclusion was that the majority of tracers in this location were immobile, this result makes sense. However, the two tracers that did move cannot be explained by the observed forces. Potential explanations for this discrepancy at both Waneta and Keenleyside include risks inherent to tracer usage, such as the fact that tracers are removed from the bed, painted, and then placed back on the bed and therefore may not be embedded and interlocked similarly to existing surface sediments. Such stones would be expected to be exposed to greater forces than otherwise and would therefore move at lower shear stresses. Similarly, definitions of mobility in the transport models may not align with the low levels of transport observed with the tracer stones. The possibility also exists that small-scale hydraulic features (e.g., boils, local flow convergence) affected tracer stones but were not adequately captured in the resolution or computational methods of the River2D simulations, or that modelled shear stress values are less reliable along model boundaries in the near-shore areas where tracers were placed.

Table 14. Summary of tracer stone mobility at Keenleyside and Waneta

Sampling Reach	Size Class (phi)	Size Class (mm)	Number of Tracers	Number Mobile	Percent Mobile	W&C Threshold (Pa)	Shields Threshold (Pa)	Simulation Used[1]	Peak Observed Shear Stress (Pa)
Keenleyside	5.5	45	10	10	100	36.6	34.4	K04	9.5
	6.5	91	10	8	80	42.2	68.9	K04	9.5
	7.5	181	5	0	0	60.1	137.7	K04	9.5
Waneta	8	256	5	2	40	123.7	194.8	W15	42.8

[1] K04 simulation may not fully represent peak shear stress conditions at Keenleyside tracer location.

5.4.5.2. Review of Substrate Images

As an alternative method of validating sediment transport model results, patterns of observed recent transport as determined through qualitative annotations of bed imagery (Section 4.2.5) were compared to predictions of mobility from the Shields and Wilcock and Crowe transport models. Simulations representing the 2018-2019 peak flow conditions were used for each reach: K09 (ALH - 1100 m^3/s,HLK - 0 m^3/s) at Keenleyside and W06 (PDO - 3700 m^3/s, LCR - 4400 m^3/s) at Waneta. It was assumed that these flows would have driven the patterns of recent transport. At Waneta, the 2018 freshet peak flow that occurred prior to sampling had a daily average of 3604 m^3/s on May 28, 2018 (25 – 50 year return period). This flow was not simulated, and instead W06 was used for the assessment given the similarity.

Figure 41 and Figure 42 show comparisons of observed and predicted transport. At Keenleyside, observed and predicted transport were relatively similar; a large zone of observed transport was documented in the downstream section of the EDZ and material in this area was predicted to be mobile in both sediment transport models used. The left-bank side of the EDZ DS had a large patch without recent mobility and points within this area were also predicted to be immobile, and a patch of both predicted and observed mobility was also present towards the downstream portion of the EDZ DS. At Waneta, patterns of observed transport were less consistent spatially but general predictions from both sediment transport models showed correspondence in limited transport along the middle portion of the EDZ with some mobility towards the downstream end of the EDZ. Within the restoration area, predictions generally matched towards the downstream end of the zone and were less consistent in the upstream portion. Overall, patterns of observed and modelled transport were qualitatively similar and provide support to the accuracy of transport models within the context of observer classification accuracy and fine-scale spatial variability in bed sediment conditions.

Figure 41. Simulated and observed transport at Keenleyside. Evidence of recent transport in images was from each field trip ranging from August 2018 to August 2019.

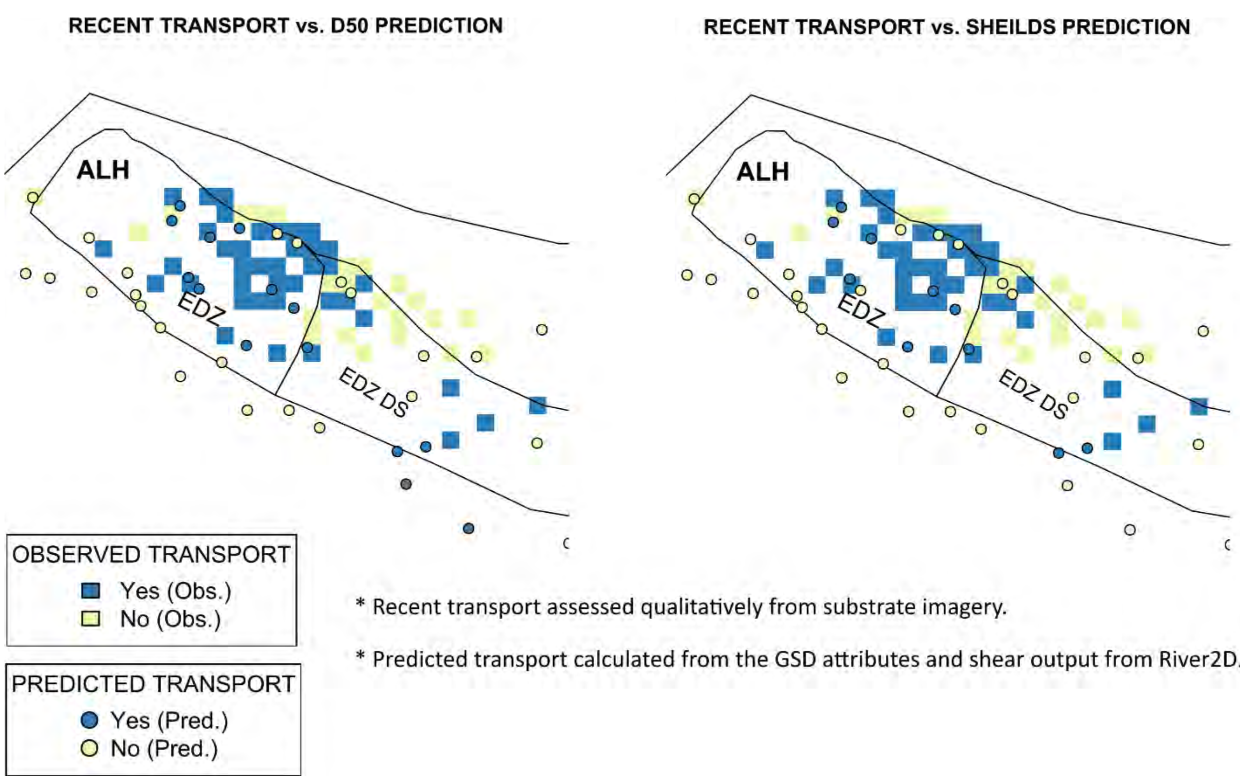
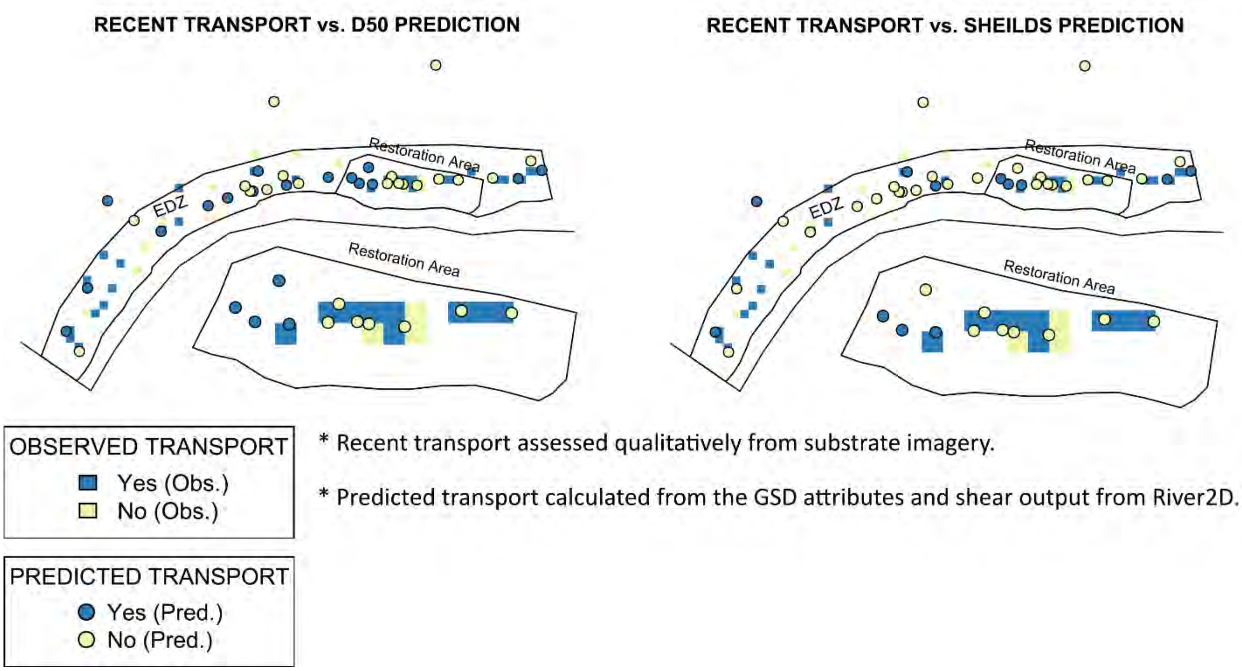


Figure 42. Simulated and observed transport at Waneta. Evidence of recent transport in images was from each field trip ranging from August 2018 to August 2019. D50 predictions were from the Wilcock and Crowe model.

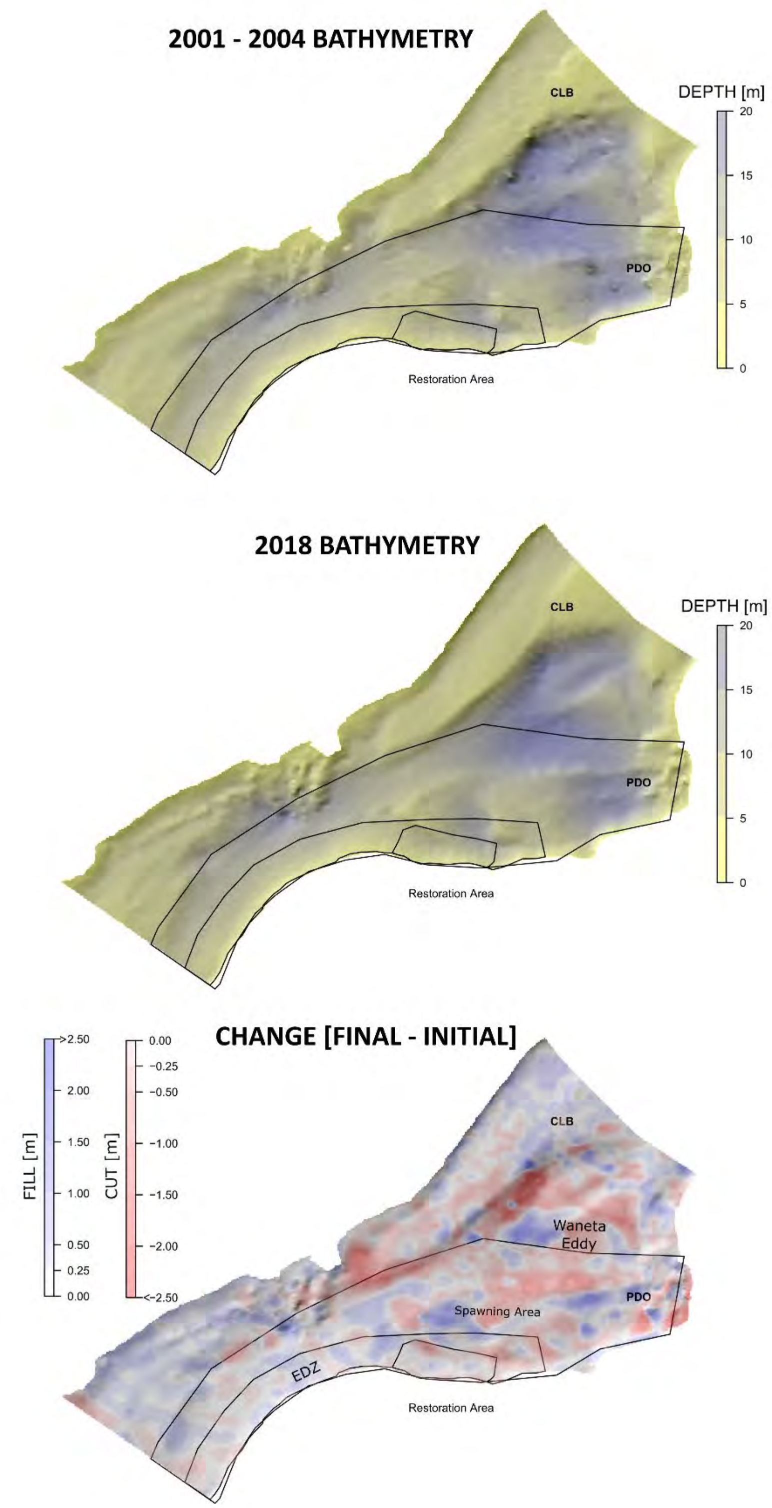


5.4.6. Bathymetric Change at Waneta (2004-2018)

The overall channel morphology of the Waneta reach has remained relatively similar over the 15-year period between 2001 – 2004 and 2018 (Figure 43). Material transport with active scour and deposition is intensified at the LCR and PDO confluence in the vicinity of the Waneta Eddy. Some locations in this area were showing elevation changes in excess of 4 m. Lower confidence should be given to any changes within ±0.25 m due to the combined uncertainty and data gaps between survey periods.

Elevation changes between periods for the shoreline margin(s) of the EDZ and proposed restoration areas are generally within 0 - 0.25 m (Figure 43). However, elevations differences in these areas of up to 1.7 m were occasionally observed along deeper portions of the channel, approximately 50 – 100 m from the shoreline. These results indicate that progressive downcutting or aggradation is not occurring within the EDZ. Therefore, if fines periodically aggrade in the EDZ, then they are either flushed out without coarse material moving very far (e.g., > a few meters), or supply of coarse material is capable of replacing lost material. The supplied material is expected to originate from upstream, but a fraction could be coming from the eroding bank within the EDZ. The moderate changes between the two surveys and random pattern of cut/fill suggest that coarse material likely moves a moderate distance and is replaced by material from upstream. This observation is consistent with both the observed evidence of recent transport during 2018 and the model predictions that show relatively frequent transport of coarse material from the EDZ.

Figure 43. Long-term change in Columbia River bathymetry at Waneta based on surveys taken during 2001-2004 (Fissel *et al.* 2017) and 2018.



5.4.7. Footprint Optimization

Results of the footprint optimization analysis for the restoration alternatives are shown in Figure 44 for Keenleyside and Figure 45 and Figure 46 for Waneta. At Keenleyside, optimal placement zones (where 20 mm sediment is mobile but D50 is stable) followed the path of the high shear stress jet downstream of the ALH tailrace, with small zones of stability directly below HLK (Figure 44). The multiple substrate mixtures effectively cover the range of shear stress conditions represented by the composite shear stress raster, with the largest mixture (GSD6) being suitable for the highest shear stresses in the strongest ALH current, followed by subsequently smaller mixtures (GSDs 5 to 1) radiating out in stable bands in lower shear stress areas. The footprint extends out into the middle of the channel towards river right under the composite shear conditions. Results from the Wilcock and Crowe and Shields models are similar in extent and pattern; the main difference is that D50 thresholds as predicted by Wilcock and Crowe are lower than those from Shields. This means that the Wilcock and Crowe predictions have gaps between the stable bands (i.e., shear stress is above the D50 threshold for one mixture but below threshold for 20 mm transport in the next largest mixture), while these gaps are filled in by the wider bands predicted by Shields. Optimized footprints that are restricted to the paths of egg drift are also similar between Shields and Wilcock and Crowe, reflecting the dominant current direction under spawning flows. Areal summaries for all footprint optimizations are presented in Table 15. Total area throughout the Keenleyside study zone for Wilcock and Crowe is 20,048 m^2 and 26,614 m^2 for Shields. For the final footprints restricted to within the egg paths, Wilcock and Crowe area is 6,504 m^2 and Shields area is 8,118 m^2.

Figure 44. Footprint optimization at Keenleyside. Panels show the locations throughout the study area where substrate mixtures will be stable based on shear stress conditions.

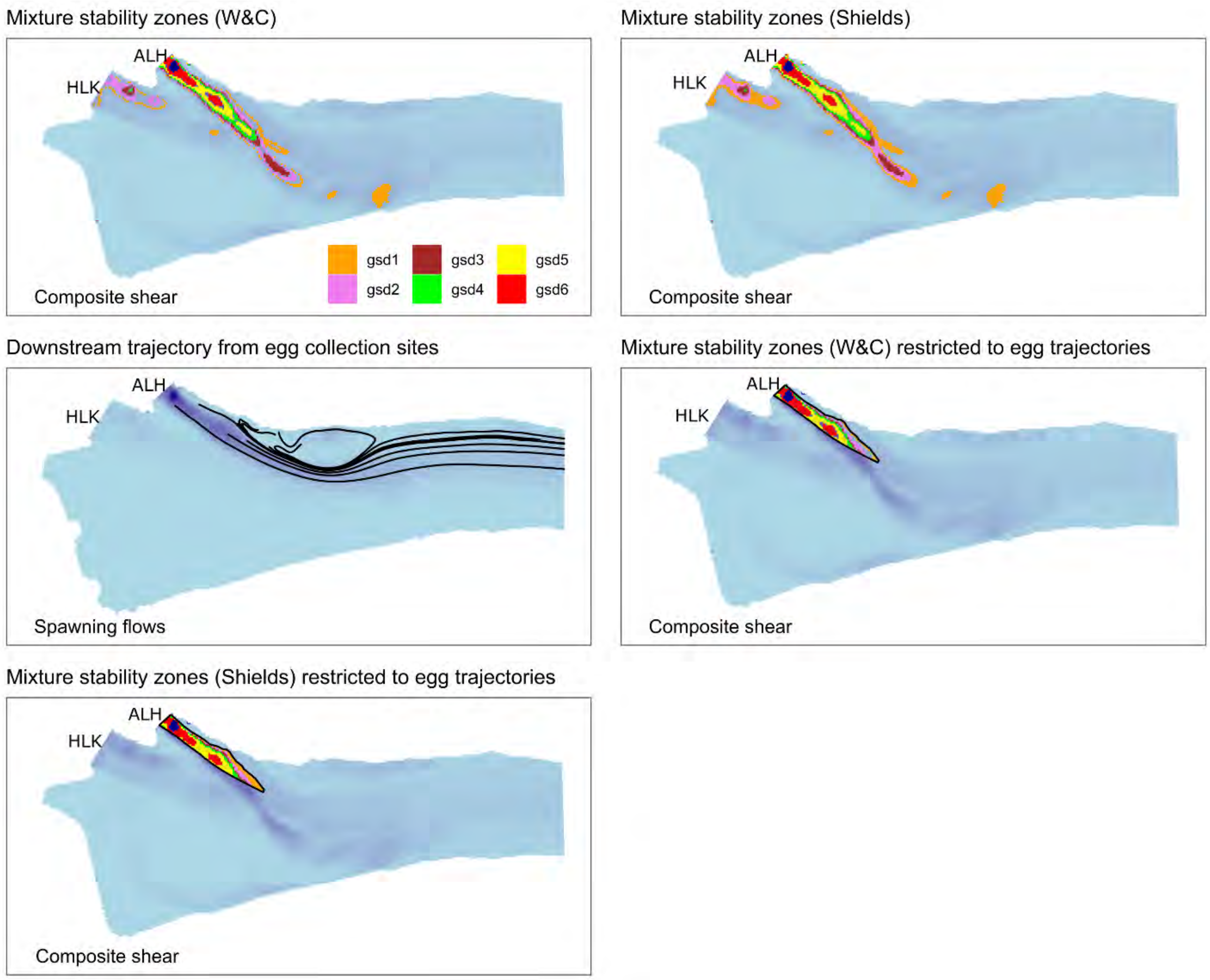


Table 15. Summary of optimized footprints areas for Keenleyside and Waneta cases.

	Flow condition	Case	Stable area (m^2)						Total area (m^2)
			GSD1	GSD2	GSD3	GSD4	GSD5	GSD6	
Keenleyside	K06+K09+K10+	All areas (W&C)	5623	4251	2961	2213	2934	2066	20048
	K19+K20	Restricted to egg paths (W&C)	565	730	472	785	1932	2020	6504
		All areas (Shields)	9820	5428	3315	2556	3346	2149	26614
		Restricted to egg paths (Shields)	1365	848	579	892	2331	2103	8118
Waneta (high freshet)	W08+W10	All areas (W&C)	26108	45294	25897	19908	8309	NA	125516
		Restricted to sediment paths (W&C)	0	0	281	654	627	NA	1562
		All areas (Shields)	54773	54588	30108	20667	12986	NA	173122
		Restricted to sediment paths (Shields)	0	3	416	702	627	NA	1748
Waneta (low freshet)	W03	All areas (W&C)	15172	13234	8028	5407	1907	NA	43748
		Restricted to sediment paths (W&C)	11	115	105	0	0	NA	231
		All areas (Shields)	31327	16034	9260	5634	3814	NA	66069
		Restricted to sediment paths (Shields)	45	149	105	0	0	NA	299

At Waneta, two flow conditions were assessed: the high freshet (W08 + W10 composite) and the low freshet (W03). These serve to bracket potential limits on the freshet conditions under which fine sediments are delivered and coarse grains may be mobilized. For the high freshet case, the optimized footprint using GSDs 1-5 shows broad areas where fines (< 20 mm) remain in transport or can be mobilized and D50 remains stable so material will not be transported away too quickly (Figure 45). A zone of shear stress concentration is evident in the egg deposition zone downstream of the bend on river left; GSD mixtures 4 and 5 are generally suitable for this area. As at Keenleyside, results from Wilcock and Crowe are comparable in pattern and extent to those from Shields except for the small gaps between stable zones predicted by Wilcock and Crowe. To assess how sediment may move if it is placed at one point at the upstream end of the EDZ and allowed to disperse downstream by the current, trajectories were traced from the placement location (Figure 45). Stability zones were then masked to within the path of transport for the final footprint. For this high freshet case, the total suitable area within the study zone is 125,516 m^2 for Wilcock and Crowe and 173,122 m^2 for Shields. For the footprint within the path of material transport, the total suitable area is 1,562 m^2 for Wilcock and Crowe and 1,748 m^2 for Shields. The small overall areas for the restricted footprints reflect the narrow path of predicted sediment transport from the placement point; this serves to highlight general direction and extent but it is highly generalized approach and it is likely that sediment would be distributed over a broader area under varying flow conditions. The Waneta augmentation location was specified to be 12 m inshore from the low flow wetted edge or 25 m out from the 5-year peak flow water level, which is assumed to be achievable by installing a structurally supported slide. Material with the finest range could be introduced first to allow greatest dispersion downstream, followed by increasingly larger mixes up to the size where movement is so limited that placement is no longer worthwhile.

For the low freshet case at Waneta (Figure 46), the total areas of predicted stability are less than the high freshet case. This pattern is mostly driven by lower overall shear stresses throughout the study zone, meaning that many areas are not suitable due to risk of fines infilling as shear stress is below the 20 mm thresholds. A zone of high suitability for GSDs 4 and 5 still exists in the same location of flow concentration evident in the high freshet case, but with a smaller extent. Restricting these low freshet stability zones to the predicted downstream material trajectory results in a similar final optimized footprint to the high freshet case, but with material from the smaller range of proposed mixtures being suitable (GSDs 1-3; Table 15). For this case, total areas throughout the study area are 43,748 m^2 and 66,069 m^2 for Wilcock and Crowe and Shields, respectively. Final optimized footprints within the sediment transport paths are 231 m^2 for Wilcock and Crowe and 229 m^2 for Shields.

Figure 45. Footprint optimization at Waneta using composite of 5-year return high freshet from PDO and from LCR. Panels show the locations throughout the study area where substrate mixtures will be stable based on shear stress conditions.

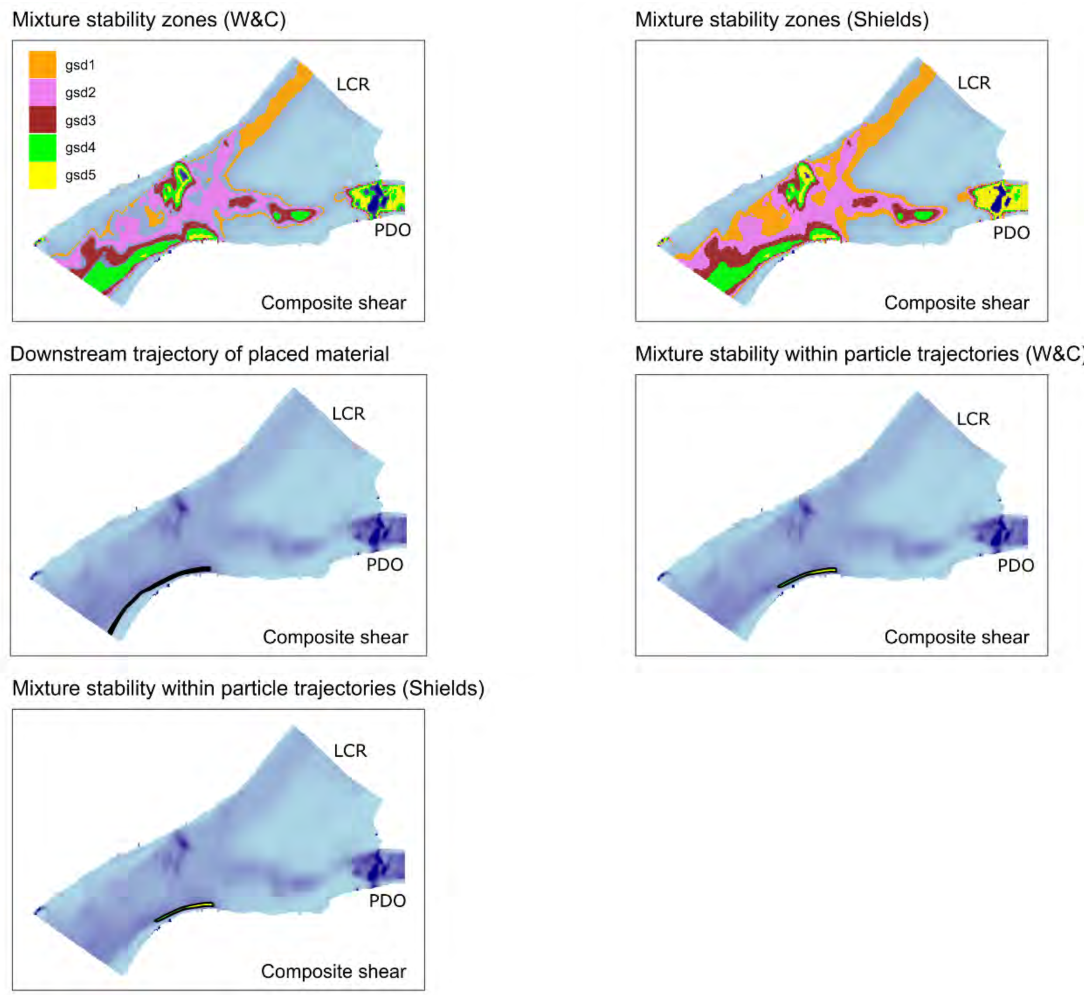
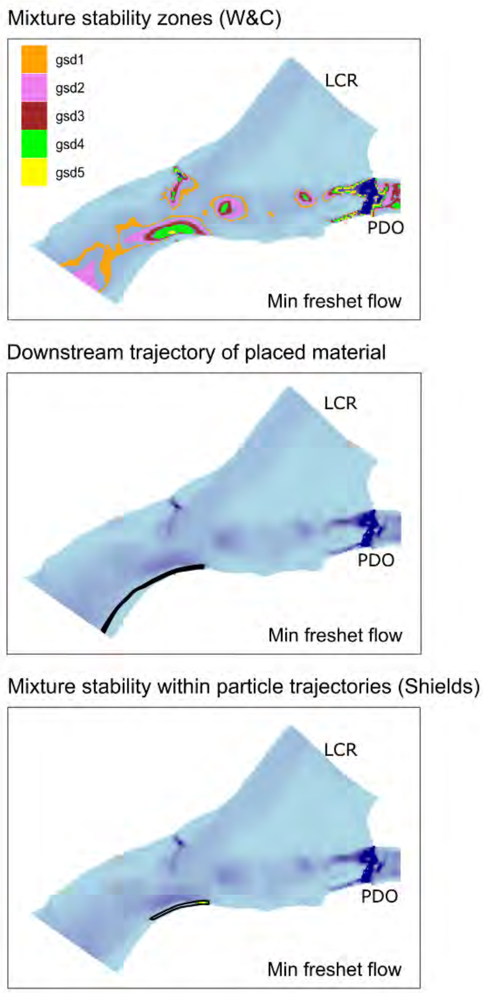


Figure 46. Footprint optimization for at Waneta (low freshet case). Panels show the locations throughout the study area where substrate mixtures will be stable based on shear stress conditions.



5.4.8. Longevity of Each Alternative

A discussion of the longevity of each restoration alternative is provided below, with estimates in years provided where possible.

5.4.8.1. Keenleyside Placement at EDZ with D50-125

The Keenleyside EDZ currently has moderate rearing suitability, with armouring and a moderate fines percentage being the apparent limiting factors. Most of the area had evidence of recent transport; however, observed transport distance was less than a few meters. Periods of deposition throughout this area were predicted by both Shields and Wilcock and Crowe models for the placement material, assuming that fines could be supplied. Analysis of fines transport from eddies suggested that supply of fines would happen extremely rarely, and therefore fouling with algae detritus may be the more likely cause of the moderate fines percentage. Supply of coarse material is negligible, and despite this, the stream bed has sections of apparently mobile gravel. Peak shear conditions are similar every year, which along with substrate observations suggests that sediments may partially transport a very short distance each year. The Shields and Wilcock and Crowe models predicted transport of coarse material on an annual basis of 44% to 56% of the EDZ with existing conditions, and between 6 to 36% of the area after treatment. The overall longevity of the treatment will depend on the distance that placed stones will travel each year, and the rate of deposition. Based on all of the results from this study, a rough estimate is that at least 50% of the treatment will last multiple years, and possibly more than 5 years, before locally scouring away in a small percentage of the area and infilling or armouring in the rest. It is unclear at what rate fines and detritus will deposit; however, given the limited supply, predictable flow regime, and predicted stability of the placed material, treatment in this area is expected to last longer than treatment at Waneta.

5.4.8.2. Keenleyside Placement at EDZ DS with D50-125

The Keenleyside EDZ DS currently has high rearing suitability in the NW corner and low to moderate throughout the rest, with armouring and a moderate fines percentage being the apparent limiting factors. Recent transport was observed in half the area, primarily as mobile patches of fine gravel. Periods of deposition throughout this area were predicted by both Shields and Wilcock and Crowe models for the placement material, assuming that fines could be supplied. Analysis of fines transport from eddies suggested that supply of fines would be moderate from either side of the treatment area. Supply of coarse material is limited to the 200 m length of channel bed and banks up to the tailrace, and despite this, the stream bed has sections of apparently mobile fine gravel in SE corner. Peak shear conditions are similar every year, which along with substrate observations suggests that fine gravel may transport a short distance each year. However, the active gravel is likely too small to provide value to rearing sturgeon. The Shields and Wilcock and Crowe models both predicted transport of coarse material on an annual basis of 29% of EDZ DS with existing conditions, and between 0 to 6% of the area after treatment. Since coarse material will be generally immobile, the overall longevity of the treatment will depend on the rate of deposition. It is unclear at what rate fines and detritus will deposit; however, it is fairly certain that placement of D50-125 would last longer in EDZ than EDZ DS.

5.4.8.3. Keenleyside Placement at EDZ and EDZ DS with D50-125

This treatment consists of a combination of the previous two treatments and will therefore have an intermediate longevity. However, this treatment is expected to expand the longevity compared to EDZ DS alone, since material transported from the EDZ will end up in the EDZ DS and likely provide suitable habitat until infilling occurs.

5.4.8.4. Keenleyside Cleaning of EDZ and EDZ DS

Descriptions of existing conditions and sediment supply are provided for the D50-125 placement treatments for EDZ and EDZ DS. While the Shields model predicts a similar amount of transport once the substrate is cleaned (39%), the Wilcock and Crowe model predicts a reduction in mobility due to lower fines content from 48% to 43%. Generally, fines percentage increases with depth into the streambed due to a percolation or sieving process, as was observed at Waneta (Appendix A). Once the cleaned and loosened layer is transported away from the treatment area, rearing suitability may worsen when the sub-layer is exposed. While the transport models show that risk of transport will reduce if anything, this risk should still be taken into consideration in case loosening the material actually makes it more mobile, as might be expected. Given that the layer of cleaned material would likely be less than 600 mm, infilling would likely occur at a faster rate than for placement. For these reasons, the longevity of cleaning is expected to be lower than both of the D50-125 placement alternatives.

5.4.8.5. Keenleyside Placement at EDZ and EDZ DS with D50-35

Descriptions of existing conditions and sediment supply are provided for the D50-125 placement treatments for EDZ and EDZ DS. Despite the reduction in fines hiding associated with D50-35, fines deposition was still predicted to occur on an annual basis throughout the restoration area. During annual peak flows, the Shields and Wilcock and Crowe models predicted a similar amount of transport of 41-43%, which is also like the amount predicted for cleaning. Therefore, the longevity of this treatment could be expected to be similar to cleaning.

5.4.8.6. Waneta Placement at Restoration Area with D50-125

The Waneta restoration area had moderately high rearing suitability during 2018, despite moderate fines percentage and armouring level. Most of the area had evidence of recent transport, which could have been a result of the extreme PDO flow (3604 m^3/s) that occurred on May 28, 2018 (25-50-year return period). Periods of deposition throughout this area were predicted by both Shields and Wilcock and Crowe models for the proposed material, even during low year freshet conditions. Analysis of fines transport from eddies suggested that supply of fines would happen on a regular basis, as suggested by Fissel *et al.* (2017). Long-term trends of scour or aggradation were not observed between 2001/2004 to 2018, although localized changes in bed elevation suggest that sediment is transported through this area. The Shields and Wilcock and Crowe models predicted transport of coarse material on an annual basis of 0% to 9% of the restoration area with existing conditions, and 0% of the area after treatment. During extreme flows (approximately 9-year return), between 0 and 2% transport was predicted following treatment, and only 22% fines fraction mobility was predicted. The overall longevity of the treatment will depend on the supply rate of fines, which was predicted to result in between 18-90 mm of deposition for a typical year (Fissel *et al.* 2017). Based on the sediment transport models, these fines deposits would be likely to remain 78% stable even during a 9-year return peak flow, which suggests that the treatment will last less than a few years. Some evidence of aggradation between the 2018 and 2019 sampling periods in the treatment area was observed (Section 5.2.3), which provides further evidence that infilling could happen quickly.

5.5. Biological Modelling (Habitat Suitability)

Results of the habitat suitability modelling aligned with expectations for the each of the study areas (Figure 47 to Figure 49 and Appendix G). The White Sturgeon habitat recruitment model (Hatten *et al.* 2018) identified large areas of Waneta and Kinnaird as being suitable habitat under current conditions. Predictions of suitable recruitment habitat for the Keenleyside reach was more restricted to the vicinity of EDZ and a small section immediately downstream.

Extending predictions from an existing habitat suitability model to new areas has risks of poor transferability and non-stationarity (extrapolation). Hatten *et al.* (2018) validated the generalization of their White Sturgeon recruitment suitability model by comparing its predictive performance for a reach of the Kootenai River in Idaho. Their model maintained a high performance (AUC 0.767). The overall accuracy was approximately 75% with a 20% false-negative rate (fails to identify known habitats) and a 30% false-positive rate (overpredicts areas that are not suitable habitat). These accuracy statistics were similar to sites in the Columbia River along the Oregon Washington border. Although the predictive performance of the Hatten *et al.* (2018) model to the LCR study areas is unknown, it is assumed to be similar to the Kootenai River and other areas assessed in their original study.

The target spawning velocity criteria (blue areas; 0.8 – 1.7 m/s) showed a high degree of overlap (green areas) with the suitable recruitment habitat (orange areas) in Figure 47 to Figure 49, although deeper sections that were outside of the target velocity range were still predicted to have suitable recruitment habitat. There were several areas that had velocity between 0.8 – 1.7 m/s, but were not predicted to have suitable recruitment habitats, regardless of the substrate condition.

Potential recruitment habitat improvements were evaluated after restoration treatment(s), by re-running the Hatten *et al.* (2018) recruitment suitability predictions but modifying the underlying embeddedness values to 0% and changing the substrate composition to 100% cobble/gravel for all study areas (a proxy for substrate restoration). This process allowed for the identification of areas that could become suitable habitat after substrate improvements. Figure 47 to Figure 49 suggests large theoretical improvements for the Waneta reach at the PDO outlet, but changes to Keenleyside and Kinnaird were much more subtle. Conditions at Keenleyside downstream of the EDZ showed the largest capacity for improvement, but the HLK tailrace and other areas across Keenleyside remained largely unchanged compared to existing conditions. Conditions at Kinnaird were also largely unchanged because this reach is predicted to already have high recruitment suitability of existing substrate through most of the reach.

Theoretical downstream drift of eggs and larvae was evaluated for Keenleyside (Figure 47) and Waneta (Figure 49). Flow simulations are shown for the spawning period (early summer, K10/W05), late summer (K17/W14) and fall (K02/W13) flows. At Keenleyside downstream drift trajectories were flow dependant. During typical spawning flows drift trajectories remained close to the left bank, but typical flows during the late summer and fall appeared to push trajectories towards the channel center and right bank (deeper slow-moving water with higher substrate fines percentage).

In contrast, drift trajectories at Waneta were similar regardless of inflow conditions. These simulations are useful to evaluate habitat immediately downstream; however, it should be noted that downstream drift will take place over the timescale of days to weeks and downstream habitat should be evaluated across kilometers of river rather than the limited extent of the study areas.

Substrate conditions in this modelling exercise only consider the proportion of cobble/gravel substrates and substrate embeddedness. Armouring, roughness, fouling, fines deposition and other criteria are not accounted for in these habitat models. A side-scanning sonar dataset (see BC Hydro 2015a) could be used to support the development of additional substrate attribute data for habitat modelling. Efforts were made during exploratory analysis to integrate the sonar data, but the acoustic classes showed no clear univariate or multivariate associations with substrate attributes.

Figure 47. **Habitat suitability predictions for Keenleyside under current conditions (top panel), and improved substrate (middle panel). The downstream drift of eggs and larvae flow trajectories for theoretical spawning locations are shown in the bottom panel for different seasonal flows.**

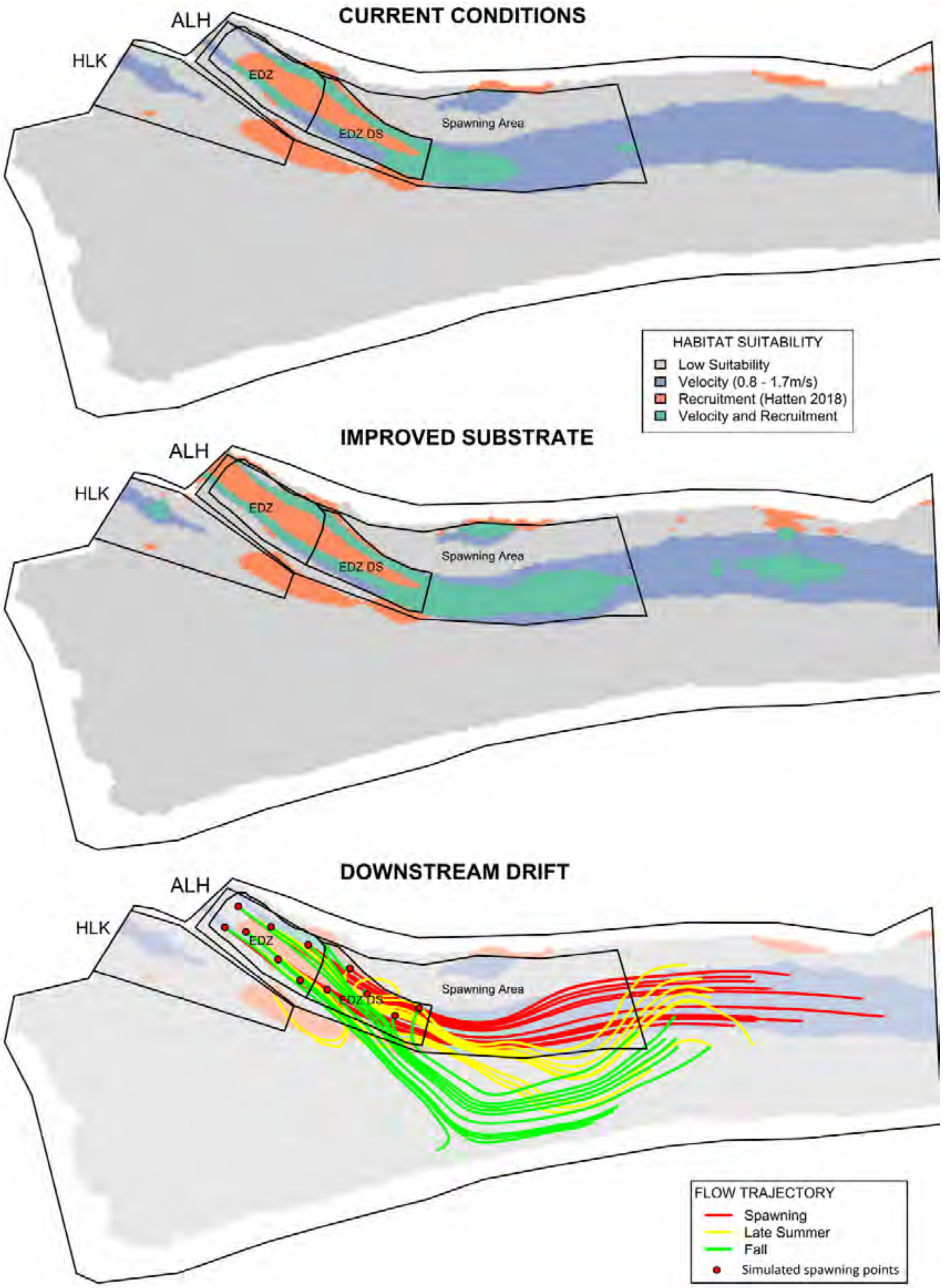


Figure 48. Habitat suitability predictions for Waneta under current conditions (top panel), and improved substrate (middle panel). The downstream drift of eggs and larvae flow trajectories for theoretical spawning locations are shown in the bottom panel for different seasonal flows.

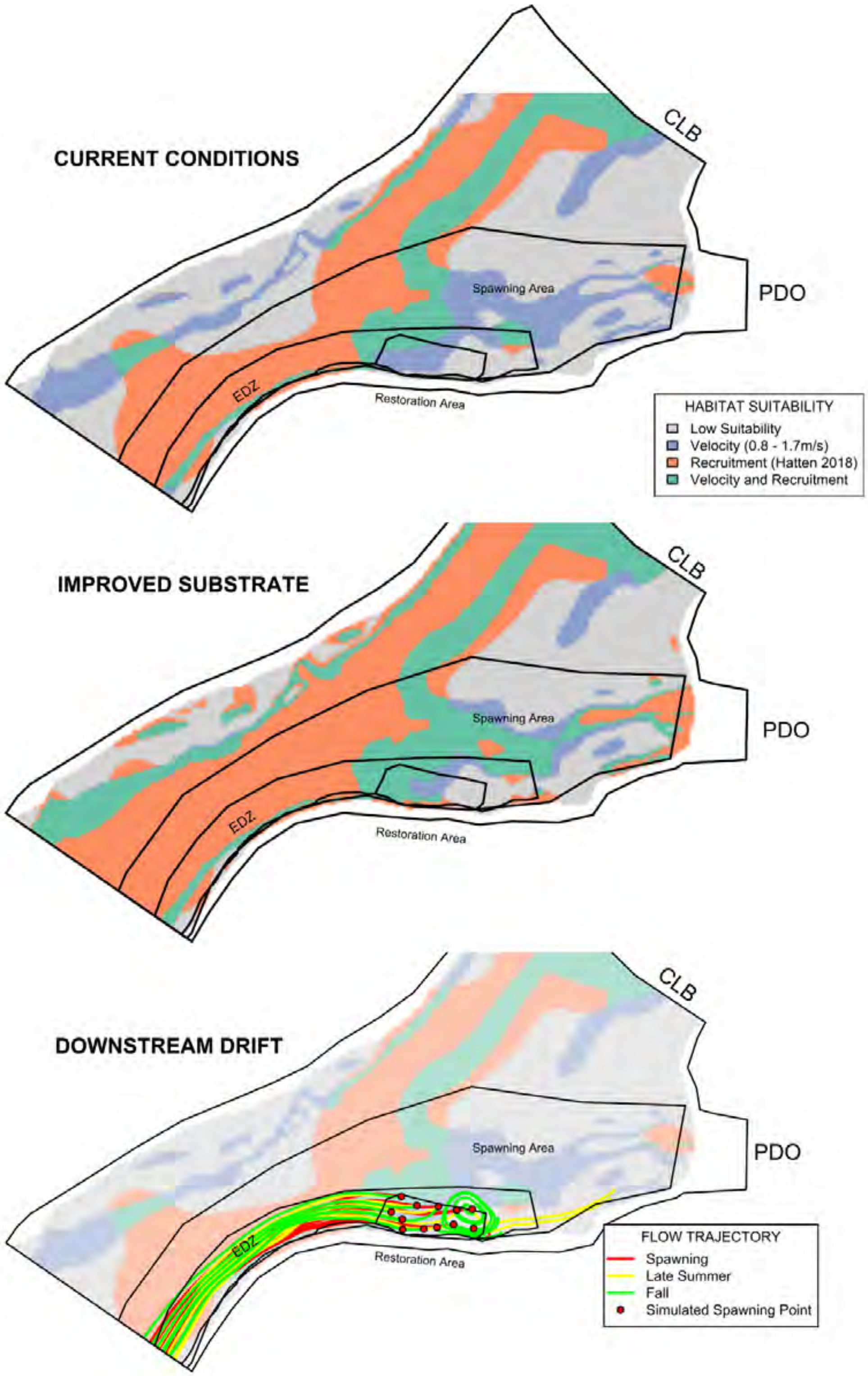
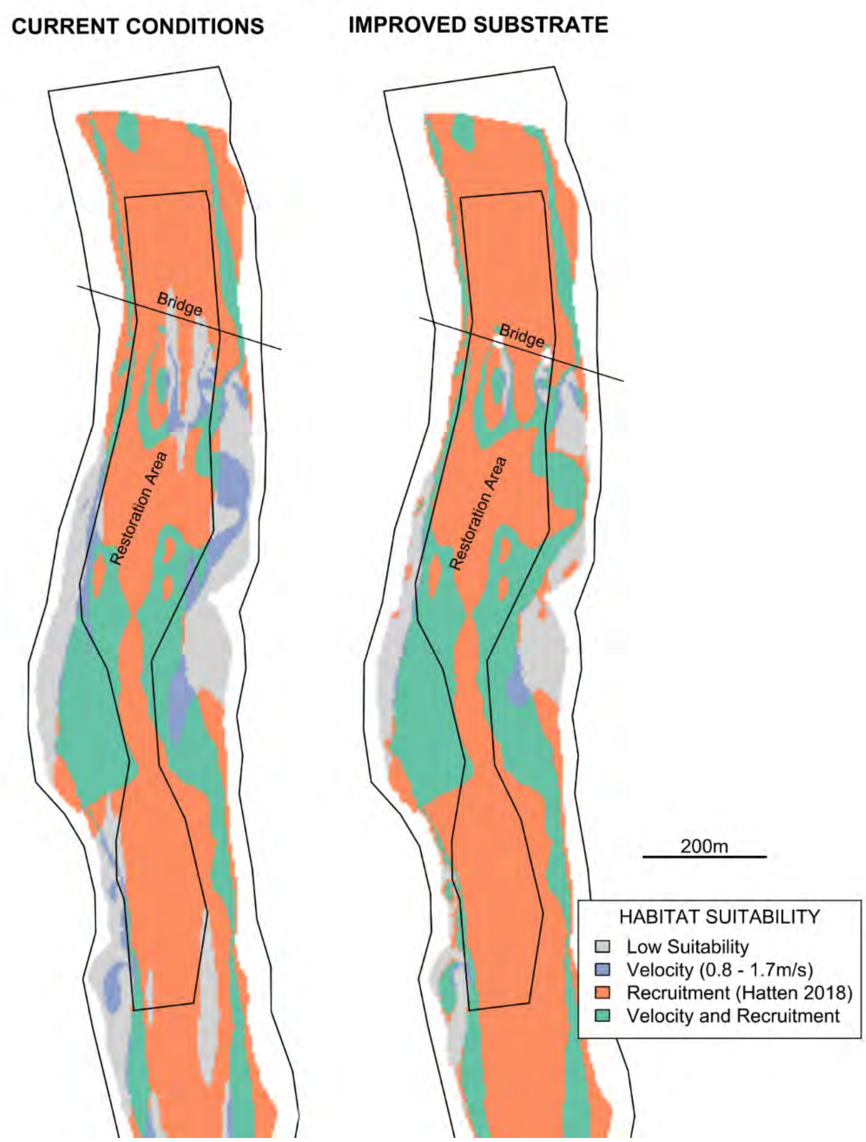


Figure 49. Habitat suitability predictions for Upper Kinnaird under current conditions (left panel), and improved substrate (right panel).



5.6. Biological Performance Measures

Food availability was considered to be one of the most important biological PMs, and therefore a description of low, medium, and high assignment rationale for each spawning area is provided below. Studies determining diets of early life stage (ELS) White Sturgeon in the LCR have not been conducted, but unpublished food availability work has been done in the Keenleyside area by BC-Hydro and CPC as well as the entire LCR (Crossman *et al.* 2016). Both studies found food of the appropriate size and type for White Sturgeon ELS existed in the study area, with the Keenleyside reach downstream of HLK and ALH having the highest food availability.

5.6.1. Keenleyside

Keenleyside alternatives were scored as 'high' due to the relatively high presence of food detected for White Sturgeon ELS (Crossman *et al.* 2016). Cooler, low productivity water above the dam flows directly into this site compared to Waneta and Kinnaird. An annual fertilization program conducted by the Fish and Wildlife Compensation Program (FWCP) inputs nutrients above ALH as compensation for this low productivity. The entrained *Mysis relicta*, a non-native pelagic crustacean from upstream of ALH, is the most common prey item for 1-2-year-old juvenile sturgeon in this section of river (Golder 2006a; DFO 2014). Benthic taxa known to be in the diets of ELS sturgeon present directly downstream of ALH include Diptera (Chironomidae) (Hatfield 2007; Plewes *et al.* 2017).

5.6.2. Kinnaird

Kinnaird alternatives were scored as 'medium-low'. The spawning area is downstream of the Lower Kootenay River (LKR) confluence; Brilliant Dam is located ~2 km upstream from the confluence. Brilliant Headpond has low productivity and there are no fertilization activities, thus this area has been scored slightly lower as compared to the Keenleyside and Waneta sites. Mysids have also been observed in stomachs of juvenile White Sturgeon age-2 to 12 within this section of the river, but they may not be available here annually depending on flow conditions (Crossman *et al.* 2016). Benthic taxa known to be in the diets of ELS sturgeon upstream of this site at the LKR confluence include Diptera (Chironomidae) (Plewes *et al.* 2017).

5.6.3. Waneta

Waneta alternatives were scored as 'medium-high'. The warmer water from the PDO is assumed to have increased productivity compared to Keenleyside and Kinnaird. The Waneta spawning area has a large concentration of sturgeon and other fish species and is presumed to have adequate food resources (that likely also drift downstream where sturgeon larvae would settle). Diets of ELS sturgeon captured ~36 km downstream of Waneta (China Bend, Washington) were comprised of Dipteran larvae (Chrionomidae larvae and pupae and Simuliidae) and Copepods (Temoridae) (Reihart 2016).

5.7. Restoration Alternative Prioritization (Task 4)

Prioritization of alternatives was completed for the Tier 1 alternatives identified in Workshop One (Table 2). Details of the prioritization process are provided below.

5.7.1. Restoration Alternative Performance Measure Refinement

The long list of PMs that were selected and calculated for each alternative from Section 3.1 and Table 2 are presented in Table 16. These PMs are grouped into five objectives including substrate mobility, substrate condition, habitat suitability, expected biological response, and feasibility. Scores for each of these PMs are provided in Table 1 of Appendix H for the Tier 1 alternatives. A detailed description of the differences between sites for each PM is provided only for the PMs that were selected for alternative ranking (Section 5.7.5). A brief description of the PMs within each objective is provided in the following subsections.

Table 16. Performance measures for evaluating alternatives.

Performance Measures	Unit	Performance Measures	Unit
Substrate Mobility[1]		***Ex. Habitat suitability (Restoration Area)***	
Mobile coarse fraction - typical freshet (W&C)	%	Velocity (% area with velocity suitable for spawning)	%
Mobile coarse fraction - typical freshet (Shields)	%	Depth (% area with depth suitable for spawning)	%
Mobile fines fraction - typical freshet	%	Recruitment Suitability (raw score)	%
Mobile fines fraction during low flows	%	Recruitment Suitability (% area with high rearing suitability)	%
Mobile coarse fraction with max shear (W&C)	%	***Ex. Habitat suitability (Spawning Area)***	
Mobile coarse fraction with max shear (Shields)	%	Recruitment Suitability (raw score)	%
Mobile fines fraction with max shear (W&C)	%	Recruitment Suitability (% area with high rearing suitability)	%
Mobile fines fraction - PDO/ALH 5-yr peak	%	***Restored Habitat suitability (Restoration Area)***	
Mobile coarse fraction - PDO/ALH 5-yr peak	%	Recruitment Suitability (area with high suitability)	%
Mobile coarse fraction - CLB/ALH 5-yr peak	%	Recruitment Suitability After-Before	%
Mobile fines fraction - CLB/ALH 5-yr peak	%	***Expected Biological Response***	
Mobile fines fraction - 5-yr low freshet	%	Biological risk (e.g. to spawning adults)	-
Existing Substrate Condition (Restoration area)		Magnitude of response	-
Coarse material supply	-	Response of other species	-
Supply of fines (total sources)	-	Biological uncertainty	-
Embeddedness (% high)	%	Food	-
Embeddedness (Average Score)	0-5	***Feasibility***	
Armouring evidence	%	Constructability	-
Evidence of Recent Transport	%	Longevity of works	-
Substrate fouling	-	Risks to generation	-
Bottom roughness (near bottom velocity)	1-3	Cost (access)	-
Fines percentage	%	Cost (size)	-
General rearing suitability	1-3	Public visibility (e.g. of signage)	-
Substrate Condition (Spawning area):		Ease of substrate monitoring	-
D50 from GSD	m		
D84 from GSD	m		

[1] Each substrate mobility PM was calculated for 1) existing in restoraiton area, 2) existing in spawning area, 3) after treatment in restoration area, 4) after - before in restoration area.

5.7.1.1. Substrate Mobility

The substrate mobility PMs predict the likelihood of either coarse substrate mobility, fine sediment deposition, or fine sediment flushing during various flow conditions. A description of the rationale for each flow simulation is provided in Section 5.3.4, and details of how the mobility was calculated is provided in Section 1.1. Flow simulations included low flows, typical spawning flows, moderately high peak flows (e.g., 5-yr return period), and extreme peak flows. Each PM was calculated for four conditions/locations including existing in each of the restoration area and spawning area, after treatment in the restoration area, and change (after compared to before) in the restoration area. The spawning area metrics provide an indication of the surrounding conditions, and change provides an indication of the improvement or degradation that would occur with treatment. Each of the PMs is represented as a percentage of the area that is above or below a transport threshold. A total of 12 substrate mobility PMs was calculated for each of the four conditions/locations.

5.7.1.2. Substrate Condition

Substrate condition PMs included the habitat suitability indicators described in Section 4.2, as well as indicators of sediment supply and evidence of sediment transport. The assignment of LMH for the sediment supply PMs is described in Section 5.4.3. Each of the PMs were calculated for the restoration areas, aside from D50 and D84, which were calculated for the entire spawning area. A total of 12 PMs was calculated or assigned. The large number of PMs reflects the difficulty in characterizing quality of habitat with fewer indices. Each of the PMs was selected for inclusion during Workshop One.

5.7.1.3. Habitat Suitability

The habitat suitability PMs include the percentage of either restoration or spawning area that were suitable for recruitment based on Hatten *et al.* (2018), as described in Section 4.5. Habitat suitability was calculated for typical spawning conditions for the restoration area and spawning area before treatment, and the restoration area after treatment. The improvement in suitability represented by change in percentage suitable from before to after treatment was also calculated. Percentage of area within the range of preferred velocities and depths for White Sturgeon spawning were also calculated. A total of eight PMs was selected for habitat suitability.

5.7.1.4. Expected Biological Response

Biological response PMs were mainly assigned during Workshop One and include various indices of uncertainty and expected response from treatment. Five PMs were identified for expected biological response.

5.7.1.5. Feasibility

Feasibility PMs include indications of constructability, cost, monitoring, and risks to existing infrastructure. Seven PMs were identified that were assigned either during Workshop One or by the Ecofish team using professional judgement.

5.7.2. Flags and Information Metrics

Flags and information metrics for each of the Tier 1 and Tier 2 restoration alternatives are provided in Table 17. None of the flags indicate that an alternative will be unfeasible; however, they provide additional considerations. The geometry metrics highlight the larger size of the Keenleyside alternatives compared to Waneta. A length to width ratio was included with the assumption that a longer narrower alternative that is oriented in the downstream direction might be better due to the trajectory of drifting larva. Spawning area to restoration area ratio was also included to highlight that projects with a larger spawning area may be better given the availability of surrounding habitat. However, the quality of rearing habitat in the spawning area and restoration area are not taken into consideration with the geometry metrics, and therefore they were not retained as part of the PM list.

Table 17. Flags and information metrics for Tier 1 and Tier 2 restoration alternatives.

Flags	Unit	Tier 1 Alternatives						Tier 2 Alternatives						
		ALH					WAN	ALH		WAN	KIN			
		Ideal Mix Placement at EDZ DS	Ideal Mix Placement at EDZ and EDZ DS	Ideal Mix Placement at EDZ	Clean EDZ and EDZ DS	Gravel Placement at EDZ and EDZ DS	Ideal Mix Placement at Restoration Area	Flow deflector	Placement at HLK	Augmentation on bank	Small substrate placements	Large placement near bridge	Augmentation near Bridge	Cleaning
Physical effects to adjacent habitats?	y/n	yes	yes	yes	yes	yes	yes	yes	yes	no	no	no	no	yes
Meet design criteria?	y/n	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Monitoring of spawning activity occuring?	y/n	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Experiment possible?	y/n	yes	yes	yes	yes	yes	yes	no	yes	no	yes	yes	yes	yes
Permitting barriers?	y/n	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Proximity to larval habitat	y/n	yes	yes	yes	yes	yes	no	yes	yes	no	no	no	no	no
<u>Information Metrics</u>														
Hydraulics (Restoration Area)														
Mean velocity - spawning flows	m/s	1.47	1.51	1.60	1.51	1.51	0.86	-	0.60	-	-	1.99	1.99	1.99
Froude number - spawning flows	-	0.12	0.13	0.16	0.13	0.13	0.10	-	0.054	-	-	0.23	0.23	0.23
Mean depth - spawning flows	m	14.3	12.6	11.4	12.6	12.6	8.8	-	13.2	-	-	6.7	6.7	6.7
Shear Velocity - spawning flows	m/s	0.10	0.11	0.12	0.11	0.11	0.06	-	0.04	-	-	0.14	0.14	0.14
D50 Shields Competence - spawning flows	mm	13.4	14.8	18.0	14.8	14.8	4.7	-	2.3	-	-	21.1	21.1	21.1
D50 Shields Competence - peak 2012	mm	14.0	13.3	12.5	13.3	13.3	22.2	-	15.8	-	-	32.5	32.5	32.5
Substrate (Restoration Area)														
Sorting (grain size range)	-	1.36	1.34	1.33	1.34	1.34	1.23	-	0.65	-	-	-	-	-
D50 from GSD	m	53	40	34	40	40	99	-	63	-	-	-	-	-
D84 from GSD	m	110	88	79	88	88	160	-	91	-	-	-	-	-
Biological Response														
Key life stage benefit[1]	-	A	A	A	I,H	A	A	-		H	A	A	A	unknown
Geometry														
Restoration area	m^2	12,000	25,000	13,000	25,000	25,000	8,000	-	22,000	-	-	170,000	170,000	170,000
Width (restoration area)	m	70	75	80	75	75	50	-	100	-	-	100	100	100
Length (restoration area)	m	180	335	160	335	335	150	-	270	-	-	1,300	1,300	1,300
Length to width ration (restoration area)	-	3	4	2	4	4	3	-	3	-	-	13	13	13
Spawning Area	m^2	77,000	77,000	77,000	77,000	77,000	157,000	-	77,000	-	-	1,057,000	1,057,000	1,057,000
Spawning Area to restoration area ratio	-	6	3	6	3	3	20	-	4	-	-	6	6	6

[1] Life stages include A=all, S=spawning, I=incubation, H=hiding.

5.7.3. Normalized Performance Measure Scores (L/M/H)

Appendix H Table 2 shows the criteria for assignment of a low, medium, or high score for each PM. A detailed rationale for the target value of each PM has not been provided given the large number of longlist PMs. However, rationale for the targets are provided for the shortlist of finalized PMs in Section 5.7.5.

5.7.4. Final Shortlist of Performance Measures

The rationale for the selection of the shortlist of final PMs is indicated in Table 2 of Appendix H. The following section includes a description of the shortlist PMs, target values, and difference between scores for each alternative.

5.7.5. Final Scores for Alternatives

Following the winnowing process, 11 PMs remained that each provided useful information. Each of the PMs were assigned an equal weighting for the evaluation. Five of the final PMs are related to substrate mobility, which represents in part longevity of the alternative. Assignment of a longevity score was considered, but the complexity associated with predicting longevity requires consideration of multiple processes that in some cases conflict with each other. Another five PMs are related to biological suitability, while the 11th PM is a composite indicator of constructability. The final scores from the prioritization process of Workshop One (Table 2, Tier 1) are shown in Table 18.

Overall placement at the EDZ and EDZ DS of D50-125 was scored highest (23), followed closely by placement of D50-125 at the EDZ (22). The lowest scoring alternatives were placement of D50-125 at EDZ and at Waneta, which each scored 18. The variability of scores across alternatives for each PM was high, which indicates that alternatives have different strengths and weaknesses, depending on the PM of interest.

If only the five substrate mobility PMs are considered, there would be a four-way tie between placement of D50-125, cleaning, and gravel placement (D50-35) at EDZ and EDZ DS and placement of D50-125 at EDZ. The lowest ranking projects in terms of substrate mobility were placement of D50-125 at EDZ DS, followed by placement of D50-125 at Waneta. Based on the results of the sediment transport modelling, it is expected that the scoring of the alternatives is sensitive to the delineation of the treatment location. The optimized footprint analysis presented in Section 5.4.7 helps to resolve this sensitivity when choosing between various stone size placements, cleaning, and between Waneta and Keenleyside.

If only the five biological PMs are considered, placement of the ideal sturgeon substrate at EDZ and EDZ DS would be ranked highest, and placement of the ideal sturgeon substrate at Waneta would be ranked lowest. The remaining alternatives would have intermediate rankings varying by less than one point.

The following subsections detail the rationale for inclusion of the final PMs and highlight the factors resulting in different scores between alternatives.

Table 18. Initial, subtotal, and final scores for Performance measures for each alternative. Subtotal and final scores are portrayed in a colour spectrum to illustrate variability from initial scores of low, medium, and high.

Performance Measures	Unit	Score Assignment	Target	Alternative							
				ALH						WAN	
				Do Nothing	Ideal Mix Placement at EDZ DS	Ideal Mix Placement at EDZ and EDZ DS	Ideal Mix Placement at EDZ	Clean EDZ and EDZ DS	Gravel Placement at EDZ and EDZ DS	Do Nothing	Ideal Mix Placement at restoration area
Existing Mobility in Spawning Area											
Mobile fines fraction - PDO/ALH 5-yr peak	%	L: 0-33, M: 33-66, H:66-100	+	29	29	29	29	29	29	50	50
Treatment Mobility in Restoration Area											
Mobile coarse fraction - typical freshet (W&C)	%	L: <10 & >40, M: 10-20 & 30-40, H: 20-30	specific	48	6	21	36	43	43	9	0
Mobile fines fraction - typical freshet	%	L: 0-33, M: 33-66, H:66-100	+	48	25	42	57	48	50	9	0
Mobility in Restoration Area after-before											
Mobile coarse fraction - typical freshet (W&C)	%	L: <-10 & 20-30, M: -10 -0 & 10-20, H: 0-10	specific	0	-23	-27	-21	-4	-5	0	-9
Mobile fines fraction - PDO/ALH 5-yr peak	%	L: ≤0, M 1-20, H: >20	+	0	-4	-6	1	0	2	0	-27
Subtotal		Colours shown as spectrum		7	5	8	8	7	8	8	7
Existing Substrate Condition in Restoration area											
Embeddedness (Average Score)	0-5	L: <1.5, -3.5 M: 1.5-2, 2.5-3 H: 2-2.5	specific	1.54	1.29	1.54	1.58	1.54	1.54	0.60	0.60
General rearing suitability	1-3	L: <1.5 M: 1.5-2, 2.5-3 H: 2-2.5	specific	2.18	2.37	2.18	2.08	2.18	2.18	2.83	2.83
Restored Habitat suitability in Restoration Area											
Recruitment Suitability (area with high suitability)	%	L: <60%, M: 60-80%, H: >80%	+	65	86	80	75	80	80	14	50
Recruitment Suitability After-Before	%	L: <20%, M: 20-40%, H >40%	+	0	9	15	21	15	15	0	36
Expected Biological Response:											
Magnitude of response	-	Selected during workshop	+	low	med	high	med	med	low-med	low	low
Subtotal		Colours shown as spectrum		9	10	12	11	11	10	6	8
Feasibility											
Constructability	-	Professional judgement	+	high	high	high	high	low	high	high	med
Overall Score (equal weighting):		Shown as spectrum		19	18	23	22	20	21	17	18

Scoring system (points):	Low = 1	Med = 2	High = 3

5.7.5.1. Mobile Fines Fraction - PDO/ALH 5-yr Peak (Existing in Spawning Area)

This PM provides a general indication of the current flow regime of the Columbia River and the fraction of fines that can be flushed out of the spawning area on a 5-year basis. This physical process could be responsible for maintaining high quality rearing habitat that infills during lower flow years and provides an indication of recruitment suitability in the surrounding area where sturgeon may ultimately rear. A target of 100% flushing was selected, with an even distribution of LMH bins from 0 to 100%.

This PM highlights that the fines flushing conditions are ~20% better at Waneta than Keenleyside, which could partially explain the greater rearing success at Waneta (McAdam 2015). The Keenleyside 5-year peak flow was taken to be the maximum shear condition in the ALH that occurs annually when ALH is at full capacity and HLK is offline. Mobile fines fraction at Waneta was 69% during the extreme 2012 conditions with a return period of ~9 years, which shows that flushing conditions can improve with higher peak flow events at Waneta, which is not the case at Keenleyside. This PM suggests that Waneta could be a better location for restoration given that the overall fines flushing conditions throughout the spawning area are likely better than at Keenleyside.

5.7.5.2. Mobile Coarse Fraction – Typical Freshet (W&C) (Treatment in Restoration Area)

This PM indicates the percentage of coarse treatment material (D50 and smaller) likely to move on an annual basis. It is expected that some level of movement of this material is likely required to flush fines that deposit in the interstitial spaces of the treatment material. The target for this metric was to have D50 mobility in 20-30% of the treatment area every year. This target was selected to prevent full scouring of the coarse material, but to ensure that some level of fines flushing is occurring.

This PM highlights the variability of coarse material mobility between each of the alternatives. Placement of 20-50 mm gravel and cleaning at Keenleyside are both predicted to have D50 mobility in 43% of the restoration area on an annual basis. It is assumed that this may be too high, resulting in requirement for material replacement on a nearly annual basis. Treatment material is only predicted to move in 6% of the area at EDZ DS, and not at all at Waneta. Placement of D50-125 in both the EDZ DS and EDZ at Keenleyside is predicted to mobilize in 21% of the area on an annual basis. While the spatial patterns of movement would likely be similar each year, this condition may result in better longevity of the treatment area since areas near the upstream may have fines flushed, while areas downstream may have deposition of fresh coarse material with high rearing suitability. Thus, this PM suggests that Keenleyside would be a better location than Waneta.

5.7.5.3. Mobile Fines Fraction - Typical Freshet (After Treatment in Restoration Area)

This PM provides a secondary indication of longevity of treatments, similar to the previous PM. This PM assumes that some fines can be flushed without mobility of coarse material. It is expected that this process may be less realistic but could be possible with enough near-bed turbulence or subtle movement of coarse material. A target of 100% flushing was selected, with an even distribution of LMH bins from 0 to 100%.

This PM provides further indication that on an annual basis fines flushing conditions would be best with placement of D50-125 in the EDZ and to a lesser extent with the other alternatives in the EDZ and EDZ DS. Placement of D50-125 at the EDZ DS alone is predicted to only experience 25% fines flushing by area, while Waneta is not predicted to experience any flushing of fines, similar to the estimate for coarse scour. Thus, this PM suggests restoration at Keenleyside rather than at Waneta.

5.7.5.4. Mobile Coarse Fraction – Typical Freshet (W&C) (Restoration Area After Treatment Subtract Before Treatment)

This PM provides an indication of the increase or reduction in coarse material mobility within the restoration area following treatment. It helps to characterize the risk of worsening fines flushing conditions if coarse scour is required to mobilize fines. A target of a 0-10% increase in area with scour of coarse material was selected, with 10% outside of this range for medium, and all else as low.

This PM Shows that >20% of the treatment area for Keenleyside alternatives will be less mobile after placement of D50-125, but only <10% of the treatment area will be less mobile at Waneta and for gravel placement or cleaning at Keenleyside. This result highlights a risk that the Keenleyside D50-125 placement alternatives could make conditions worse if transport of coarse material is required to flush fines, while the other alternatives have less risk of this response. Thus, this PM suggests restoration at Waneta and cleaning or gravel placement at Keenleyside over placement at Keenleyside.

5.7.5.5. Mobile Fines Fraction – PDO/ALH 5-year Peak (Restoration Area After Treatment Subtract Before Treatment)

This PM provides a similar purpose to the PM above but for a less frequent/higher peak flow and with a focus on fines transport. An increase in fines transport compared to existing conditions is the desired outcome of treatments. A target of >20% increase was selected, with a medium bin from 0-20%, and low for anything less than 0%.

This PM highlights that treatments at Keenleyside will have a modest effect on fines flushing potential of between -6% to 2%. At Waneta, placement of D50-125 treatment material is predicted to result in a 27% decrease in area where fines flush during a 5-year return peak flow. The reduction at Waneta is due to an existing high gravel fraction near the downstream extent of the restoration area, where fines can likely be flushed along with the gravel. It should be noted again that the existing Waneta conditions measured during 2018 could represent a disturbed more mobile state, given the high PDO peak flow that occurred during May 2018. Thus, this PM suggests restoration at Keenleyside over Waneta.

5.7.5.6. Average Embeddedness Score (Existing in Restoration Area)

This PM provides an indication of the current habitat suitability conditions in terms of embeddedness. Low existing embeddedness would indicate minimal room for improvement, while high embeddedness could indicate high fines supply that could limit the longevity of treatments. Therefore, an intermediate value for embeddedness of 2-2.5 (out of 5) was assumed as the target condition.

Current embeddedness conditions were lowest at Waneta, followed by EDZ DS. The low Waneta embeddedness indicates that habitat conditions may not be limited by embeddedness at this location, and perhaps substrate in general; however, the high flow event from PDO that occurred during spring 2018 may have lowered embeddedness relative to typical conditions. The lower embeddedness at EDZ DS was somewhat surprising, given that shear is lower at this location compared to EDZ; however, similar to conditions observed in Kinnaird, embeddedness in the EDZ may be higher due to scour without any supply and associated interlocking/armouring of remaining substrate. Thus, this PM suggests restoration at Keenleyside rather than at Waneta.

5.7.5.7. General Rearing Suitability Score (Existing in Restoration Area)

This PM was included in addition to embeddedness to provide an additional indication of habitat quality based solely on professional judgement by the sturgeon experts. Although these observations only represent a snapshot in time, they provide a direct indication of whether existing substrate conditions are suitable for rearing sturgeon. Similar to the previous PM, a target of 2-2.5 was assumed.

General rearing suitability was found to be relatively high in the Waneta restoration area, which aligns with the low embeddedness score from the previous PM. Rearing suitability was also higher in the EDZ DS than EDZ, which highlights uncertainty in the benefits of treatment in the EDZ DS, given that both model predictions of fines deposition and scores for the fines percentage PM (Appendix H) suggest that this area may be less suitable for rearing due to fines deposition. Thus, this PM suggests restoration at Keenleyside rather than at Waneta.

5.7.5.8. Recruitment Suitability - Area with High Suitability (After Treatment in Restoration Area)

This PM provides an indication of expected rearing suitability following treatment using the Hatten *et al.* (2018) model (Section 5.5) that includes hydraulics (Froude number) in addition to substrate indices. It was assumed that perfect substrate suitability would be achievable, thus this PM indicates the suitability of restoration areas based on hydraulics. It should be noted that this PM does not take into account the longevity of the treatment. A target of >80% suitability was selected for the high ranking, since hydraulics were generally found to be non-limiting.

Recruitment suitability is predicted to be only 50% following treatment at Waneta. This was expected given that the treatment area is in a location where there is frequently a backwater eddy, which would limit the Froude number. The EDZ DS area had the highest score, followed closely by the EDZ and EDZ and EDZ DS areas. Therefore, based on hydraulics alone, this PM suggests that the EDZ DS location would have greatest suitability if treatment material remained in place and free of fines. Thus, this PM suggests restoration at Keenleyside rather than at Waneta.

5.7.5.9. Recruitment Suitability After – Before Treatment in Restoration Area

This PM provides an indication of the improvement in recruitment suitability associated with treatment. Similar to the previous PM, this PM indicates the degree to which habitats are limited by substrate, but with different targets. For this PM, a target of >40% was selected.

Contrary to the previous PM, this PM indicates that the greatest improvement in recruitment suitability could be achieved at Waneta (36%), followed by the EDZ (21%), EDZ and EDZ DS (15%), then EDZ DS (9%). This result suggests that substrate conditions are currently poorest at Waneta and the EDZ, and these locations stand to gain the most from substrate treatment provided that the material would stay in place and free of fines. The dominant/subdominant substrate assignments shown in Appendix C indicate that the Waneta restoration area was limited most by having too high of boulder fraction, rather than high embeddedness or poor hydraulics. Thus, this PM suggests restoration at Waneta rather than at Keenleyside.

5.7.5.10. Expected Magnitude of Biological Response

This PM was determined during Workshop One and is a general indicator of the magnitude of benefits at each site. Scores of LMH were assigned during the workshop, rather than starting from a quantifiable PM.

The workshop participants indicated that D50-125 placement at the EDZ and EDZ DS would provide the greatest response, while D50-125 placement and cleaning at this location and D50-125 placement at EDZ and EDZ DS independently would have moderate magnitude of response. Benefits of gravel placement at EDZ and EDZ DS and D50-125 placement at Waneta were predicted to be low. Thus, this PM suggests restoration at Keenleyside rather than at Waneta.

5.7.5.11. Constructability

This PM indicates the overall constructability of each alternative based on ease of access for equipment and challenges of hydraulic conditions at the site. Scores of LMH were assigned by the Ecofish team using professional judgement.

The Keenleyside placement alternatives were identified as the most constructible given the ease of access for barges and trucks and relatively calm hydraulic conditions. Constructability at Waneta was assessed to be moderate given the steep banks adjacent to the site that would impede transfer of substrate from truck to barge and the swiftness of current in this area. Cleaning at Keenleyside was flagged as having the lowest constructability given the uncertainty with how cleaning would be performed.

5.8. Workshop Two Summary

Workshop Two was held February 6, 2020 with the following objectives:

- Review methods and results of technical analysis;
- Build common understanding of the alternatives assessed and the priorities for habitat restoration;
- Prioritize alternatives developed during Workshop One using the preliminary ranking results;
- Develop initial considerations for restoration design, pre- and post-project effectiveness monitoring and environmental archaeological assessments to be conducted in Phase 2; and
- Agree on the next steps and timelines.

The scope of Workshop Two included consideration of the prioritized list of alternatives from Workshop One and a decision of whether to continue to phase 2 of the project with one or more of the alternatives. The sessions of the workshop included:

1) Overview of project;
2) Review of technical analysis;
3) Re-prioritization of alternatives;
4) Initial design considerations;
5) Initial monitoring considerations; and
6) Next steps.

During the sessions, participants reviewed trends in the substrate information that was re-evaluated using additional parameters and data collected during summer 2019. Changes in substrate conditions were reviewed between 2018 and 2019 at Waneta, and participants agreed that the 2018 photos were likely unrepresentative of typical conditions, given the extreme flow event that happened during spring 2018 prior to sampling. The participants agreed that the 2018 observations of substrate suitability parameters should be treated with caution. An apparent correlation between armouring level and overall substrate suitability was flagged for further investigation.

Suggestions for additional analysis were put forward and incorporated into the methods and results described above. Design and monitoring considerations were discussed and incorporated into the recommendations detailed in Sections 7.2 and 7.4 below. A summary of conclusions and recommendations that were generally agreed upon by the workshop participants is provided below.

5.8.1. Keenleyside Summary

The EDZ was identified as the highest priority area for restoration given that it is a known spawning site and has more predictable hydraulic conditions than the other sites. The participants agreed that an initial experiment would be beneficial that could be used to investigate short-term physical response. One limitation of this alternative was that the area of the EDZ is relatively small, and the treatment may produce only a minor increase in the total amount of suitable area for rearing. This limitation was also identified for the EDZ DS area, along with the risk that spawners may not use the EDZ DS.

Cleaning was discussed to be a valuable option if it could effectively emulate pre-dam transport conditions. However, the risks of cleaning were agreed to outweigh the potential benefits. Further discussion is provided in Section 6.3.

Participants agreed that gravel placement should remain low priority, given that the treatment would have a short lifespan and require maintenance. The difficulty of assessing benefits was also highlighted as a concern, since the placed gravel may be washed out before a response is measured. Uncertainties were also identified with ability to replicate results (i.e., new material may change transport conditions following initial flushing).

Ultimately, it was decided that the cleaning and gravel placement uncertainties were too large at this time, and these alternatives were not pursued further. Participants recommended developing an optimization strategy (Section 5.4.7) that maximized the area of placed material that would be also expected to be stable. It was suggested that a primary benefit of placement in the ALH tailrace was that it could serve as a learning opportunity with lower risk relative to placement at Waneta or Kinnaird. It was agreed that the technical team should prescribe placement zones where the stone class would be expected to be stable and within the suitable size range for White Sturgeon. The exact area to be treated during subsequent phases would potentially be reduced to allow for variation in experimental treatments (e.g., to allow for comparison of control and treatment areas).

5.8.2. Waneta Summary

The workshop participants decided there was insufficient information to make a decision on a treatment at Waneta at this time, and that results from treatment at Keenleyside could be used to inform potential for success elsewhere in the system. Participants also agreed that a placement in the previously defined restoration area (upstream of the bend apex) was likely to infill given the hydraulic and sediment transport conditions that were presented.

The approach of dumping augmentation material near the restoration area that was previously classified as a Tier 2 alternative was reconsidered. It was noted that augmentation could benefit the area given that input of suitable material already occurs naturally to some degree from a failing slope. The location of augmentation was also discussed and it was speculated that a greater supply of suitable material throughout the EDZ may improve overall recruitment. Challenges with assessing the transport frequency of augmentation material were noted by the technical team, including uncertainties with predicting movement of material deposited on channel banks associated with model boundary limitations. The ability to effectively track movement of the augmentation material was also identified as a limitation. The technical team noted that transport of the augmentation material could be tracked once the material was on the channel bed, but the frequency and amount of material sloughing from a bank deposit would be difficult to predict. The workshop participants recommended that the technical team further consider the potential efficacy of augmentation if time allows.

5.8.3. Recommendations from Workshop

Participants agreed that initiating Phase 2 of the project is well justified given that White Sturgeon is an endangered species and restoration alternatives are likely to have biological benefits, despite some uncertainties in their physical performance over time. The highest priority alternative was assessed to be treatment within the ALH tailrace spawning area wherever material would be stable and in the downstream flow path of known spawning locations. Additional alternatives were suggested for further investigation, but only after ALH placement was conducted as a trial. The additional alternatives with greatest support from participants included cleaning of ALH, placement at Waneta in the restoration area, and augmentation at Waneta into the existing core EDZ. Final considerations and recommendations for the ALH design were incorporated into the optimization Section 5.4.7.

The workshop participants discussed monitoring considerations and decided that the initial treatment should involve some level of formal experimentation to assess biological and physical response. Placing material that was slightly smaller than the size predicted to move and observing transport after one year was considered. This approach would allow calibration of the sediment transport equations while limiting the risk of placing material that is too large and may become stuck in place permanently and subject to infilling. If the substrate moved too much, a slightly larger size could be placed during the following year that is closer to the transport threshold. Material close to the transport threshold is expected to be ideal so that some stones can move a small distance and in doing so release fines that have aggraded in interstitial spaces. Biologists cautioned that such an approach would be difficult to assess from a biological perspective, since recruitment would not be detectable for multiple years (ca. 5 years) and is difficult to assess in general. DFO staff also cautioned that the experiment itself could not adversely affect existing conditions for White Sturgeon.

Table 19. Participants at Workshop Two.

Workshop Participant	Affiliation
Dean Watts	DFO
Ahdia Hassan	DFO
Steve McAdam	FLNRORD
Connie Chapman	Comptroller of Water Rights
Robyn Laubman	Splatsin First Nation
Wendy Horan	CPC
James Crossman	BC Hydro
Katy Jay	BC Hydro
Toby Michaud	BC Hydro
Todd Hatfield	Ecofish Research Ltd.
David West	Ecofish Research Ltd.
Mike Parsley	Consultant (USGS retired)
Toby Perkins	Knight Piesold Ltd.

6. DISCUSSION

6.1. Substrate Trends

Overall substrate character trends were considered for Keenleyside and Waneta based on the results from Section 5.2. A discussion of applicable findings is detailed below.

6.1.1. Keenleyside

The study area at Keenleyside had substrate ranging from fines in the HLK eddy and river left bank downstream of the ALH jet to boulders located in the ALH jet and adjacent to it on the river left bank (Appendix C). The majority of the ALH tailrace was dominated by cobbles that tapered to gravel domination further downstream. The embeddedness conditions roughly matched the substrate size, with fines dominance correlating to high embeddedness, and boulders and cobbles correlating to low embeddedness (Appendix D).

Within the Keenleyside restoration area, the substrate size was small at many locations, indicating a lack of transport capacity. The existing size class was mostly gravel and cobble (approximately 70%). Rearing suitability was also high and embeddedness low, which suggests a risk that conditions are already suitable for sturgeon. These observations could indicate limited room for improvement of existing material. However, fines percentage was higher at Keenleyside than Waneta, which could partially explain the discrepancy in recruitment between the two areas that McAdam (2015) found. Roughness was also much higher at Waneta than Keenleyside, which is another indicator of rearing suitability. Roughness increase can be achieved by placing new material.

Much of the Keenleyside EDZ had areas where recent transport had apparently occurred, as evidenced by high interstitial space and low fouling, while other locations were packed tightly with minimal interstitial space. The source of recently transported material is unclear, as ongoing erosion in this location is unlikely due to the 50 years without upstream sediment supply and constant peak flows since dam installation. Possible explanations are that (1) the substrate appears recently mobile but is not, (2) gravel augmentation for other purposes has been occurring, (3) progressive downcutting is occurring, or (4) stones move very short distances on annual basis which prevents compaction. Evidence of recent transport was similar between Waneta and Keenleyside, which is odd since Waneta would have been expected to have more given the recent peak flow.

The river right side of the Keenleyside restoration area had low roughness as a result of smaller grain size (often fine to medium gravel). Although some of this area had high fines content, much of the area could be ideal for placement since current conditions are unsuitable but risk from fines infilling and scour are both low.

Surprisingly, the sorting of material and gradient of substrate size in the longitudinal direction from the ALH tailrace downstream was often weak or irregular. Patches dominated by sand, gravel, or cobbles were distributed throughout the EDZ. The patches could be an indication of turbulence patterns dominating sediment transport pattern, rather than reduction in average shear as flow from the ALH and HLK jets disperse in the wider channel. These patches could indicate that localized erosion or deposition on the order of 10s of meters could be expected with placed material.

6.1.2. Waneta

The Waneta study area was dominated by cobbles, within boulder dominant patches along the PDO jet, and fines dominant patches in the confluence bar (Appendix C). Embeddedness was generally low to medium throughout the PDO jet, and high in the confluence bar (Appendix D). However, high embeddedness did occur with boulder dominant areas along some areas near the river left bank.

Large boulders were dominant in much of the Waneta EDZ, which, while considered ideal for spawning (Parsley and Beckman 1994), may be larger than ideal for rearing. Approximately 50% of the spawning area at Waneta was dominated by boulders, which are likely lag deposits as cobbles and gravel are washed away. There was some evidence of fouling on the stones within the restoration area, while the rest of the spawning area had moderate quality substrate. The high rearing suitability conditions observed primarily during 2018 could have been resultant of the 25-50-year peak flow that occurred during spring 2018. Evidence of an increase in fines deposition and fouling was observed during 2019 (Section 5.2.3). Fines deposits were not found downstream of the restoration area in the core EDZ, where the sediment transport model predicted frequent flushing conditions. Fines loading is considered a moderate risk however, given the findings of Fissel *et al.* (2017) and the large sand deposits observed immediately upstream of the LCR and PDO confluence that could be transported to the restoration area (Section 4.4.3).

During the second engagement meeting, it was noted that armouring was quite high in the Waneta EDZ, and this parameter could be a negatively-correlated indicator of rearing quality. It should be noted that armouring levels were difficult to assign qualitatively, since the level of armouring depends on the subsurface sediment size, which is largely unknown. Instead, armouring was assessed similarly to compaction, where stones are closely interlocked. Given the subjectivity of assigning armouring, it is likely that armouring level correlated with other variables that are better indicators of rearing suitability. For example, roughness is an indicator of interstitial space and was also found to be high throughout the Waneta EDZ.

6.2. Uncertainty

6.2.1. Hydraulics

Discussion of uncertainty with the hydrodynamic model predictions is provided throughout Section 5.3. Overall, the hydrodynamic model predictions were assessed to be good near the EDZ and restoration areas given the reasonable match between ADCP measurements and modelled conditions. Also, the general pattern of eddies and the ALH jet was similar to the Golder (2014a) observations. Similarly, the model flow patterns at Waneta were similar to the Fissel *et al.* (2017) results. A summary of sources of uncertainty and relative influence are provided below.

- Although ADCP measurements were used throughout this project for calibration and validation of the hydrodynamic models, it is important to be aware that these values have their own internal sources of error and should not be regarded as a perfect representation of actual conditions. During FT3 (and to some degree FT4) lower flows, deep water, heavy backwatering and eddies were believed to have decreased the reliability and performance of the ADCP in some areas. In the vicinity of some of the larger eddies, lower velocities and turbulence resulted in different ADCP flow trajectories for repeated transects over the same area. There was limited bias in the measured vs. modelled hydraulics conditions overall, and it is expected that the model accuracy likely exceeds the ADCP accuracy in some locations. Calibration and validation plots are shown in Appendix E.
- The accuracy of the ADCP GPS should be 1 m but could have been worse depending on satellite conditions. The effect is likely minimal.
- Accuracy of upstream and downstream boundary water surface elevation was assumed to be reasonable given that stage data was available at Waneta and Keenleyside. Boundary hydraulics likely had more of an influence, since eddies or backwatering at the boundaries may have been present that would affect upstream conditions. These uncertainties likely have a moderate effect on model predictions within approximately 100 m from the downstream boundaries.
- Roughness was assumed to be uniform in each spawning reach. A cursory sensitivity analysis was performed, and it was determined that the model was insensitive to roughness, which

was expected given the depth. Eddy viscosity and inflow angle appeared to have a stronger control on model predictions and were therefore adjusted as part of calibration.

- The bathymetry data was high resolution and is expected to have limited effect on uncertainty relative to other parameters. Lidar data for the shoreline was also high accuracy; however, the section between the Lidar and bathymetry was interpolated, and therefore uncertainty of model predictions in these areas (~10-20 m from shoreline at high flow) is likely moderate.

- Turbulence was not accounted for in the model, which could influence localized short-term forces on the stream bed that are not captured by a time averaged shear prediction such as that used in River2D.

6.2.2. Sediment Transport Equations

Sediment transport modeling analyses are subject to several inherent uncertainties. Some of these have been discussed in Section 4.3.6; further details are expanded upon here. A fundamental issue common to all sediment transport models is the effective parametrization of incipient motion. Different models address this issue in different ways such as by defining a small measurable transport rate assumed to be indicative of entrainment, or through empirical observation of when the first grains begin to move in experimental flume settings. Thresholds are then used in applied settings under varying environmental conditions that may or may not by governed by the same physical mechanisms that the models were developed for. Similarly, sediment entrainment is in reality a probabilistic process; subject to the randomness of turbulent bursts, local hydraulics and particle interactions. Given the non-linear nature of the relationship between shear stress and transport rate, small errors in shear stress or thresholds may result in large errors in transport predictions. To account for this uncertainty, different sediment transport equations should be tested and carefully chosen to be appropriate to the physical setting under investigation.

Calibration of the chosen transport equation is also often beneficial, allowing determination of site-specific entrainment conditions and adjustment of models to match observed processes. In this study, two models were chosen to provide complementary results, serving to explicitly highlight the fact that different models can give different results. This allows for honest discussion of model assumptions and comparison of results to best address uncertainty. While a systematic investigation of in-situ transport rates for calibration was not feasible in the scope of this project, two methods of indirect calibration were performed: a comparison of transport predictions with substrate images classified into whether they show evidence of recent transport or not, and a tracer stone study to document transport of certain size clasts under the conditions observed throughout the study period. Observations of recent transport in the bed images served to support predictions from the transport models (Section 4.3.6), reducing uncertainty in the thresholds and models used. The results from the tracer stones were difficult to explain in the context of the modeled flows, which could reflect uncertainties in River2D results near model boundaries, the lack of a modeled scenario that best captures the peak shear stress conditions at each tracer deployment location, the potential for smaller-scale hydraulic features not captured through River2D modeling such as lateral/vertical secondary circulation, short term velocity increases within the streambed boundary layer, or turbulent bursts affecting local transport conditions.

Bed surface state (e.g., armoring, imbrication, or interlocking) is another factor that plays a strong role controlling entrainment and transport. While the Shields model accounts for this by varying the Shields parameter, this is still a generalization and determining an appropriate parameter is a subjective procedure. The Wilcock and Crowe model does not address bed surface state explicitly, but its multi-size fraction setup allows for some inherent incorporation of relationships between large and small grains that can account for some of the same mechanisms that could be explained by armoring or interlocking. This difference between the two models is also important in the consideration of the effects of substrate cleaning; cleaning the fine sediments from a surface mixture tends to raise D50 and reduce sand content, resulting in a predicted lower overall mobility with the Wilcock and Crowe model. With the Shields model, however, cleaning was accounted for by a lowering of the Shields parameter, reflecting a reduced level of armoring and a more easily mobilized bed. Differences between the two models again serve to provide multiple ways to interpret results and highlight the importance of discussing uncertainty and model assumptions explicitly.

6.2.3. Grain Size Distributions

Accurate characterization of grain size distributions is fundamental to results of sediment transport modeling and interpretations of bed conditions. In this study, grain size distributions were determined through qualitative observations and classifications of bed substrate images (Section 4.2.1) and through quantitative automated image analysis (Section 4.2.8). To reduce uncertainty in qualitative classifications, rigorous training between observers and experts was used to ensure consistency in interpretation, as well as assessment of agreement in classifications after the fact. Classifications were then interpreted in the context of determined uncertainty to ensure appropriate use of the results to draw conclusions. Uncertainty in the automated grain size analysis was less operator based and more dependent on limitations to technology, data sources, and methodology. As discussed in Section 4.2.8, the quality of bed substrate images used in the wavelet method was a main constraint on algorithm applicability; images with blur, oblique viewing angles, improper height of reference object above the bed surface, or an excess of large or small grain fractions can all compromise resultant grain size distributions. Care was taken to apply the wavelet method to images that minimized these complications, but this limited the spatial coverage of bed substrate sizes to only select appropriate images. Uncertainty in the wavelet method was also reduced by the dry-ground calibration procedure in comparison to traditional Wolman samples (Figure 20). A final source of uncertainty in the automated procedure was the difficulty of properly accounting for sand content in the images. Because the automated method cannot resolve individual sand grains, sand content was assigned to each image subjectively. While these sand content assignments were compared with observations of fines in the qualitative image classifications, some uncertainty is unavoidable and would be expected to affect final grain size distributions and transport rates.

6.2.4. Sediment Supply

Sediment supply rate to Keenleyside and Waneta was assessed using qualitative inferences based on upstream sources, existing substrate conditions, and secondary circulations (Section 4.4.3 and Section 5.4.3). The assessment relies on the assumption that fines are likely delivered to the spawning areas by near-bed transport during high flows, rather than settling out from suspension during low flows. This assumption is supported by previous observations of low turbidity at Keenleyside (NHC 2007). At Waneta, the rate of fines delivery was assumed to be high enough to allow suspended load settling based on the upstream length of erodible channel and modelling completed by Fissel *et al.* (2017).

At Waneta, the supply and deposition rate predicted by Fissel *et al.* (2017) was high enough that the restoration area is likely transport limited and was assessed as such with transport frequency modelling. At Keenleyside, there was reasonable confidence in the assumption of low fines supply from upstream of the dam; however, the forebay is somewhat narrow and it is possible that boat traffic could cause erosion and transport of fine sediment. Another assumption was that the sand deposits at the HLK eddy and the eddy downstream on river left were active. Evidence of a silt layer was observed in some of these locations, which could provide cohesion of particles and a greater resistance to erosion than the modelling indicates. There is a chance that sediment transport throughout the Keenleyside spawning area is negligibly low, and existing deposits have generally been static for decades. However, observations of clean and loose sediment and the model predictions both provide evidence that the material is somewhat active. The analysis of optimal treatment size and location at Keenleyside was performed with a conservative assumption that fines supply could be moderate, and therefore the longevity assessment in Section 5.4.8 is also conservative.

6.2.5. Comparison of Waneta Results to Fissel *et al.* (2017)

The Fissel *et al.* (2017) study involved an analysis of annual and long-term deposition and erosion regime in the Waneta spawning area. They found that sediment deposition would be substantial in a typical year (18-90 mm); however, the annual freshet flows were predicted to remove fine Columbia River sediments deposited in the EDZ. They also predicted that the greatest deposition would occur during years when PDO had a weak freshet. A key difference with the Fissel *et al.* (2017) model was their use of uniform substrate sizes for analysis, which they applied due to a lack of substrate information. Treating the streambed as having one size class is expected to have substantial limitations at Waneta due to the wide size range (fines up to boulders). The hiding effect of fines in the interstitial spaces of large boulders likely substantially increases the transport threshold required to liberate the fines, and could require movement of the boulders themselves.

The hydrodynamic models from this study and Fissel *et al.* (2017) produced similar shear stress predictions. The greatest shear force occurred near the bend apex (C4 in Fissel *et al.* 2017), and was moderate downstream of the apex and much weaker upstream in the eddy. As a means of testing agreement in sediment transport predictions from both studies, Figure 50 and Figure 52 show the predicted transport conditions assuming a uniform grain size for the 1997 flow condition.

Both models predict transport of cobbles near the bend apex on river left, and both show a lack of transport (or deposition) of progressively small material downstream towards the US border. The agreement is also similar comparing model results from this study for the 2012 extreme flow condition (Figure 51) to the 1997 results from Fissel *et al.* (2017). Fissel *et al.* (2017) also predicted a progressively larger eddy upstream of the bend apex with decreased PDO flows, which we also predicted with our model. This agreement builds confidence in the hydrodynamic modelling results.

The sediment transport conditions for fine sand were also compared from Fissel *et al.* (2017) during low year freshet (Figure 53) to a similar flow level modelled for this study (average spawning period flows in Figure 36) looking at medium sand transport. Both models show erosion at the bend apex and settling downstream; however, the Fissel *et al.* (2017) results show erosion of fine sediment from most of the restoration area, whereas results from this study only show erosion of the furthest downstream fraction of the restoration area (albeit for sand). This discrepancy could be explained by hydrodynamic model uncertainty, but more likely it could be the difference between the Fissel *et al.* (2017) assumption of uniform fine sand in this region compared to this study where fine sand would be trapped in the interstices of coarser material (See Section 4.4.2). For example, they found that the critical shear stress for coarse sand was 0.96 to 1.44 Pa at Waneta, whereas our model with hiding considered predicts 27.4 Pa. They used a reduction of 5 times for the erosion rate to account for hiding of sand particles, which perhaps should have been a reduction of 20-30 times.

Another difference is the degree of deposition shown in each model downstream of the bend apex. The Fissel *et al.* (2017) model shows deposition of fine sand throughout the downstream area, while this studies model shows transport of sand in much of the downstream area. This is expected to be resultant of an additional 400 m^3/s from LCR in the simulation for this study. The results from Fissel *et al.* (2017) highlight an infilling risk that aligns with predictions from this study for lower flows (e.g., scenario W02). Since the prediction of fines deposition from Fissel *et al.* (2017) negates the effect of hiding, their predictions point to an even greater risk of long-term sediment infilling in the lower spawning area. This deposition prediction along with scenario W02 indicate that the augmentation alternative may require annual input of material, since fines settling conditions generally occur each year and Fissel *et al.* (2017) predicted suspended load in this region to be high.

Figure 50. **Modelled D50 competency for Waneta during 1997 extreme flow conditions (Scenario W06) using Shields equation (no hiding effect).**

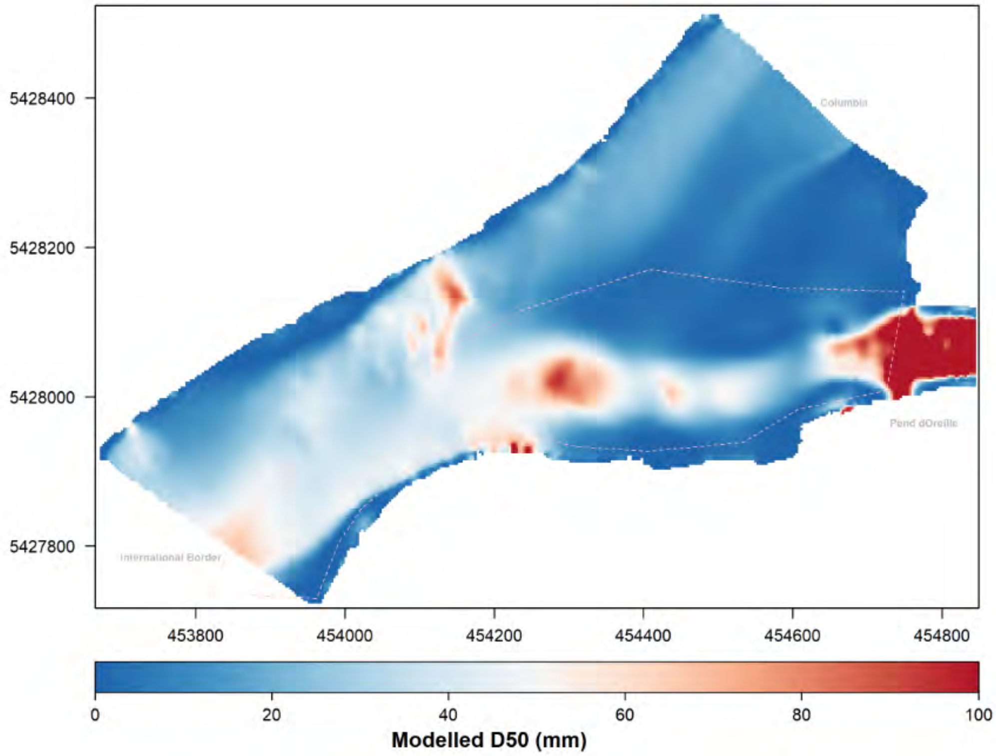


Figure 51. Modelled D50 competency for Waneta during 2012 extreme flow conditions (Scenario W07) using Shields equation (no hiding effect).

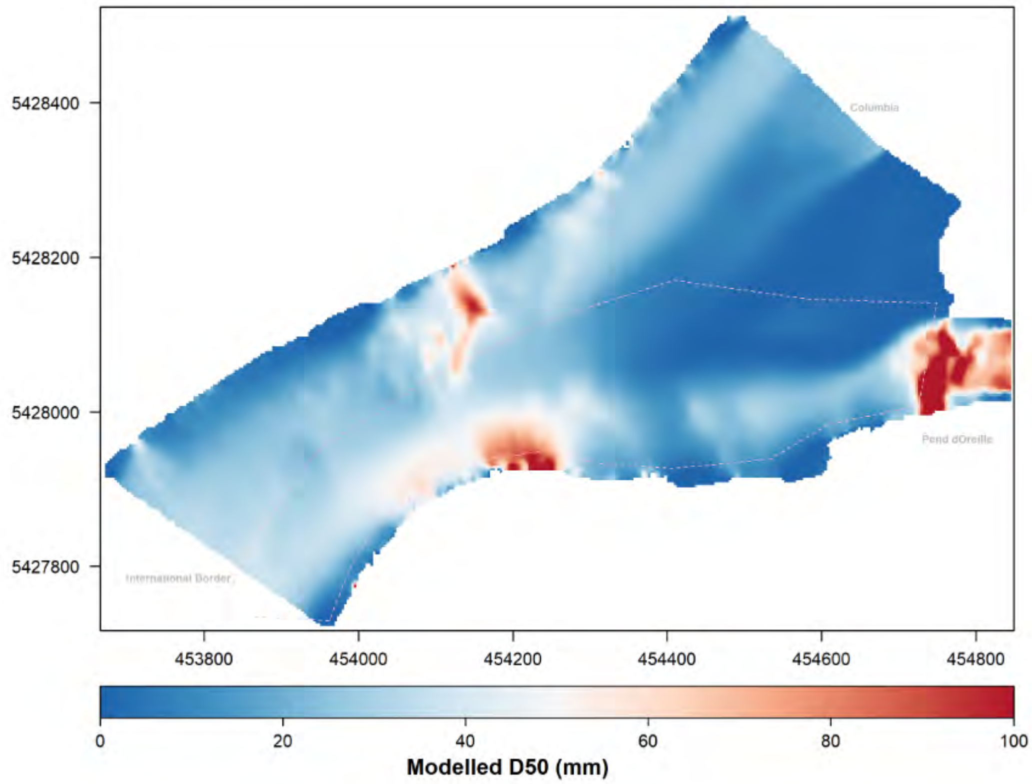


Figure 52. Model results of morphological change (colour) over the river bed for fine pebbles (top panel), coarse pebbles (middle panel), and cobbles (bottom panel) during the extreme freshet discharges (1997). Vectors are near bottom shear stress. (Reproduced from Fissel *et al.* 2017).

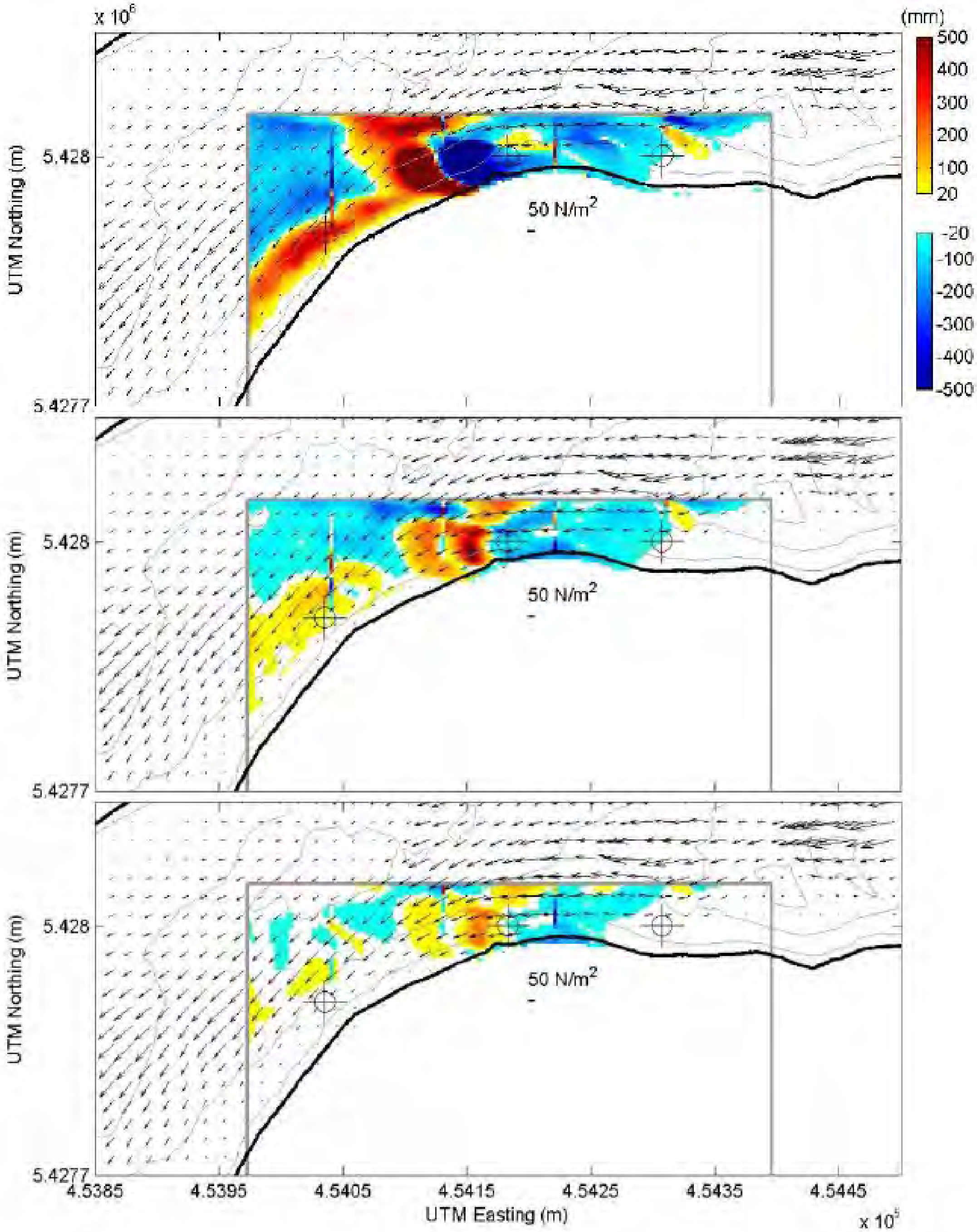
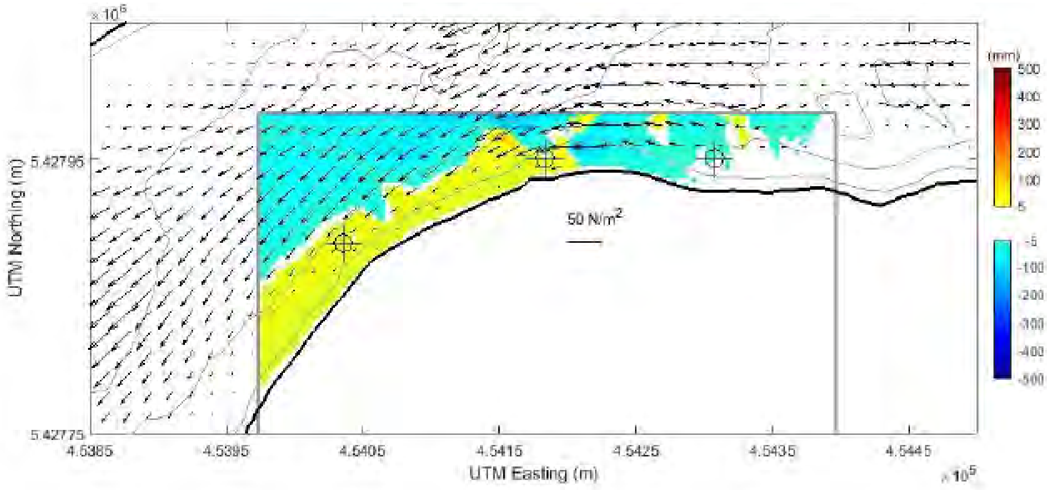


Figure 53. Model results of morphological change over the river bed for fine sand during below average freshet discharge (PDO = 950 m^3/s, LCR = 2300 m^3/s). (Reproduced from Fissel *et al.* 2017).



6.2.6. Habitat Quality Parameters

Substrate quality parameters estimated from images is challenging, with different individuals reviewing the same substrate image sometimes assigning different rankings. To help assess uncertainty and repeatability in scores, three Ecofish team individuals compared embeddedness rankings under a double-blind trial (Ecofish Analyst vs Sturgeon Expert 1, n = 229; Ecofish Analyst vs Sturgeon Expert 2, n = 32; Sturgeon Expert 1 vs Sturgeon Expert 2, n=32). Two-sample Mann-Whitney U tests were used to test if embeddedness ranking differences between individuals were statistically significant. Embeddedness rankings were similar between Ecofish Analyst and Sturgeon Expert 2 ($P = 0.158$), but Sturgeon Expert 1 ranked embeddedness lower than Ecofish Analyst ($P < 0.001$) and Sturgeon Expert 2 ($P < 0.001$). Examples of where agreement was consistent for both high and low embeddedness, and inconsistent for both high and low embeddedness are provided in Appendix I. After reclassifying the embeddedness scores to a simple low (<50% embedded) vs high (>50% embedded) as a sensitivity test, rankings between all three individuals were not statistically different from each other (Chi-squared X^2: 5.1 - 9.2; P < 0.05). The Ecofish Analyst conducted the bulk of the embeddedness scoring, but these results further emphasize a need to improve standardized methodology for embeddedness ranking. Classifications could be further improved by a more extensive review of images as a group and development of consensus on how the score each image should receive.

An additional uncertainty with substrate quality classification arose with the armouring metric. Armouring is an indication of the size ratio of bed surface to subsurface stone size. The term armouring was also used in this study to indicate level of interlocking of large particles. Assignment of armouring scores was done with the former assumption, which resulted in armouring closely aligning with embeddedness and overall rearing quality. This was because large stones on the surface with minimal fines generally provide ideal rearing conditions.

Regarding the habitat suitability modelling, it is important to remember that although these habitat suitability predictions are highly detailed, they are not absolute. There is still a large degree of variation in recruitment habitat that is not explained by the Hatten *et al.* (2018) model. Additional work would be required to improve and validate the applied habitat suitability model.

6.3. Risks

The primary risks from substrate enhancement activities at Keenleyside and Waneta is the potential to negatively impact existing habitat suitability for white sturgeon or power generation capacity. Additional environmental risks will be considered in more detail in further phases of this project. Placing material could also cause an increased risk of erosion of local channel banks; however, the amount of added material being considered for each of the restoration alternatives is not expected to affect bank erosion rates.

The greatest risk to existing habitat associated with placement at Keenleyside is that the material could become infilled over time if flows are insufficient to flush fines. The proposed treatment material at ALH is generally larger than the existing material, which means that it could be less mobile. If fines supply rate to the ALH tailrace is high enough to infill interstitial spaces in a short duration (as discussed in Section 5.4.3), then flushing the fines could be unachievable with the limited maximum flow capacity through ALH. Such a condition has happened to some of the rip-rap placed along the river left bank downstream of ALH (Figure 54). Although the Wilcock and Crowe (2003) model indicates that fines could be flushed without transport of coarse material, it could be that mobilizing coarse material is required for fines flushing. If infilling of an immobile bed were to occur, placement of additional material would likely be unfeasible due to the potential effect to power generation, and therefore cleaning would likely be required. This risk is lesser at Waneta given the large existing material and variable annual peak flows. The highest risk areas at Keenleyside are at the margins of the ALH jet, where fines deposits have been observed (e.g., in the seam of fines between the HLK and ALH jets).

The risk to power generation is assumed to be negligible at Waneta given the moderate gradient between the Waneta Dam and spawning area. At Keenleyside, preliminary modelling indicated that placement of material has the potential to backwater the ALH tailrace by approximately 10 cm, which could cause a loss of generation (Section 5.4.4). During design phase, the placement thickness and extent may need to be iteratively adjusted to ensure impacts to generation are minimal.

The proposed Waneta and Keenleyside treatment locations are listed as Critical Habitat under the Species at Risk Act. As such, the design will need to carefully consider potential impacts to existing habitat for each White Sturgeon life history stage. For example, treatment alternatives were considered during Workshop One that would involve installing a berm near the HLK eddy to focus flow energy in the rearing area. These alternatives were abandoned due to risk to adult sturgeon holding habitat. Aside from White Sturgeon, the proposed restoration areas include habitat for other species such as Sculpin and Rainbow Trout that would need to be considered during construction. Placement of material anywhere could also change the hydraulics of an area and affect local scour and deposition regime, which could potentially impact existing rearing habitat. The scour conditions before and after treatment could be compared during detailed design stage. For example, if augmentation consisted of depositing material at a fixed location, a build-up of material could occur if shear is not high enough to move the material.

A risk also exists that substrate condition is not actually the limiting factor for White Sturgeon recruitment, despite outcomes from the weight of evidence assessment by McAdam (2015). In this scenario, the treatment may meet its stability objectives, but fail to improve recruitment. In addition, documenting natural recruitment resulting from a substrate treatment may be challenging given the lag time between larval dispersal and juvenile recruitment to sampling gear (5-7 years). Further discussion of this risk is provided in Section 2.1.4.

The primary risk with cleaning alternatives was that loosening the bed surface layer could cause transport of the newly cleaned coarse material and reveal an underlying layer of fines. Evidence of an under-lying layer of fines was observed at Waneta during ground-based sampling (Figure 55), and an underlying fines layer could be expected as per the standard process of armouring during sediment supply disruption (Rowiński and Radecki-Pawlik 2015). The net result could be an initial increase in habitat quality followed by a decrease in quality if the cleaned material is transported and fines revealed. An additional complication at Waneta is of the possibility of slag deposits beneath the stream bed (Golder 2006b). Disturbing the stream bed at this location was assumed to entail too high of risk of mobilizing slag, and therefore the cleaning option was abandoned. Placement of material on the stream bed or stream bank was expected to entail low risk to slag mobilization; however, this risk should be re-examined during design phase.

For most of the Waneta spawning area, qualitative evidence of recent transport (Section 5.2.3), modelled coarse material transport predictions (Section 5.4.7 and Fissel *et al.* 2017), and observed long-term changes in bathymetry (Section 5.4.5) each indicate that if substrate becomes infilled with fines, the fines will likely be flushed by movement of the coarse substrate. Given that progressive downcutting has not occurred, supply of coarse material from upstream or the nearby eroding bank is likely adequate to replace material transported out of the EDZ. This conclusion suggests that placement of material anywhere within the EDZ could be expected to produce limited benefit. The current material has a size range suitable for rearing. In the Waneta restoration area, if coarser material were placed, it would likely become infilled with fines that could not be flushed. If a finer mixture was placed, it would likely provide benefits for a short duration until the next peak flow that mobilizes this material. Increased supply or placed material would also be subject to similar infilling risk during lower flow seasons, as is expected to occur with the existing material.

Finally, there is a low risk that the underlying substrate that will become buried by placement alternatives provides better rearing suitability than the proposed material.

Figure 54. Example of location where placed coarse material has infilled and is unlikely to flush with the maximum flow from ALH. Location is approximately 370 m downstream of the ALH powerhouse on river left bank.

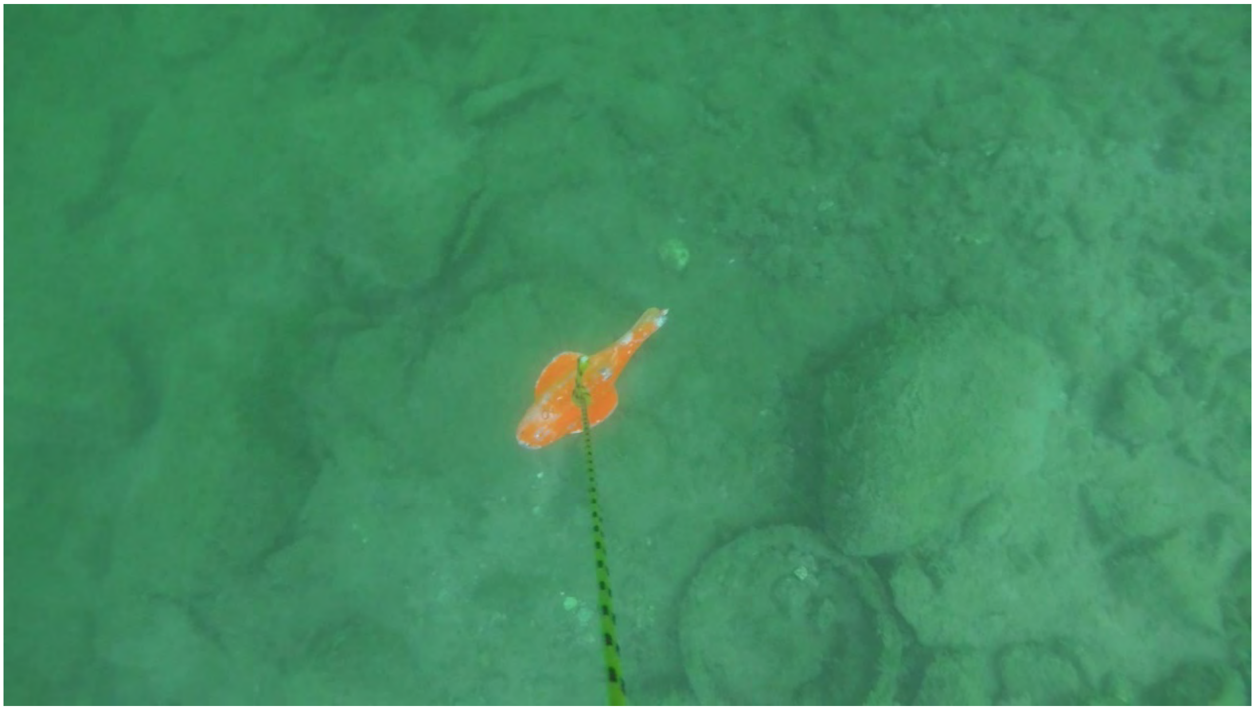
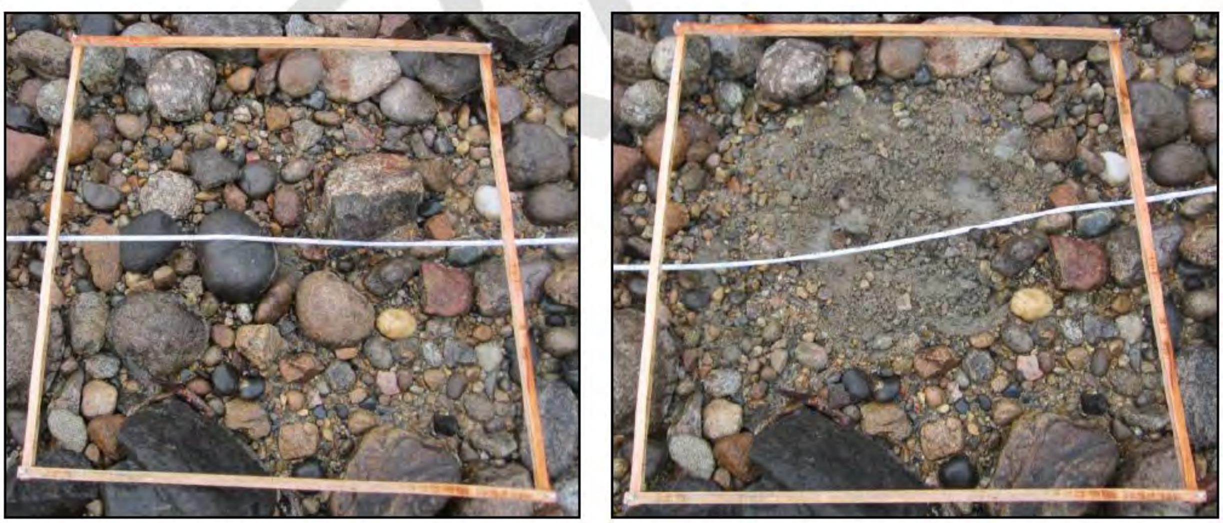


Figure 55. Evidence of fines layer beneath surface armour layer at Waneta.



6.4. Summary of Trade-offs Between Alternatives

The focus of this project has been the biological benefits associated with different restoration alternatives, but trade-offs with other objectives have also been noted to inform longer-term considerations. Trade-offs between each alternative were discussed during the two workshops, and highlighted during the prioritization process. Four alternatives emerged from Workshop Two as worthy of further consideration. Pros and cons for each of these four alternatives were summarized in Table 20.

Table 20. Summary of trade-offs between top alternatives identified during second engagement meeting.

Objective	Placement at ALH	Clean ALH	Augmentation at Waneta (placement from shore and dispersal during high flow)	Placement at Waneta Restoration Area
Substrate Stability				
Pros	- Existing substrate is smaller than proposed substrate - Fines supply is relatively low - Flows are relatively predictable - Mobile coarse fraction will be low but non-zero, which could be ideal condition for self-cleaning - Mobile fines fraction will be moderate	- Mimics natural flushing processes - Cleaning has been shown to be effective elsewhere	- Enhances natural bank supply process - Material will deposit in more natural locations - Transport similar to spring 2018 could be replicated	- Existing mobile fraction in greater spawning area is higher than ALH (more force) - mobile coarse fraction will be similar to ex.
Cons	- Overall area that will be stable is small - Coarse fraction will be less mobile, and could infill	- Risk of losing coarse material and exposing fines layer - Lack of coarse material supply from upstream - Cleaned material would be more mobile	- Difficult to predict transport conditions if material is not supplied to main current - material could disperse downstream and become ineffective - Substrate may be smaller than ideal	- Mobile coarse and fines fraction during 5-yr flow will be zero - Mobile fines fraction will be less than existing
Biological				
Pros	- Less risk to existing recruitment than Waneta - Potential to expand area suitable for rearing rather than simply improve conditions - Existing rearing suitability is moderate/high and could be improved - Recruitment suitability less limited by hydraulics - Current spawning is occurring but not fully functional	- Existing substrate size is maintained, which may be useful for other species	- Material could be supplied during peak flows when risk to fish will be similar to natural conditions	- Existing embeddedness was low in 2018, but could be due to preceding extreme flow - Recruitment suitability could be improved substantially
Cons	- Uncertainty of what locations spawners will use - Existing embeddedness is moderate in some areas, meaning more likely to recur following treatment	- Turbidity and fine sediment delivered to downstream	- Fishing are spawning in this area already, so higher risk	- Existing rearing suitability is already high and may not be improvable, but could be due to extreme flow during spring 2018 - Recruitment suitability is limited by hydraulics (50% of area) - Could adversely affect other species
Feasibility/Cost				
Pros	- Better construction access than Waneta - Easier hydraulic conditions for barging	- No requirement for imported material	- Cheap and easy to implement using a slide - Requires well timed supply events	- More certainty of where material ends up than augmentation
Cons	- Risk of backwatering ALH tailrace	- Low lifespan/high maintenance - Could be difficult to clean	- Likely requires annual replacement - Less certainty on permitting barriers - Dumping material along bank likely ineffective	- Difficult conditions for barging. - Less certainty on permitting barriers
Monitoring				
Pros	- Easier to complete pilot study/experiment	- Difficult to assess movement of material while cleaning	- Aggregated material could be assessed during low flows - Tracers could be added to mixture	- Easy to monitor infilling in an area not expected to have coarse transport
Cons	- An experiment would require a control that would limit the area improved	- Difficult to assess benefits (risk of substrate flushing before response is measured)	- Difficult to track material	

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Recommended Design

Participants of Workshop Two agreed that placement of material at Keenleyside within and downstream of the ALH EDZ was the highest priority restoration alternative and should be pursued with Phase 2 of the project. Based on the subsequent analysis in Section 5.4.7, the technical team recommends placement of stone mixtures with specific size classes within six prescribed zones to promote functionality and longevity across the entire EDZ. The number of zones could be adjusted depending on the limitations of the construction machinery and approach. Reduction of the prescribed placement material size classes by approximately 10% should be considered for an initial placement, because (1) the placed material will be less likely to infill, (2) it will be more mobile during higher flows, which will flush fines that may have aggraded, (3) periodic transport may be necessary to free up interstitial spaces, and (4) some of the material transported downstream will continue to provide high quality substrate. Nevertheless, fines loading to the uppermost portion of the EDZ is expected to be low, and larger material than prescribed could be placed here to ensure stability. It is expected that increases or decreases in the prescribed material size will be decided during detailed design phase with consideration of longevity vs. risk tradeoffs (e.g., Table 20). As described below, placement in approximately half of the prescribed areas during the initial placement should also be considered, along with robust monitoring of transport conditions in the treatment and control area. If material is transported too easily, then the transport models could be re-calibrated, and larger material placed in the entire prescribed area. This approach relies on the assumption that ALH flows reach maximum capacity each year.

Participants of Workshop Two agreed that placement of material in the previously defined Waneta restoration area would likely infill too quickly. Based on recommendations from the workshop and subsequent analysis (Section 5.4.7), shore-based augmentation near the river left bend apex was found to be worthy of further consideration but not recommended for Phase 2 of the project. Workshop participants agreed that this alternative should only be pursued if treatment at Keenleyside is shown to provide a measurable biological benefit. The following sections pertain to the recommended Keenleyside alternative.

7.2. Design Considerations

It is expected that the key steps in progressing this project to construction and beyond would involve detailed design (including drawings and specifications), permitting, tendering, construction (including environmental monitoring and quality control/assurance), effectiveness monitoring and adaptive management. Specific design and construction considerations are detailed below:

Design. It is recommended that detailed design undertake finalized modelling of the hydraulic conditions when bathymetry has been updated to reflect final placement area and thickness. The modelling and recommended treatment at ALH described above includes prescribed substrate size, position, and thickness of placement material. Although the change in hydraulics is expected to be minimal with 600 mm thick stone placement, if the area is large enough the placement could affect backwatering of the ALH tailrace and potentially the transport threshold of the placed material. Design drawings should be prepared to define the area and thickness of works and specifications for the materials to be placed.

Mobilization to the site. This task includes mobilization of all necessary construction equipment and setup of any temporary facilities at the work site. It is expected that material could be stockpiled in the clearing downstream of ALH on the left bank. Boat launches are available between Keenleyside and Castlegar that could be used to deploy a barge (e.g., Lion's Head boat launch or Interfor ramps). Ideally, a barge already deployed in this reach could be utilized.

Sediment Management. Sources of possible sedimentation include fines within the placement material and machine movement on shore. Placement material will need to be cleaned prior to loading onto a barge to ensure it is free of fines, and an environmental management plan will need to be prepared to limit shore-based sediment input to LCR for permitting approval requirements.

Material size. The final material size classes for placement should be considered in terms of risk to existing habitat. Material slightly smaller than prescribed should be considered to limit the risk of permanent infilling, as discussed in Section 5.8.3.

Material sourcing. The recommended placement material includes several grain size distributions that will need to be prepared. Ideally, the material could be sourced from a nearby alluvial pit, where stone angularity could be expected to roughly match existing bed material (i.e., sub-rounded). Shot rock (angular stone) could be considered for placement if more feasible; however, the transport conditions of this material would be different than modelled, and there is uncertainty regarding the habitat value. Hauling material to site may be a large component of cost if nothing is available nearby. Assuming that a truckload is approximately 16 m^2 x 0.6 m, then 400 loads would be required to place material in the recommended 6,500 m^2 treatment area. Once identified, the material will need to be carefully screened into the recommended size ranges and mixed appropriately. Specifications for the material will also need to be developed including angularity and chemical composition (e.g., non-potentially acid generating).

Accurate Placement. Placement of material with the prescribed depth will be challenging without some form of real-time elevation confirmation. Given the proximity to the ALH tailrace, appropriate vertical tolerance (to be determined during detailed design) will be required to avoid impacts to tailwater levels. High accuracy horizontal placement will also be important if a control site is located adjacent to the placement. Realtime confirmation of both elevation and horizontal position could be achieved by loading the high resolution existing bathymetric contours prepared for this study onto a high resolution GPS/depth finder that can be used to compare real-time depth soundings to the existing bathymetry.

Demobilization from the site. This task includes demobilization of all construction equipment and temporary facilities from the work site.

7.2.1. Operational considerations

Analysis did not focus on assessing flow regime improvements; however, a few operational adjustments were identified during the sediment transport and hydraulics analysis that could improve the functionality of restoration alternatives. These are described below.

A common finding at each spawning area was relatively high level of compaction compared to natural conditions and less-than-ideal embeddedness conditions. These conditions are expected to result from reduced transport rates and lower supply of coarse material. NHC (2007) suggested that coarse material supply rate from eroding channel banks has likely been reduced since pre-regulation due to lower water levels during peak flow. The flow competency (maximum grain size the flow is capable of transporting) has also been reduced resulting in less mobility of existing streambed substrate. The reduction in mobility has likely also led to compaction and armouring in some areas, where cobbles or boulders become tightly packed together with limited interstitial space. Compaction is expected to reduce rearing quality for early life stages of sturgeon, and further reduce transport of the bed material by increasing transport threshold. Increases in annual peak flows would be expected to limit the degree of compaction and embeddedness on rearing suitability by loosening coarse material and flushing fines.

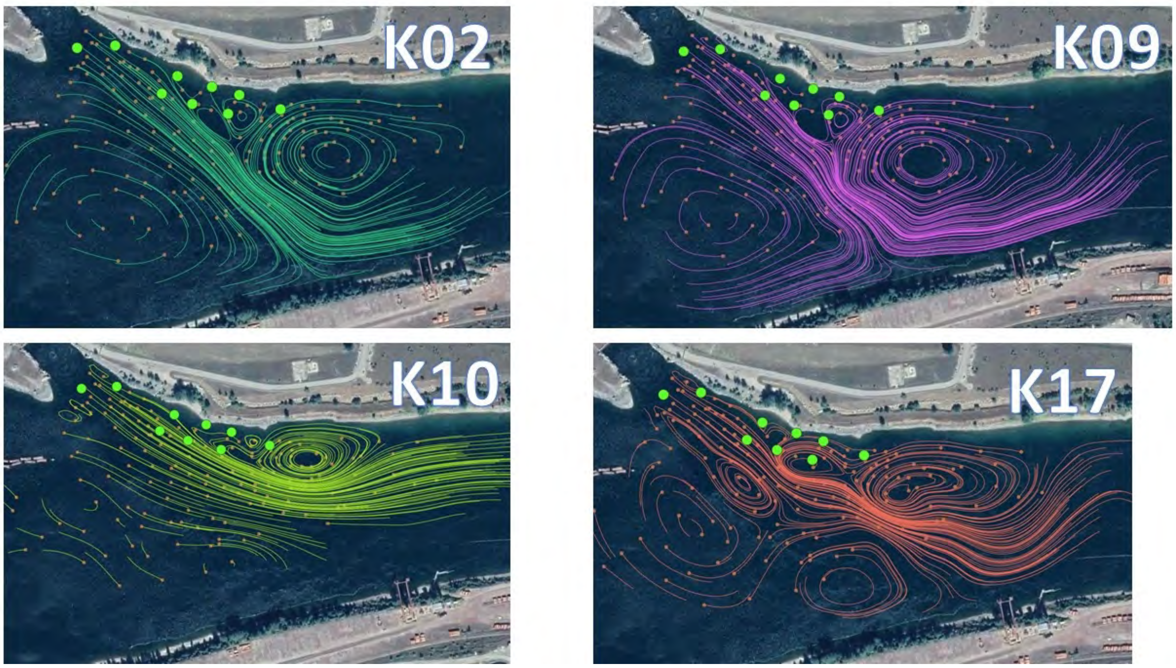
Specific flow regime adjustments that could provide benefit to restoration options at Waneta and Keenleyside are described below.

7.2.1.1. Keenleyside

During previous monitoring (Terraquatic Resource Management 2011; BC Hydro 2016), eggs were captured along the downstream left bank where the streamline trajectory would likely send them into the river left eddy; the eddy occurs because of the unnatural position and angle of inflows. Without the dams, the flow energy would be more uniform across the channel and the eddy would be less prominent. If flow regime adjustments are possible, it could be beneficial to increase the flow rate through HLK during the post-spawn period to break up both river left and river right eddies. A higher flow from HLK results in a wider combined jet and smaller eddies (K10 in Figure 56), while lower HLK flows result in stronger eddies and a narrower combined jet (K02,09,17 in Figure 56).

Maintaining maximum flow from ALH during freshet and the spawning period, as has typically been the historical case during most years, was assessed to be beneficial. The ALH jet likely prevents fines from migrating over from the HLK eddy (Section 5.4.3). It was also noted that when there is a planned shift from ALH to HLK, HLK would ideally be ramped up while ALH is at least at half capacity. It is expected that fines may deposit in the HLK tailrace during periods when ALH is at capacity and HLK is low. If HLK is ramped up quickly and ALH is ramped down quickly, then fines from the HLK tailrace could be pushed into the ALH tailrace, which is predicted to have a back eddy and depositional conditions when ALH approaches zero and HLK is moderate (e.g., 500 m^3/s).

Figure 56. Egg path trajectories from random locations within the Keenleyside spawning areas. Higher flows from HLK diminish the size of eddies that likely entrain drifting eggs and juveniles. Green dots indicate locations where eggs have been historically captured. Flow simulations are described in Table 6.



7.2.1.2. Waneta

This study provided further evidence to support the findings of Fissel *et al.* (2017), in that sediment deposition risk in the Waneta EDZ is increased substantially when LCR flow is high and PDO flow is low. The 1997 and 2012 peak flows were also found to be insufficient to move material from a large portion of the analyzed restoration area at the upper extent of the EDZ. It appears that transport conditions required to clean EDZ bed material are best when LCR and PDO peak flows match; however, additional analysis would be required to confirm. At a high level, further analysis of optimized flow combinations and timing from LCR and PDO appears worthy of consideration. Although it is recognized that the ability to control peak flows from PDO is limited, it was generally determined that peak flows of greater than approximately 3000 m^3/s would promote flushing conditions in the restoration area (i.e. Figure 37). The duration of flows would ideally be multiple days based on previous flushing flow studies summarized in Reiser *et al.* (1985).

7.3. Cost Estimate

A preliminary cost estimate for the preferred alternative (placement at ALH) with approximately -50% to +100% accuracy is provided below. Detailed estimates will be produced during the design phase of this project. Unit rates for major cost components were prepared by estimating the size of required equipment fleets and their production rates, and review of rates on other projects undertaken by the study team. The cost estimate does not explicitly consider construction sequencing and site logistics. A preliminary cost estimate for placement at ALH is presented in Table 21. The total estimated cost of $1,040,000 assumes placement of material in half of the 6,500 m^2 recommended treatment area and would be $448,500 higher if the entire area was treated. The cost estimate includes only one year of monitoring, and would need to be scaled up by approximately $60,000 for each additional year.

Key assumptions in the cost estimate include:

- The estimate is calculated in Canadian dollars with no allowance for inflation. Costs do not include applicable taxes (e.g., GST, PST).
- The estimate includes the following major provisional sums:
  - Indirect costs (12.5%) – Mobilization and demobilization, bonding, insurance, permits, accommodation, transportation, survey etc.;
  - Engineering (10%) - Detailed design, site inspection for quality assurance, technical documentation etc., full-time construction monitoring; and
  - Owner's costs (15%) - Contract administration, procurement, schedule, project management, land owner negotiations etc.
- Contingency (20%) - To address unidentified tasks and uncertainties related to definition of project scope, conceptual level design, barge size, etc.

Table 21. Approximate cost estimate for optimized ALH placement alternative (- 50 to +100%). Assumes treatment of 50% of optimized area and one year of physical monitoring. Does not include biological monitoring.

Item	Description	Quantity	Unit	Rate	Cost
1.0	**Pre-construction planning**				
1.2	Environmental management plan and permitting	1	Provisional Sum	$ 25,000	$ 25,000
2.0	**Design**				
2.1	Supplemental modelling and reporting	1	Each	$ 7,500	$ 7,500
2.2	Adaptive Management after Year 1	1	Each	$ 10,000	$ 10,000
3.0	**Construction**				
3.1	Supply and install restoration material	1,950	m^3	$ 230	$ 448,500
3.2	Bardge	10	days	$ 10,000	$ 100,000
3.5	GPS and sonar equipment	1	Each	$ 10,000	$ 10,000
4.0	**Monitoring (first year)**				
4.1	Record Survey	1	Each	$ 20,000	$ 20,000
4.2	traps, benchmark stones, sediment traps, and camera install	2	Each	$ 5,000	$ 10,000
4.3	Monitoring analysis and reporting	1	Each	$ 30,000	$ 30,000
5.0	**Subtotal**				$ 661,000
	Indirects[1]	12.5%			$83,000
	Engineering	10.0%			$66,000
	Owner's Costs	15.0%			$99,000
	Contingency	20.0%			$132,000
6.0	**Total**				$1,040,000

[1] Including mobilization and demobilization, bonding, insurance, accomodation, etc.

7.4. Monitoring Recommendations

7.4.1. Physical Response

For placement alternatives, a placement experiment could be setup as a before-after control-impact (BACI) design. Since the hydraulics are somewhat variable throughout the study area, the location of control and impact zones would need to be carefully selected to ensure similar hydraulic and sediment supply conditions. For example, the area of the ALH jet where the streamlines are parallel in the longitudinal direction and uniform in the transverse direction could be partitioned to have control and impact longitudinal strips. The longitudinal strips would prevent complications from sediment transport in the downstream direction either from the placed material or other mobile material. The limitation of this experiment method is that it will delay placement of material in the control areas. Therefore, it may be advantageous to apply a short (e.g., 1-year) experiment at ALH that can be used to inform wide-scale placement during subsequent years. This adaptive management approach would allow for learning about logistics and other factors, and allow for re-calibration of the transport models and revised substrate size and placement location recommendations.

The questions of interest for physical response monitoring include (1) How quickly does material infill? (2) Where does infilling occur? (3) Does coarse material move? And if so, how far, at what frequency, to where, and what are the conditions like where the coarse material is eventually deposited? and (4) How does rearing suitability evolve in placement areas and downstream? An additional objective could be to develop a better understanding of sediment supply rate and the inter-annual variability in infilling/scour that could be applicable to other sturgeon spawning locations on Columbia River or elsewhere.

The primary variables recommended for monitoring in the control and impact locations include:

- Inclusion of coloured tracer stones of various sizes on the surface of the placed material and controls that can be tracked with repeated photographs. The sizes should span the range of placed material. These stones could be dropped into place from a boat during low flows.
- Inclusion of coloured, fixed benchmark stones on the surface of placed material to act as reference points for repeated photographs. The benchmark stones could be dropped into place from a boat. Repeated photographs will provide an indication of coarse material mobilization, and fines aggradation on the bed surface.
- Installation of sediment traps within the control and impact sites that can be used to detect fine sediment deposition and coarse material movement. The traps could consist of closed bottom cylinders that are placed in holes excavated in the bed and either filled with local coarse material to detect fines, or left empty to detect coarse material transport. Some of the traps could be excavated following freshet, and others excavated following the end of the autumn low flow period. For fines detection, the cylinders could be capped underwater and brought to the surface to analyze with a sieving technique. If the fines deposition rate was

found to be high, this would indicate that the size of coarse material should be reduced in subsequent placements to promote occasional transport that could liberate the fines.

- Real-time video camera installation within the control and impact locations is recommended to detect transport conditions throughout the flow range. Small video cameras could be mounted to large pieces of rebar that are anchored into the bed and surrounded with larger material that is expected to remain stable. The cameras would need to be installed by a dive team.

Since treatments are expected to last a few years, monitoring for at least 5 years after placement is recommended to detect annual and inter-annual changes. Repeated photographs are recommended twice per year, once during the late winter low flow period to evaluate transport that has occurred over the winter, and once following freshet during early fall to evaluate transport. Evaluating sediment trapping is recommended once per year during late winter so that divers have minimal impact on spawning or rearing sturgeon. Videos are expected to be active throughout the 5-year period.

7.4.2. Biological Response

Biological monitoring should demonstrate that habitat remediation is supporting all targeted life stages of White Sturgeon (McAdam *et al.* 2018). BC Hydro's ongoing monitoring programs such as White Sturgeon adult (CLBMON-28) and juvenile (CLBMON-29) studies are recommended to assess use of the remediation area by spawning adults and recruitment success. These ongoing studies will help address the following key questions: (1) Is spawning occurring in the restored habitat? and (2) Is there evidence that remediation influences juvenile recruitment? Additional monitoring may include acoustic telemetry (e.g. positional array) to determine use of the remediation area by spawning adult sturgeon (e.g., presence, activity, density) and/or using genetic techniques on collected larvae to determine the number of adults contributing to offspring (e.g., Jay *et al.* 2014).

Monitoring of early life stage survival and production of feeding larvae directly within treatment and control areas is recommended to answer the following key questions: (1) Are eggs and larvae retained in the restored habitat?, (2) Does egg and larval development (e.g. Jay *et al.* 2020) or physiology differ in the restored habitat?, and (3) What is the timing of larval dispersal in the restored habitat? Other questions relating to drift patterns may also be of interest. An experimental design similar to that outlined in Crossman and Hildebrand (2012) using hatchery-reared larvae released simultaneously over treatment and control areas may be necessary to determine more immediate remediation effectiveness and timing of larval dispersal.

Use of the remediation site by non-target species (positive or negative) may also warrant consideration, especially if there is a potential for responses by non-target species to interact with or overwhelm responses of White Sturgeon (McAdam *et al.* 2018). BC Hydro's ongoing LCR fish population indexing surveys (CLBMON-45) as well as the use of acoustic cameras are examples that may determine non-target species responses.

Duration of monitoring should reflect the time scale of expected biological responses (e.g., juvenile production, adult returns) (McAdam *et al.* 2018). At minimum, baseline spawn and juvenile monitoring should be conducted for 5 years post-treatment since there is a delayed vulnerability to capture methods (e.g., gill net, set line). Identifying successful recruitment to older juvenile stages as a result of treatment will be a long-term management question (8+ years).

7.4.3. Construction Monitoring

An environmental monitoring and mitigation plan will need to be developed for each alternative to be implemented. The scope of the environmental monitoring plan will depend upon the construction method chosen and specific permitting requirements, but is expected to at minimum include a description of water quality monitoring, reporting and incident response, roles and responsibilities, and when the environmental monitor must be on site (i.e., during all instream works).

7.5. Permitting and Implementation Timeline

Implementation of placement alternatives is recommended during either the spring low flow season prior to freshet or late autumn. Previous studies have been approved during autumn (Crossman and Hildebrand 2012). Placement during spring would limit the risk of fines infilling or scour prior to the first spawning cycle; however, there is uncertainty regarding regulatory approval. Potential effects of implementation to other local species (e.g., Rainbow Trout) and especially SARA-listed species will also need to be considered during Phase 2. If augmentation or cleaning alternatives are pursued, they should be implemented during the peak flow conditions to facilitate dispersal of the augmentation material and flushing of fines during cleaning.

The proposed Project will involve instream works in designated White Sturgeon critical habitat, so the required permits and associated review times will likely include:

- Notification as per Part 3 of the provincial Water Sustainability Regulation (45 days);
- Request for Review to Fisheries and Oceans Canada (DFO) as per the *Fisheries Act* (120 days);
- *Species at Risk Act* (SARA) permit (90 days); and
- Review of the *Canadian Navigable Waters Act Minor Works Order* to ensure compliance (if cannot comply then application to Transport Canada, Navigation Protection Program is required).

All of the above-noted permitting applications will require a discussion of environmental mitigation and monitoring. It was noted by DFO to be mindful of rationalizing expected benefits of experiments when applying for permits. Including all alternatives and mitigation options considered will be important to include in the rationale.

Consultation with local First Nations and an archaeological assessment are also anticipated requirements that could take months or years to complete. It is possible that further permitting may be required depending upon the construction method chosen and the possibility of international concerns if a Waneta alternative is pursued.

Detailed design is expected to take approximately three months from the award of contract, assuming that additional field data collection and analysis are not required. Preparation and submission of permit applications prior to completion of the detailed design is assumed to be feasible and could likely be completed within two weeks of contract award. Cleaning, placement, and augmentation options are each expected to require less than two weeks to implement. Based on each of these elements, the total time required from contract award to project completion is approximately four months, assuming an aggressive schedule and early approval by First Nations. The work would then need to be carried out during an approved window.

7.6. Future Research

Future research ideas that could benefit development or maintenance of substrate restoration activities for White Sturgeon are provided in the following bullets:

- The primary habitat limitation downstream of the bend apex at Waneta is that much of the reach is boulder dominated. Preliminary modelling indicated that augmentation could help fill the boulder interstices with rearing-suitable material. An experimental trial could be conducted of dumping the material mix described in Section 5.4.7 into the augmentation location at the river left bend apex during freshet conditions, starting with the finest material range and moving up to the largest to ensure the material disperses. Material could be stockpiled nearby on land and annual augmentation could be performed using a structurally supported slide that descends the channel bank. If this experiment was shown to improve substrate conditions following the spawning period, then annual augmentation may be a means of improving recruitment at Waneta.

- Side-scan and acoustic camera sonar technology has been improving, and collection of new data with a higher resolution multi-beam system could allow detection of stronger correlations between acoustic class and habitat quality. Adult and moderate sized juvenile White Sturgeon can also be detected with modern side-scan and acoustic camera sonars, which could aid with identifying locations where spawning is occurring.

- High resolution bathymetry data collected by MOTI in 2013 were available near the Hwy 3 bridge that crosses the Kinnaird reach. The MOTI data could be compared to the GLS (2018) bathymetry data collected for this study to assess inter-annual erosion/deposition patterns or long-term trends at Kinnaird. Similarly, bathymetry data collected by Golder (2014b) could be converted to a georeferenced grid and compared to data collected for this study.

- Studies would need to be done to understand egg deposition including spatial dispersal, settling location within substrates, and benefits of each to hatch success. The cursory egg and larval drift trajectory modelling described in Section 5.5 could be expanded to help establish a probability of where eggs and larvae are expected to deposit. The hydrodynamic model applied in this study could be coupled with an egg or larvae transport model that incorporates density and swimming ability. The frequency and duration of flows that are expected to cause transport could be considered to help predict egg transport distance. Alternatively, a robust statistical approach that considers environmental covariates such as water depth, water velocity, and substrate size could be applied similar to Finley *et al.* (2018). Such studies would be large undertakings and may be too challenging to achieve useful results.
- Better estimates of sediment supply rate through long-term monitoring of bedload and suspended load could allow for the calibration of a morphodynamic model. Modelling sediment aggradation and degradation dynamics as a function of time using a morphodynamic model was considered for this project and ultimately not pursued because uncertainties associated with sediment supply rate and the underlying sediment transport equations of the model were expected to result in low accuracy results. Such a model may provide insights into the timing, magnitude, and frequency of transport patterns, despite the associated uncertainty.
- The recommended monitoring methods in Section 7.4.1 would also provide insights into the sediment transport regime of the system. The associated observations of fines aggradation and coarse mobility regime could be informative for White Sturgeon habitat assessment or restoration in other regulated reaches or systems.

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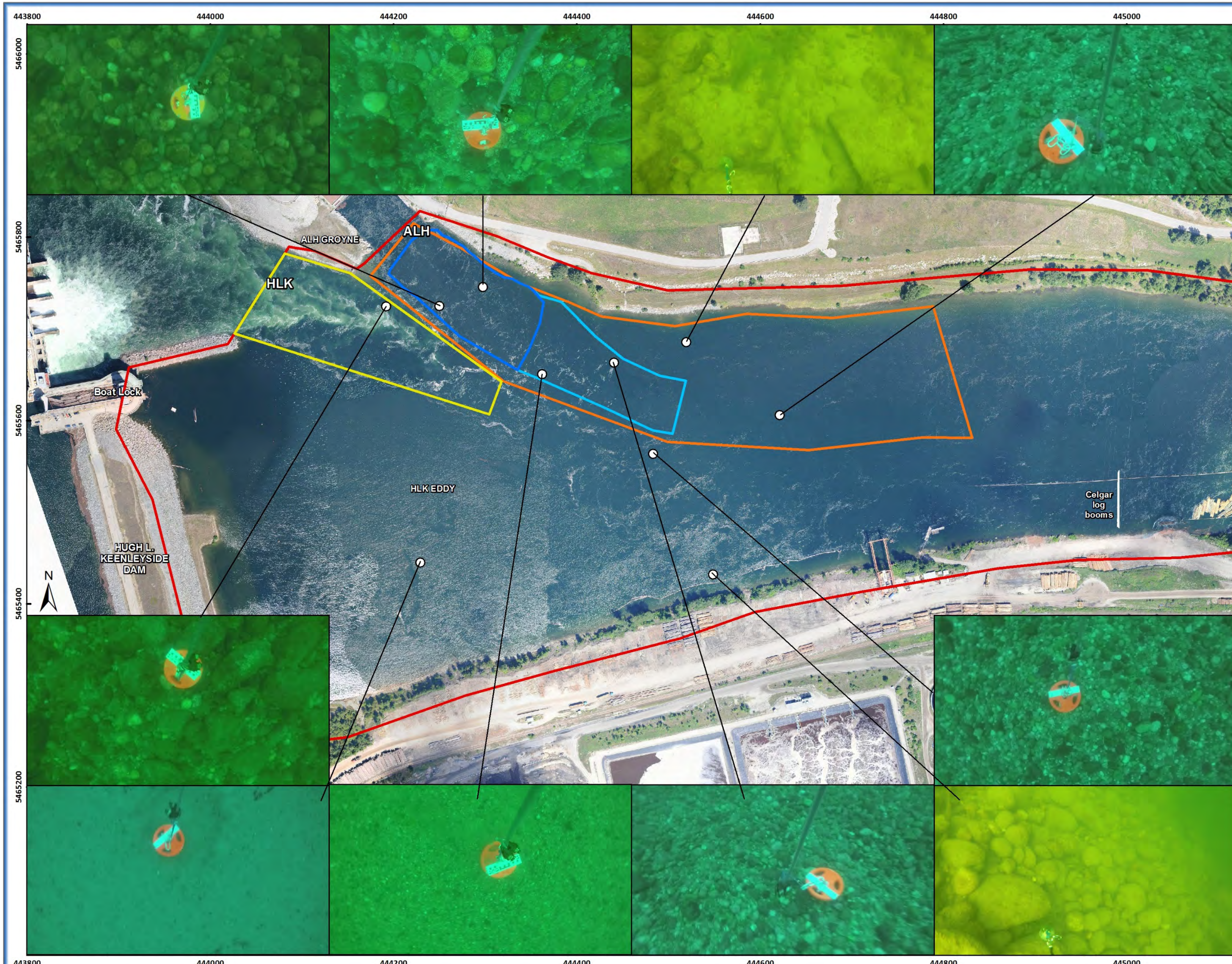
PROJECT MAPS

CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Columbia River Substrate Overview - Keenleyside



Legend

- Photo Location
- EDZ
- EDZ DS
- HLK
- Spawning Area
- Study Area

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

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2			
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Date Saved: 09/12/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map 2

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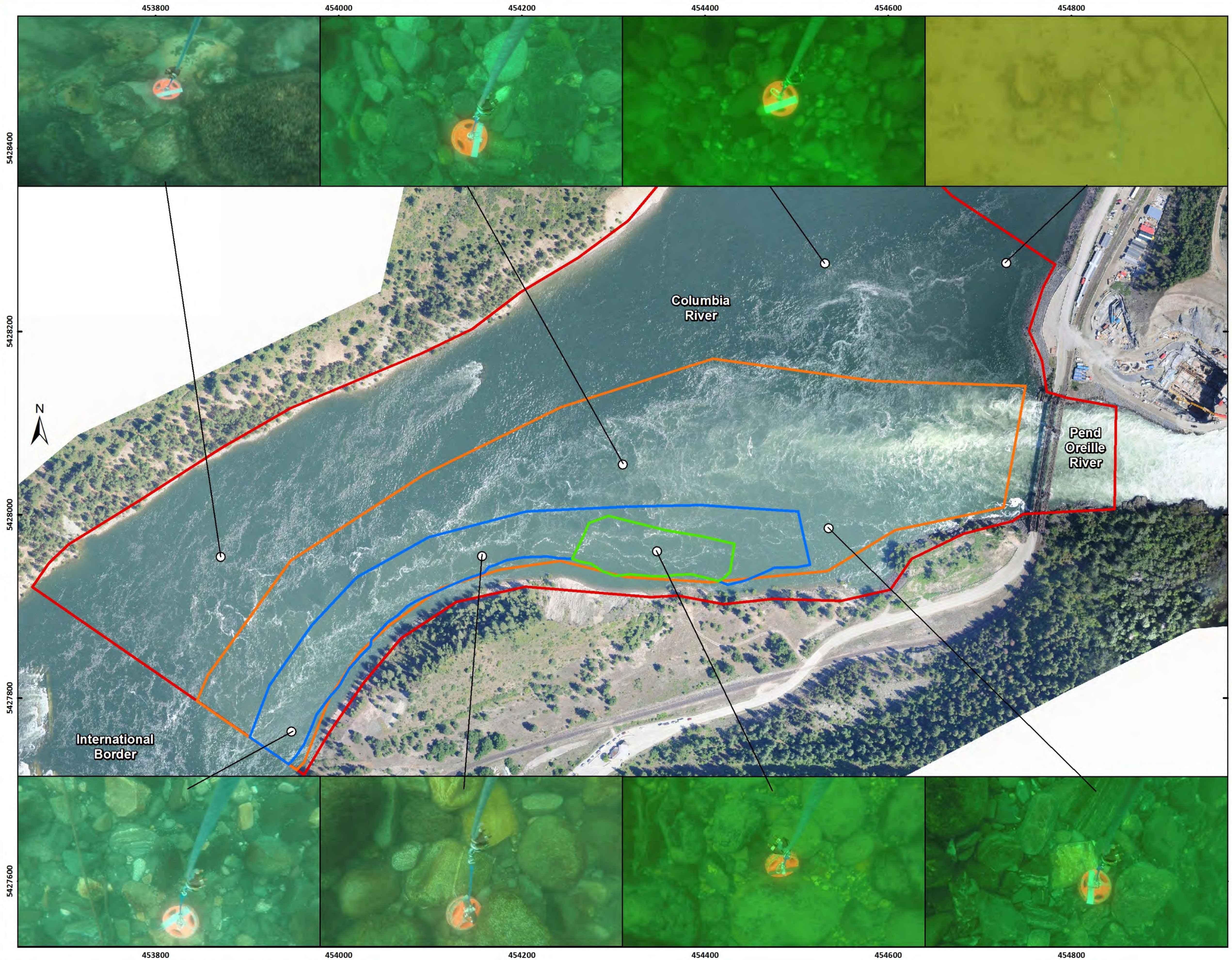
CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Columbia River Substrate Overview - Waneta



Legend

- Photo Location
- EDZ
- Restoration Area
- Spawning Area
- Study Area

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

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Date Saved: 09/12/2019
Coordinate System: NAD 1983 UTM Zone 11N

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Map 3

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APPENDICES

Appendix A. Site Visit #3, bed material sampling and ADCP data summary

April 15, 2020

Mr. Todd Hatfield
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Dear Todd,

Re: CLBWORKS-27 – Site Visit #3, Bed Material Sampling and ADCP Data Summary

1.0 INTRODUCTION

Knight Piésold Ltd. (KP) is a sub-consultant to Ecofish Research Ltd. (Ecofish) on the Columbia River Sturgeon Habitat Restoration (CLBWORKS-27) project for BC Hydro. Between October 31 and November 3, 2018, KP and Ecofish conducted a site visit to the project area to conduct bed material sampling, under water bed material videography, and bathymetric and hydraulic data collection. The site visit was attended by Toby Perkins and Alyson Fretz from KP and Mark Latham of Ecofish. Marco Marrello of Terraquatic Resource Management was the boat operator.

This letter presents bed material, bathymetry and river hydraulics data collected during the trip. Ecofish will review and process the underwater videography. The objective of the bed material sampling is to provide observations of bed material characteristics at sites proximal to Sturgeon spawning areas, to add to and validate bed material observations collected by under water videography. Bathymetry and river hydraulics data will support hydraulic model development and calibration.

2.0 SITE VISIT OVERVIEW

2.1 FLOW CONDITIONS

The trip was scheduled to coincide with low flow conditions so that bed material data collection would be as close as possible to spawning areas and locations previously covered by under water video. Provisional streamflow reported by Water Survey of Canada (WSC) at the Columbia River at Birchbank station (08NE049) are presented on Figure 1. The Birchbank station is located downstream of the Kinnaird study site. The Kootenay River enters between the Keenlyside and Kinnaird study sites, and Pend Oreille River enters at the Waneta Study site. The Columbia River, Kootenay River and Pend Oreille River are all regulated by hydropower facilities. It is noted that flows were changing rapidly during the work day on November 2, 2018.

Figure 1 **Provisional WSC streamflow at the Columbia River at Birchbank station (08NE049)**

2.2 STUDY SITES

2.2.1 BED MATERIAL

The project area is split into three study areas, referred to as Keenleyside, Kinnaird and Waneta. Within each study area, at one least bed material sampling site was selected in a location proximal to the identified spawning areas. At Keenleyside and Kinnaird, two and three sampling sites were selected, respectively. Although the sampling sites are relatively close to each other, they have quite different bed material characteristics and represent different geomorphic settings.

At each site, Wolman counts, photographic sampling, subsurface grab samples and/or tracer placement was conducted. Sampling sites and data collection are summarized in Table 1.

2.2.2 BATHYMETRY AND RIVER HYDRAULICS

Bathymetry data were collected over approximately 300 m of river at the upstream end of the Kinnaird study site to supplement data collected on previous site visits. Depth and velocity data were collected at transects within each study site. Three transects were measured at Keenlyside and Waneta, and four at Kinnaird.

Table 1 Bed Material Sampling Sites

Bed Material Sampling Site	Location		Sampling completed			
	Easting (m)	Northing (m)	Wolman Count	Bed Material Photos	Subsurface Grab Samples	Tracer Placement
Keenleyside 1	0444578	5465718	Yes	Yes	Yes	Yes
Keenleyside 2	0444842	5465729	Yes	Yes	No	No
Kinnaird 1	0453358	5457042	Yes	Yes	Yes	Yes
Kinnaird 2	0453266	5456949	No	Yes	No	No
Kinnaird 3	0453088	5459427	Yes	Yes	Yes	No
Waneta 1	0454487	5427940	Yes	No	No	No
Waneta 2	0454230	5427950	Yes	Yes	Yes	Yes

NOTES:
1. ALL COORDINATES ARE IN UTM ZONE 11U.

3.0 BED MATERIAL SAMPLE SITES

3.1 KEENLEYSIDE

Two bed material sample locations were selected at the Keenleyside site, downstream of the BC Hydro Keenleyside Dam, as can be seen on Figure 2. Bed material photos and Wolman counts were collected at both sample locations, and subsurface grab samples were completed at the Keenleyside 1 site, closer to the dam. Tracers were placed at the downstream end of Keenleyside 1.

Figure 2 Keenleyside Site Locations

3.2 KINNAIRD

There are three sample locations at the Kinnaird site. Kinnaird 1 and Kinnaird 2 are just upstream of the Waterloo Eddy on the Columbia River main channel, as can be seen on Figure 3. Kinnaird 3 is located further upstream, approximately 975 m downstream of the Columbia Bridge on Highway 3A, as shown on Figure 4. Bed material photos were taken at all three sample locations, and Wolman counts, and subsurface grab samples were taken at Kinnaird 1 and 3. Stone tracers were placed at the Kinnaird 1 site.

Figure 3 Kinnaird Site 1 and 2 Locations

Figure 4 Kinnaird Site 3 Location

3.3 WANETA

Two sample locations were selected for the Waneta site, as shown on Figure 5. Three Wolman counts were completed in total, one at Waneta 1 and two at Waneta 2, and bed material photos were taken along each transect at Waneta 2. Subsurface samples were taken, and tracers were placed at Waneta 2.

Figure 5 Waneta Site Locations

4.0 BED MATERIAL GRAIN SIZE ANALYSIS

Grain size distribution at each of the study sites was determined using one or more of the following methods; Wolman counts, photographic sampling, subsurface grab samples. Details are provided in the following sections.

4.1 WOLMAN COUNTS

Wolman counts were used to characterize surficial grain size distribution. Each sample was conducted by laying a 30 m tape measure along the shoreline, parallel to the waters edge. Stones were sampled at either 0.5 m or 1 m intervals along the tape, then the tape was moved 1 m up the shore and sampling repeated until over 100 stones were measured. The 1 m intervals were selected at sites with large boulders to avoid double counting the same clast.

Stones were selected directly below the tape measure mark and measured with a gravelometer. If the stones were too large or too embedded to be lifted, the b-axis length was estimated with a tape measure. Stones were counted by ½ Phi class sizes, as shown in Table 2.

Table 2 Grain Size Classification

Size less than	Phi Class	Classification
>512	>9	Boulders
512	9	
360	8.5	
256	8	Cobbles
180	7.5	
128	7	
90	6.5	
64	6	Gravels
45	5.5	
32	5	
23	4.5	
16	4	
11	3.5	
8	3	
5.6	2.5	
4	2	

The resulting grain size distributions are shown on Figure 6 and tabulated in Appendix A. Photos collected during bed material sampling are presented in Appendix B.

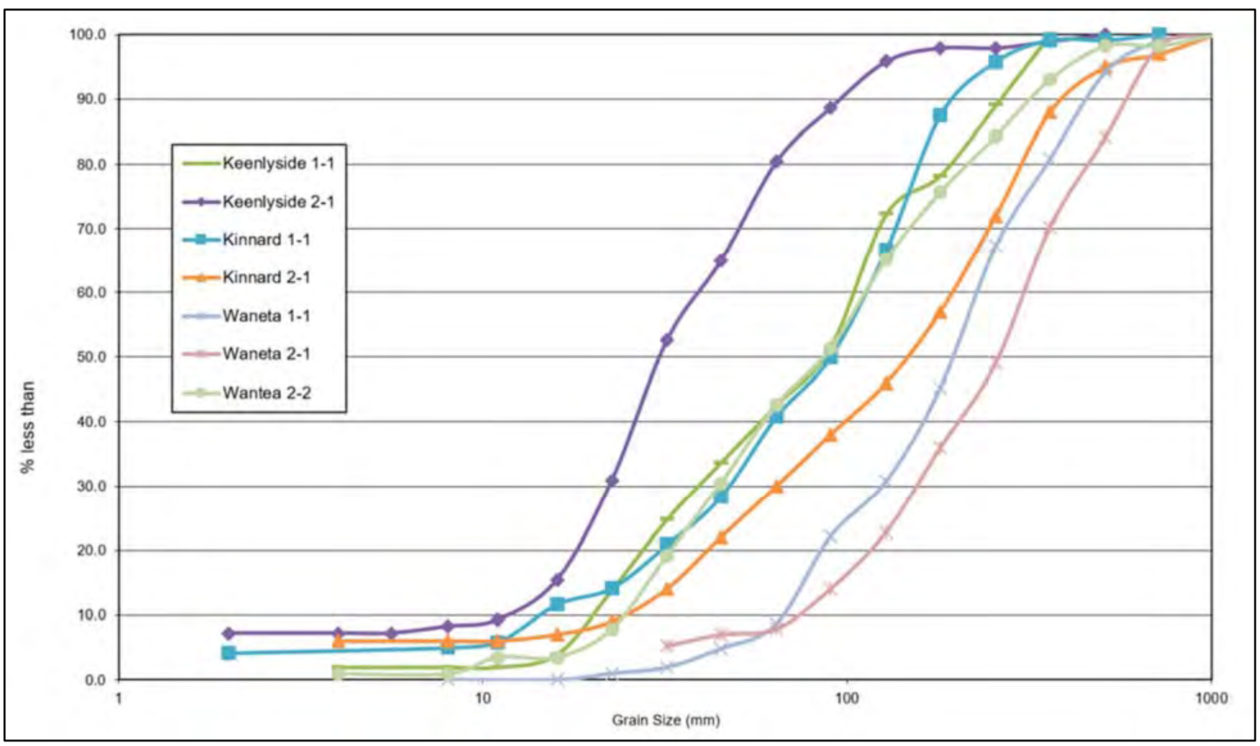

Figure 6 Grain Size Distributions

4.2 PHOTO SAMPLING

Bed material photos were collected at the same sample locations as the Wolman counts. These photos can be processed with digital fragmentation software to determine grain size, but this has not been completed at this time. All photos were taken by hand from a constant height of 1.6 m above the streambed (operator eye height), so have an approximately constant scale, however, are not perfectly vertical. Each photo includes a 1 m x 1 m (inside dimension) frame to provide scale and allow for obliqueness correction.

At each site, at least 10 photos were taken. They were collected along the tape measure used for the Wolman counts at approximately 2.5 – 3 m intervals. The fixed spacing per transect was set to help avoid operator bias.

4.3 SUBSURFACE GRAB SAMPLES

During vertical photo sampling, subsurface samples were collected at three of the ten photo points. Once the vertical photo was taken, the coarse surface materials were removed, and a grab sample of the finer underlying materials was collected. Approximately 1 kg samples were collected at each sampling site. These samples do not represent the bulk parameters of the subsurface material, but are simply an indication of the sand, silt and clay content within the subsurface matrix. The samples are currently in storage; lab analysis is pending.

Following sample collection, a vertical photo of the exposed material was collected for reference. Example photos are shown in Appendix B.

5.0 BED MATERIAL TRACERS

Stone tracers were collected and placed in the Columbia River at the Keenleyside-1, Kinnaird-1, and Waneta-2 sample locations. A Wolman count was conducted at each location to determine the D_{50} (median) grain size. At the Keenleyside and Kinnaird sites, ten stones from the D_{50} Phi class, as well as 10 stones from one Phi class above and below the D_{50} were collected. Due to the large D_{50} (260 mm) at Waneta-2, only five stones from the D_{50} Phi class were collected. Stones were then randomly selected from the sampling area within those classes for use as tracers. The Phi class size and number of tracer stones that were placed is summarized in Table 3.

Following selection, the stones were taken to BC Hydro's workshop, where they were dried and painted white. On November 2, 2018 the tracers were returned to the site they were collected from. Details of tracer placement at each location is described in the sections below to aid recovery and assessment of movement.

Table 3 Stone Tracer Site Locations and Sizes

Stone Tracer Site	Location		Tracer Data			
	Easting (m)	Northing (m)	D_{50} (mm)	Phi Class (number of stones)		
Keenleyside	0444578	5465718	85	7.5 (5)	6.5 (10)	5.5(10)
Kinnaird	0453358	5457042	90	7.5 (5)	6.5 (10)	5.5 (10)
Waneta	0454230	5427950	260	8 (5)	-	-

NOTES:
1. ALL COORDINATES ARE IN UTM ZONE 11U.

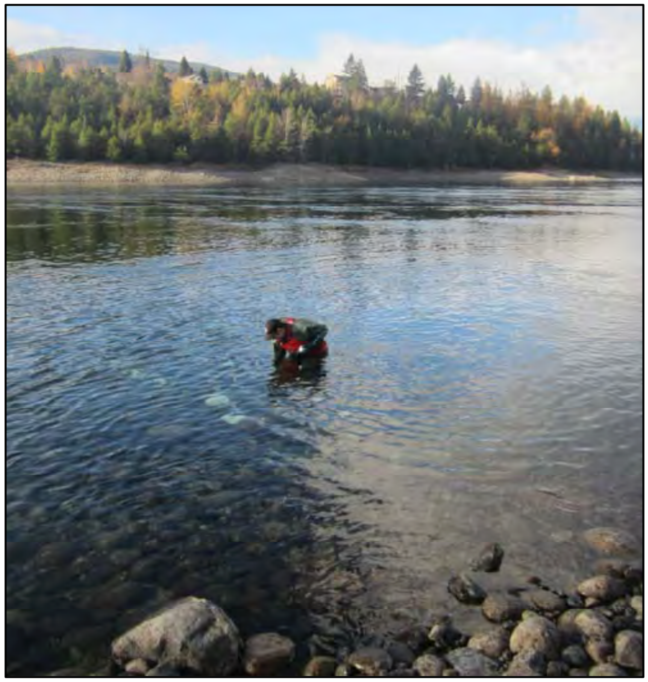

Photo 1 Tracer placement at Kinnaird-1 on November 2, 2018

5.1 KEENLEYSIDE

Three rows of tracers were placed perpendicular to the shore line at Keenleyside-1. The 10 medium, D_{50} size class tracers were placed farthest upstream, followed by a row of the five large tracers, and a row of the 10 small tracers. The row of small tracers was placed approximately 7.6 m upstream of the pipe that runs from the bank down to the water. The tracers closest to shore were placed approximately 7.1 m from the vegetation line. A hand drawn sketch, and photo of the tracer placement can be seen in Appendix C.

5.2 KINNAIRD

Three rows of tracers were placed perpendicular to the shore line at Kinnaird-1. The 10 medium, D_{50} size class tracers were placed farthest upstream, followed by a row of the five large tracers, and a row of the 10 small tracers. There is track that appears to be a private boat launch at this site, approximately 10 m downstream of the row of small tracers. The distance from the tracers placed closest to shore was 28 m to the vegetation line (shrubs and grasses), and 37 m to the shoreline trees. A hand drawn sketch and a photo of the tracer placement can be seen in Appendix C.

5.3 WANETA

The five D_{50} size class tracers were placed in one row at Waneta-2, parallel to shore line. This was done as the bank was quite steep and the velocity swift, and it was not possible to place the tracers in one line horizontal to flow direction. The tracers were placed in approximately 0.3 m of water depth and spread approximately 1 to 1.5 m apart. The distance between the furthest upstream and downstream tracers was 5.3 m. The tracers were placed approximately 20.3 m from the flagged reference tree directly upslope on the bank, of the placement location. A hand drawn sketch and photos of the tracer placement and the reference tree are shown in Appendix C.

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6.0 BATHYMETRIC AND HYDRAULIC DATA COLLECTION

Bathymetric and hydraulic data were collected with a Sontek M9 Acoustic Doppler Current Profiler (ADCP), utilizing a vertical beam echosounder and four dual frequency transducers with a 25° slant angle to provide depth profiling. Horizontal position is from DGPS, which is built into the ADCP. Data were collected from a 27 ft jet boat. The ADCP was mounted on a Sontek Hydroboard and secured to the jet boat, approximately mid-ship on the starboard side.

6.1 BATHYMETRY

Output from the ADCP was position and depth of each sounding. The data were reviewed and screened for anomalies. The soundings need to be adjusted to elevations. Data were collected with a section that overlaps with data collected by Grant Land Surveying with the intent of determining an appropriate offset.

6.2 DEPTH AND VELOCITY

Depth and velocity data were collected in transects to support hydraulic model calibration. The data were screened and post processed to develop a consistent dataset. Low flows, and therefore low velocities, and significant back eddies at some transects caused challenging conditions for data collection, including high boat speed relative to water speed and compass interference. Consequently, there is a moderate level of uncertainty with some of the data. The limitations of the dataset should be considered during hydraulic model development. Transect data are summarized in Table 4.

Table 4 ADCP Transect Summary

Columbia River Site Location (Upstream to Downstream)	Transect Data				
	# of passes	Av. Flow (m^3/s)	Std. Dev (m^3/s)	Date	Notes
Keenleyside Upstream	2	742	35.70	10/31/2018	High uncertainty due to significant backwater on river right
Keenleyside Mid	4	577	11.78	10/31/2018	These measurements were all consistent, however Q too low
Keenleyside Downstream	3	703	13.40	10/31/2018	
Kinnaird Upstream	2	1,024	17.34	11/2/2018	
Kinnaird Upper Mid	2	1,012	2.53	11/2/2018	
Kinnaird Lower Mid	2	1,037	11.95	11/2/2018	
Kinnaird Downstream	3	1,128	14.59	11/2/2018	
Waneta Upstream	2	841	3.87	11/1/2018	
Waneta at Pend Oreille	1	1,513	-	11/1/2018	Very high velocities and standing waves. Data collected to aid velocity distribution at model boundary
Waneta Downstream	2	1,352	14.26	11/1/2018	High uncertainty due to significant backwater on river right

7.0 CLOSURE

Between October 31 and November 3, 2018, KP and Ecofish conducted a site visit to the project area to conduct bed material sampling, under water bed material videography, and bathymetric and hydraulic data collection. This letter presents field methods and all reviewed and corrected data are attached. We trust this letter meets your current requirements. If you have any questions or comments, please contact the undersigned.

Yours truly,
Knight Piésold Ltd.

Prepared: ______________________
Toby Perkins, M.A.Sc., P.Eng.
Senior Engineer

Reviewed: ______________________
Craig Nistor, M.Sc., P.Geo.
Specialist Geoscientist | Associate

Approval that this document adheres to Knight Piésold Quality Systems: CN

Attachments:

Appendix A	Grain Size Distributions
Appendix B	Bed Material Sampling Photos
Appendix C	Tracer Placement Locations

/tp

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APPENDIX A

Grain Size Distributions

(Pages A-1 to A-7)

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TABLE A1

ECOFISH RESEARCH LTD
CLBWORKS-27

WOLMAN COUNT DATA SUMMARY
KEENLYSIDE 1-1

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Size Class (mm)	Count	Cumulative Total	% finer	D_{50} (mm)
4	2	2	2	
8	0	2	2	
11	0	2	2	
16	2	4	4	
23	10	14	14	
32	11	25	25	
45	9	34	34	
64	9	43	43	
90	9	52	51	85
128	21	73	72	
180	6	79	78	
256	11	90	89	
360	11	101	100	

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Knight Piésold CONSULTING

TABLE A2

ECOFISH RESEARCH LTD
CLBWORKS-27

WOLMAN COUNT DATA SUMMARY
KEENLYSIDE 2-1

Print Apr/09/20 16:58:41

Size Class (mm)	Count	Cumulative Total	% finer	D_{50} (mm)
2	7	7	7	
4	0	7	7	
6	0	7	7	
8	1	8	8	
11	2	9	9	
16	8	15	15	
23	15	30	31	
32	21	51	53	31
45	12	63	65	
64	15	78	80	
90	8	86	89	
128	7	93	96	
180	2	95	98	
256	0	95	98	
360	1	96	99	
512	1	97	100	

M:\1\03\00641\01\A\Data\Task 2_Data Collection and Analyis\Field Data\Site Visit_Oct 29 to Nov 2\[Wolman Counts.xlsx]kEEN 2-1 Table

0	14APR'20	ISSUED WITH LETTER VA18-02216	AIF	TJP
REV	DATE	DESCRIPTION	PREP'D	RVW'D

Knight Piésold CONSULTING

TABLE A3

ECOFISH RESEARCH LTD
CLBWORKS-27

WOLMAN COUNT DATA SUMMARY
KINNAIRD 1-1

Print Apr/09/20 16:58:41

Size Class (mm)	Count	Cumulative Total	% finer	D_{50} (mm)
2	5	5	4	
8	1	6	5	
11	2	7	6	
16	8	14	12	
23	3	17	14	
32	8	25	21	
45	9	34	28	
64	15	49	41	
90	11	60	50	90
128	20	80	67	
180	25	105	88	
256	10	115	96	
360	4	119	99	
512	0	119	99	
720	1	120	100	

M:\1\03\00641\01\A\Data\Task 2_Data Collection and Analyis\Field Data\Site Visit_Oct 29 to Nov 2\[Wolman Counts.xlsx]kinn 1-1 Table

0	14APR'20	ISSUED WITH LETTER VA18-02216	AIF	TJP
REV	DATE	DESCRIPTION	PREP'D	RVW'D

Knight Piésold CONSULTING

TABLE A4

ECOFISH RESEARCH LTD
CLBWORKS-27

WOLMAN COUNT DATA SUMMARY
KINNAIRD 3-1

Print Apr/09/20 16:58:41

Size Class (mm)	Count	Cumulative Total	% finer	D_{50} (mm)
4	6	6	6	
8	0	6	6	
11	0	6	6	
16	1	7	7	
23	2	9	9	
32	5	14	14	
45	8	22	22	
64	8	30	30	
90	8	38	38	
128	8	46	46	
180	11	57	57	145
256	15	72	72	
360	16	88	88	
512	7	95	95	
720	2	97	97	
1024	3	100	100	

M:\1\03\00641\01\A\Data\Task 2_Data Collection and Analyis\Field Data\Site Visit_Oct 29 to Nov 2\[Wolman Counts.xlsx]Kinn 3-1 Table

0	14APR'20	ISSUED WITH LETTER VA18-02216	AIF	TJP
REV	DATE	DESCRIPTION	PREP'D	RVW'D

Knight Piésold CONSULTING

TABLE A5

ECOFISH RESEARCH LTD
CLBWORKS-27

WOLMAN COUNT DATA SUMMARY
WANETA 1-1

Print Apr/09/20 16:58:41

Size Class (mm)	Count	Cumulative Total	% finer	D_{50} (mm)
8	0	0	0	
16	0	0	0	
23	1	1	1	
32	1	2	2	
45	3	5	5	
64	4	9	9	
90	14	23	22	
128	9	32	31	
180	15	47	45	
256	23	70	67	194
360	14	84	81	
512	14	98	94	
720	5	103	99	
1024	1	104	100	

M:\1\03\00641\01\A\Data\Task 2_Data Collection and Analyis\Field Data\Site Visit_Oct 29 to Nov 2\[Wolman Counts.xlsx]wANETA 1-1 Table

0	14APR'20	ISSUED WITH LETTER VA18-02216	AIF	TJP
REV	DATE	DESCRIPTION	PREP'D	RVW'D

Knight Piésold CONSULTING

TABLE A6

ECOFISH RESEARCH LTD
CLBWORKS-27

WOLMAN COUNT DATA SUMMARY
WANETA 2-1

Print Apr/09/20 16:58:41

Size Class (mm)	Count	Cumulative Total	% finer	D_{50} (mm)
32	6	6	5	
45	2	8	7	
64	3	9	8	
90	8	16	14	
128	10	26	23	
180	15	41	36	
256	15	56	49	
360	24	80	70	260
512	16	96	84	
720	16	112	98	
1024	2	114	100	

M:\1\03\00641\01\A\Data\Task 2_Data Collection and Analyis\Field Data\Site Visit_Oct 29 to Nov 2\[Wolman Counts.xlsx]Waneta 2-1 Table

0	14APR'20	ISSUED WITH LETTER VA18-02216	AIF	TJP
REV	DATE	DESCRIPTION	PREP'D	RVW'D

Knight Piésold CONSULTING

TABLE A7

ECOFISH RESEARCH LTD
CLBWORKS-27

WOLMAN COUNT DATA SUMMARY
WANETA 2-2

Print Apr/09/20 16:58:41

Size Class (mm)	Count	Cumulative Total	% finer	D_{50} (mm)
4	1	1	1	
8	0	1	1	
11	3	4	3	
16	3	4	3	
23	5	9	8	
32	13	22	19	
45	13	35	30	
64	14	49	43	86
90	10	59	51	
128	16	75	65	
180	12	87	76	
256	10	97	84	
360	10	107	93	
512	6	113	98	
720	0	113	98	
1024	2	115	100	

M:\1\03\00641\01\A\Data\Task 2_Data Collection and Analyis\Field Data\Site Visit_Oct 29 to Nov 2\[Wolman Counts.xlsx]Waneta 2-2 Table

0	14APR'20	ISSUED WITH LETTER VA18-02216	AIF	TJP
REV	DATE	DESCRIPTION	PREP'D	RVW'D

APPENDIX B

Bed Material Sampling Photos

(Pages B-1 to B-6)

APPENDIX B – SAMPLING TRANSECTS
CLBWORKS-27

PHOTO 1 – Keenleyside-1 Bed Material and Sub-Surface Sampling Transect, Oct. 31, 2018.

PHOTOS 2 & 3 – Keenleyside-1 Bed Material and Subsurface Sampling, Nov.1, 2018.

APPENDIX B – SAMPLING TRANSECTS
CLBWORKS-27

PHOTO 4 – Keenleyside-2 Bed Material Transect, Nov. 1, 2018.

PHOTO 5 – Kinnaird-1 Bed Material and Sub-Surface Sampling Transect, Oct. 31, 2018.

APPENDIX B – SAMPLING TRANSECTS
CLBWORKS-27


PHOTOS 6 & 7 – Kinniard-1 Bed Material and Subsurface Sampling, Nov.1, 2018.

PHOTO 8 – Kinnaird-2 Bed Material Transect, Nov.1, 2018.

Knight Piésold CONSULTING

APPENDIX B – SAMPLING TRANSECTS
CLBWORKS-27

PHOTO 9 – Kinnaird-3 Bed Material and Sub-Surface Sampling Transect, Nov. 1, 2018.

PHOTOS 10 & 11 – Kinniard-3 Bed Material and Subsurface Sampling, Nov.1, 2018

APPENDIX B – SAMPLING TRANSECTS
CLBWORKS-27

PHOTO 12 – Waneta-1 Bed Material Sampling Transect, Oct. 31, 2018.

PHOTO 13 – Waneta-2 Bed Material Sampling Transect 1 of 2, Nov. 2, 2018.

PHOTO 14 – Waneta-2 Bed Material Sampling Transect 2 of 2, Nov. 2, 2018.

APPENDIX C

Tracer Placement Locations

(Pages C-1 to C-4)

APPENDIX C – TRACER PLACEMENT
CLBWORKS-27

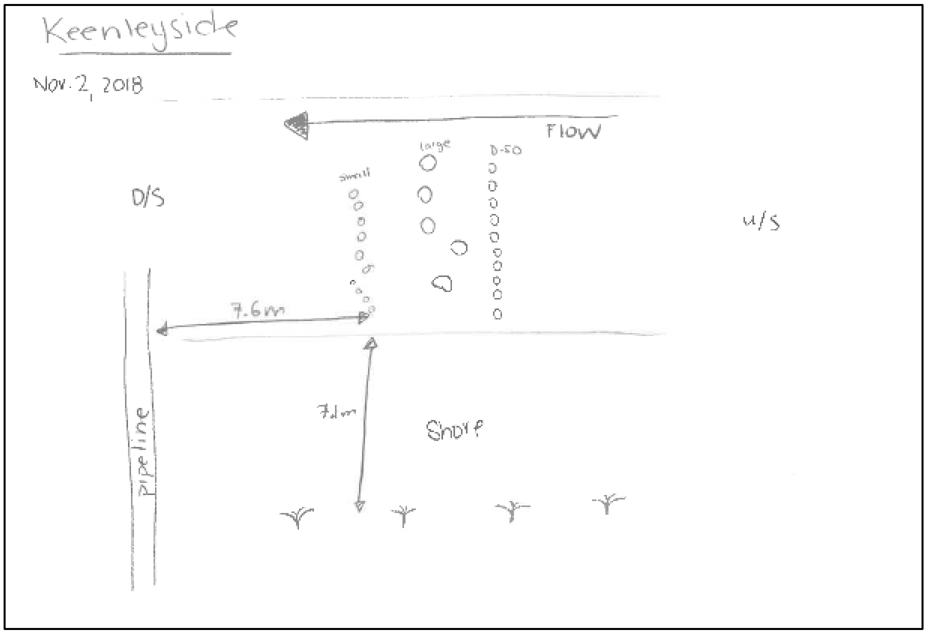


FIGURE 1 – Hand drawn sketch of the three rows of tracer stones placed at Keenleyside 1.

PHOTO 1 – Tracer stone location at Keenleyside 1 on November 2, 2018.

APPENDIX C – TRACER PLACEMENT CLBWORKS-27

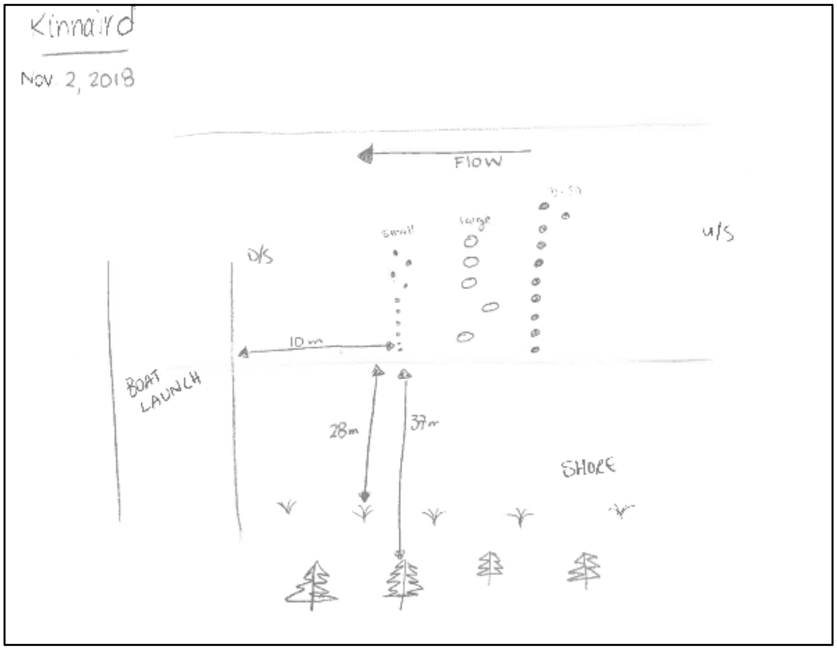


FIGURE 2 – Hand drawn sketch of three rows of tracers placed at Kinnaird 1.

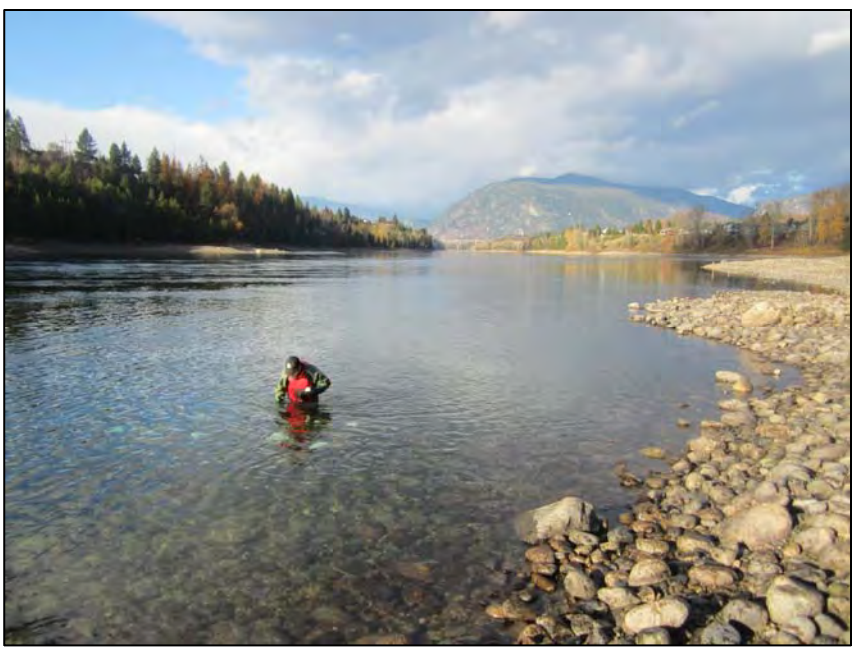


PHOTO 2 – Tracer Location at Kinnaird 1 on November 2, 2018.

APPENDIX C – TRACER PLACEMENT
CLBWORKS-27

PHOTO 3 – Tracer stone position on November 2, 2018.

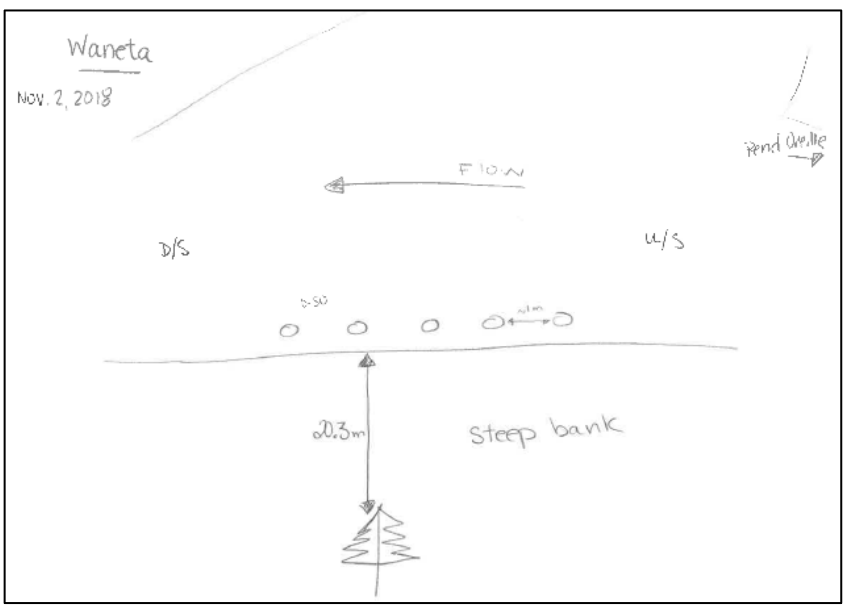


FIGURE 3 – Hand drawn sketch of tracer placement at Waneta 2.

PHOTO 4 – Tracer position at Waneta 2 on November 2, 2018.

PHOTO 5 – Flagged tree directly up bank from Waneta tracer location on November 2, 2018.

Appendix B. Bathymetric data collection report and bathymetric maps

GRANT LAND SURVEYING
1 - 1841 Comox Ave
Comox, BC V9M 3M3
T 250.941.0804
F 250.941.0805
GrantLandSurveying.com

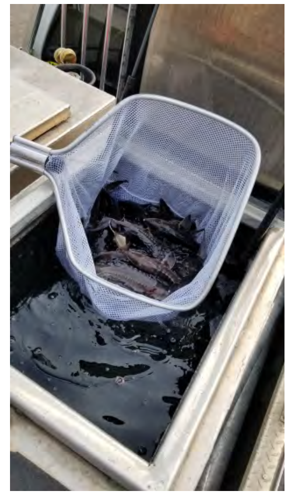
Report on the Bathymetric Survey of Select Sites on the Columbia River – Keenleyside, Kinnaird and Waneta

Location: Castlegar, BC

Survey Date: 2018.09.12 – 18

Sandy Grant BCLS
Grant Land Surveying Inc.
1-1841 Comox Ave
Comox BC V9M 3M3

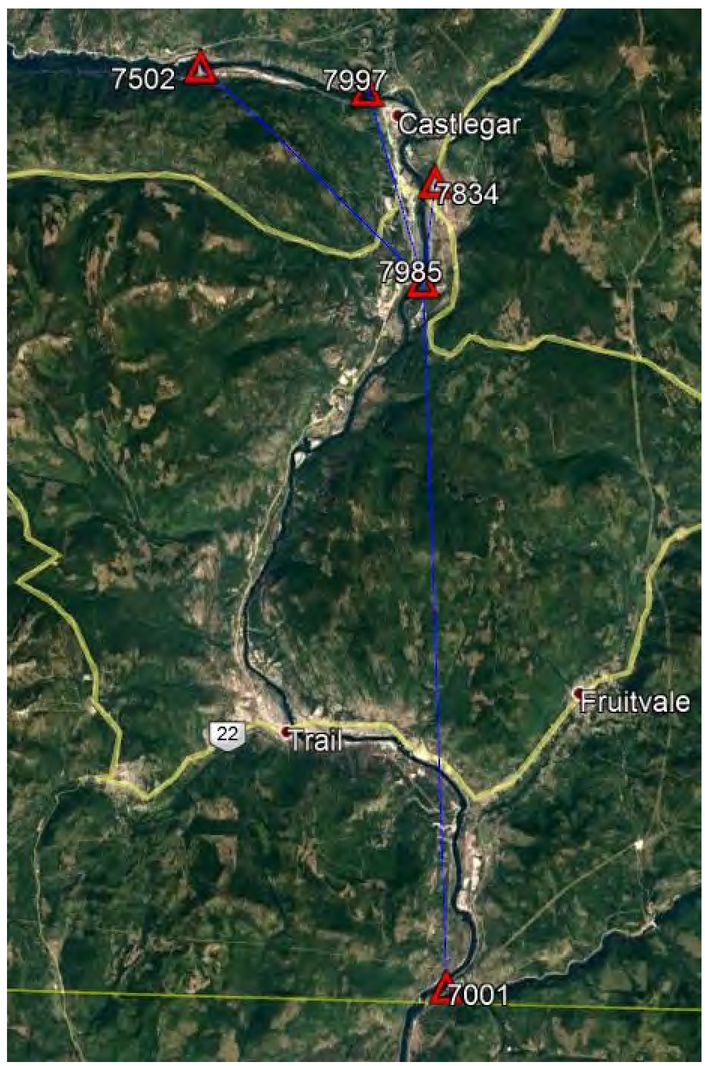
Overview



The purpose of the bathymetric survey was to support the study of Sturgeon habitat restoration areas on the Columbia River. The three study areas selected were a 1 km reach below the Keenleyside Dam, a 5 km reach below the Kinnard Bridge (Hwy. 3), and a 1 km reach above the Canada-US border at Waneta. The bathymetric survey was conducted between the wetted portions of the river where the water depth would allow boat access. The survey excluded the areas of the river below the spill-ways of the Keenleyside and Waneta Dams due to safety concerns.

Methodology

GPS Network



At each of the three survey areas, an RTK Base station was established from which the GPS Rover in the boat received real-time position corrections. Spikes were set to act as temporary reference points and to allow re-occupation for the GPS base stations. The initial positions were established using Code only GPS solutions, and pseudo-range data was recorded for the duration of the surveys to allow post-processing and network adjustment.

The raw data from the three base stations located at each site was processed using Natural Resource Canada PPP (Precise Point Position) Service. To provide additional redundancy GPS vectors were measured between Kinnaird (7985) and Keenleyside (7502) as well as Kinnaird (7985) and Waneta (7001) stations. Also, a GPS vector was measured to the geodetic control monument 97H2191 (GCM No:918243)(7834) to provide a redundant vertical check.

The GPS vectors were processed in StarNet

V9, and the final PPP position of the Kinnaird (7985) base station was fixed in 3D. The PPP positions for Keenleyside (7502) and Waneta (7001) were entered "un-constrained" for comparison. The differences between the RTK GPS computed positions, and the PPP positions were excellent; the average difference was 0.010m horizontally and 0.030m vertically.

- Horizontal Datum: NAD83(CSRS) 2002.0
- Vertical Datum: CGVD2013 (CGG2013a)

Boat Based Survey

The surveys were conducted using a Knudsen Engineering dual frequency echo sounder using a 200 kHz high-frequency and 50 kHz low-frequency Airmar transducer. The horizontal and vertical position of the transducer was tracked in real-time by our Leica GS15 dual-frequency RTK GPS system. A depth and position were collected every 50ms along the survey track and sent to the field computer. The raw depth and position were merged, converted to an elevation of the bottom, and stored in real-time using Hypack 2018 Hydrographic software.

The RTK antenna was mounted directly over the transducer, and no horizontal correction was required between the transducers depth measurement and the GPS 3d position. The vertical offset between the GPS antenna and the transducer was recorded and applied during the post-processing stage of the bathymetric reduction.

Parallel survey lines were run perpendicular to the flow of the river. A line spacing specification at Keenleyside, Kinnaird and Waneta of 10, 20 and 10 metres respectively was used. At the completion of the parallel lines, check lines were run parallel to the river flow. At various times and locations during the survey, the boat was stopped, and a bar-check was performed to confirm the calibration of the sounder.

Office Processing

The raw sounding data was post-processed in Hypack SBMax editor. The sounding data was initially cleaned of random noise using a 1m spike/gate filter and adjusted vertically to correct the initial and post-processed base station positions. The raw sounder trace was then visually checked for anomalies and misinterpretations by the software.

1 - 1841 Comox Ave
Comox, BC V9M 3M3
T 250.941.0804
F 250.941.0805
GrantLandSurveying.com

The edited sounding data was then down-sampled at a 6m radius spacing at Keenleyside, a12m spacing at Kinnaird, and a 4m spacing at Waneta. The re-sampled data was imported to Autodesk Civil 3d 2018 where a 3d surface was generated for a final visual check.

Summary

We are pleased to have completed this project without any problems of note and with the able assistance of BC Hydro, Ecofish, Marco and Bob Chapman.

Final Base Station Coordinates:

	Point #	**Northing**	**Easting**	**Geod. Elev**
Keenleyside	7502	5465489.223	443999.563	423.424
Kinnaird	7985	5456918.492	453246.443	416.802
Waneta	7001	5428195.555	454771.032	412.730

Average Water Levels at the time of the survey:

- Keenleyside = 421.6m
- Kinnaird
  - Upper = 416.8
  - Middle = 416.2
  - Lower = 416.0
- Waneta = 397.4

Final delivery included:

- Comma-delimited points file of bathymetric data including a separate file of rejected data
  - Format: Grid Northing, Grid Easting, Elevation
  - Note all coordinates are UTM Zone 11
- KML file of GPS Vectors

The field survey was performed between August 13-17, 2018 by:

Sandy Grant BCLS
Marco Marrelo (Boat Operator)
Bob Chapman (Boat operator)

Sandy Grant BCLS

CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Keenleyside Bathymetry Field Trip 1 July Typical Spawning Flows

Legend

Known Spawning Area

Contour 0.5 m

Depth

Deep

Shallow

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
1	4/11/2019	1210_Engagement_Bathymetry_190404	
2			
3			
4			
5			

Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map B1

Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_Bathymetry_190404.mxd

CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Kinnaird - Upper Bathymetry Field Trip 1 July Typical Spawning Flows

Legend

- Known Spawning Area
- Contour 0.5 m

Depth

Deep

Shallow

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
1	4/11/2019	1210_Engagement_Bathymetry_190404	
2			
3			
4			
5			

Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map B2

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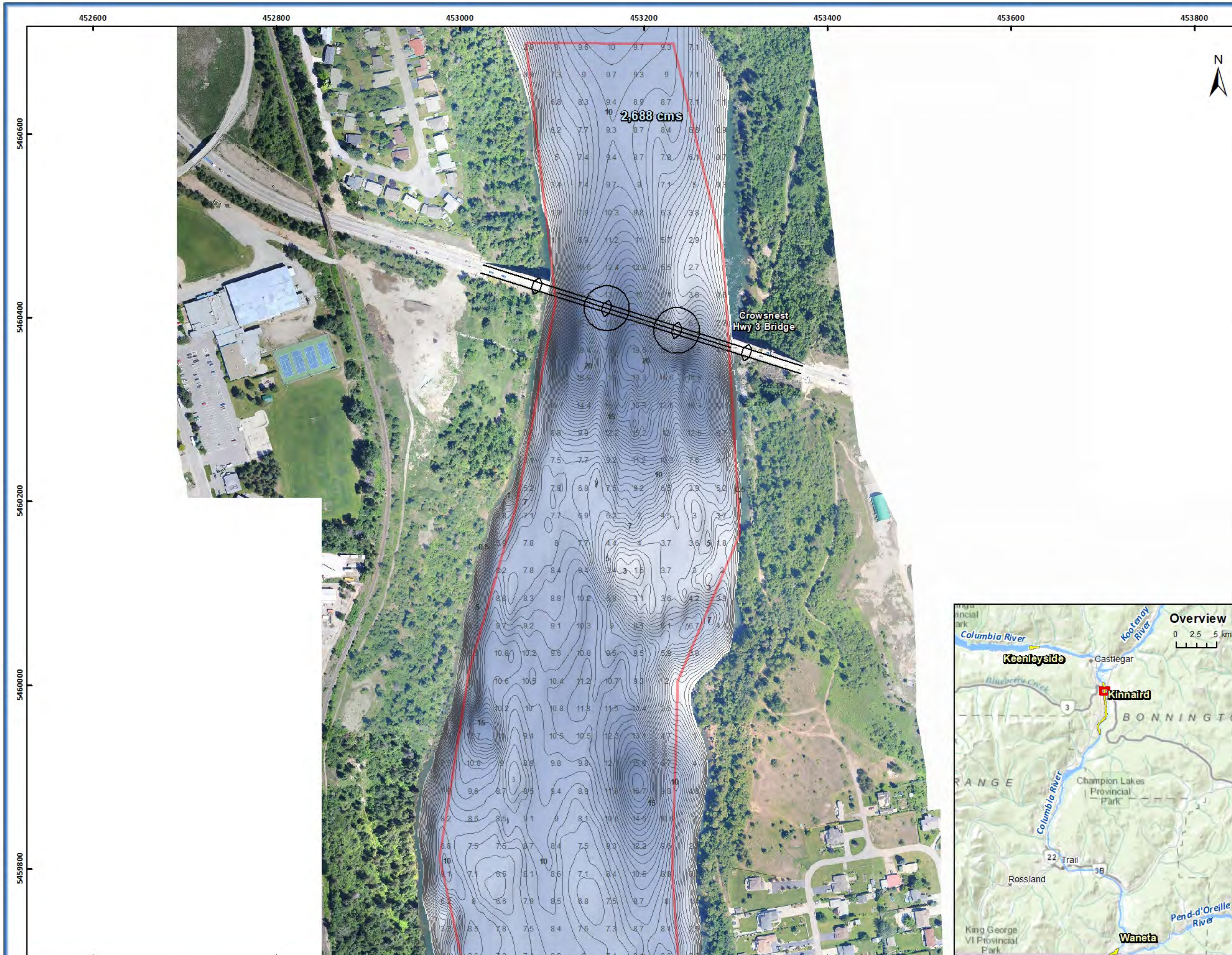

CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Kinnaird - Upper
Bathymetry Field Trip 1 July
Typical Spawning Flows

Legend

Known Spawning Area

Contour 0.5 m

Depth

Deep

Shallow

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
1	4/11/2019	1210_Engagement_Bathymetry_190404	
2			
3			
4			
5			

Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map B3

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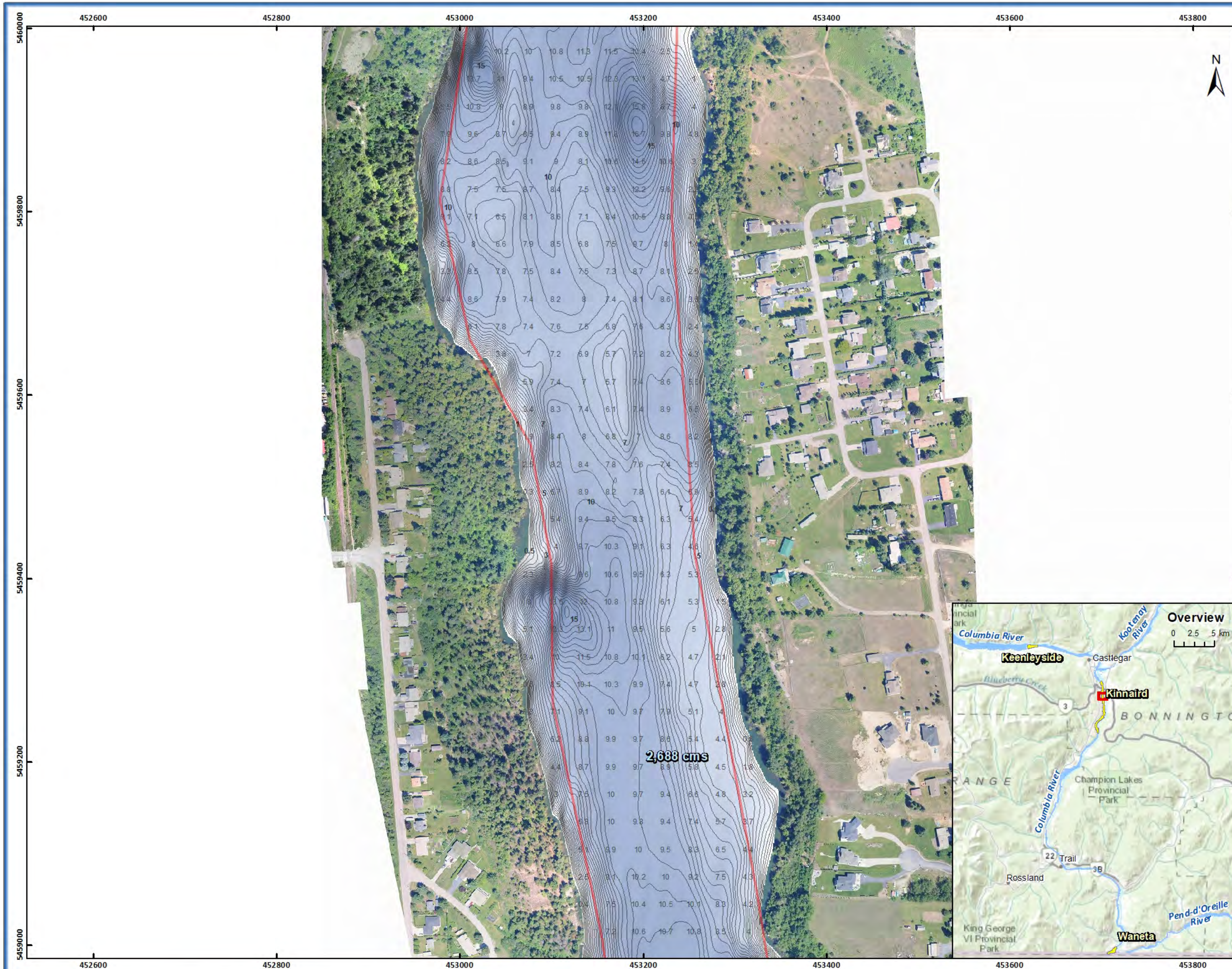

CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Kinnaird - Upper Bathymetry Field Trip 1 July Typical Spawning Flows

Legend
Known Spawning Area
Contour 0.5 m
Depth
Deep
Shallow

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m
Scale: 1:4,000

NO.	DATE	REVISION	BY
1	4/11/2019	1210_Engagement_Bathymetry_190404	
2			
3			
4			
5			

Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map B4

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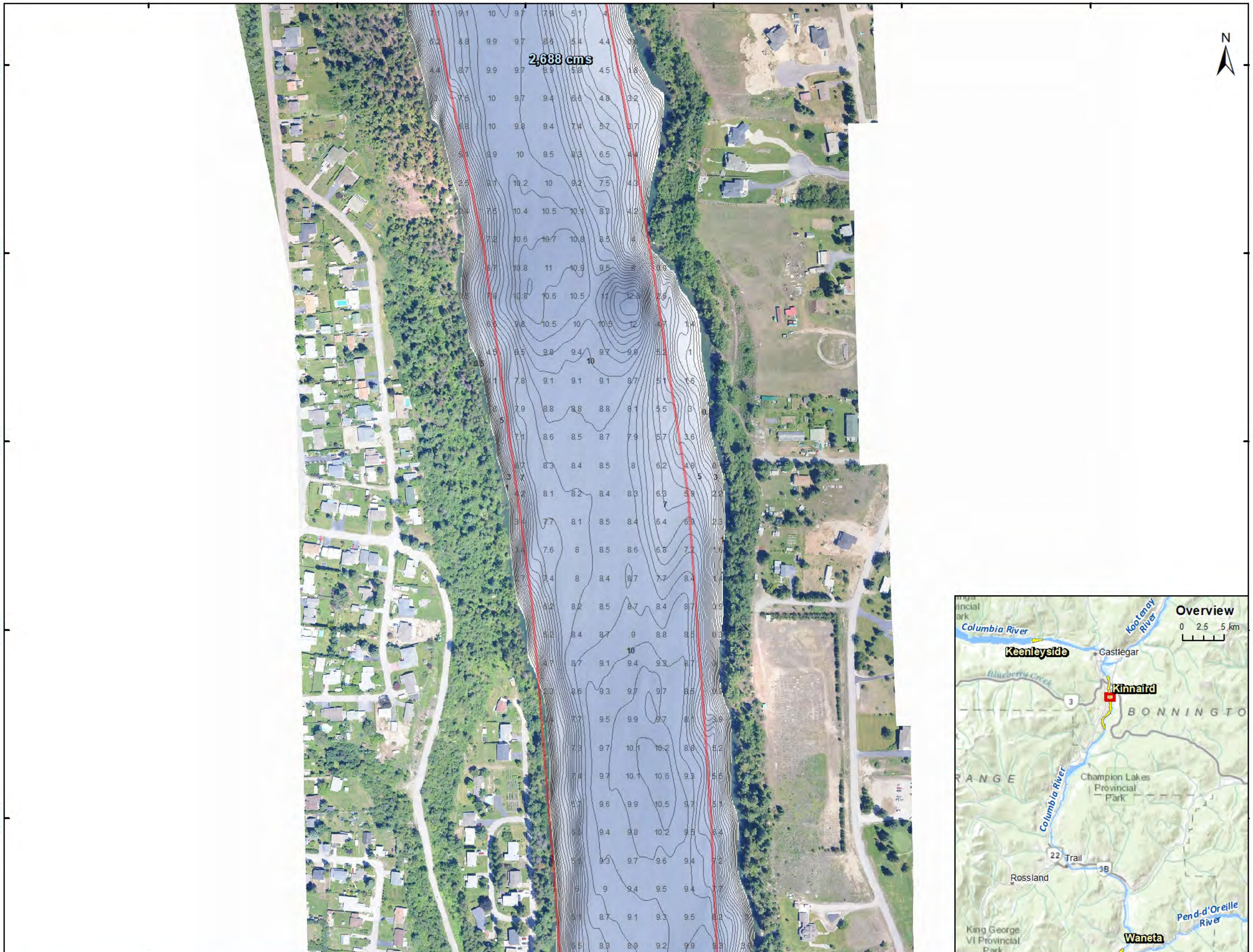

CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Kinnaird - Upper
Bathymetry Field Trip 1 July
Typical Spawning Flows

Legend

Known Spawning Area
Contour 0.5 m
Depth
Deep
Shallow

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m
Scale: 1:4,000

NO.	DATE	REVISION	BY
1	4/11/2019	1210_Engagement_Bathymetry_190404	
2			
3			
4			
5			

Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map B5

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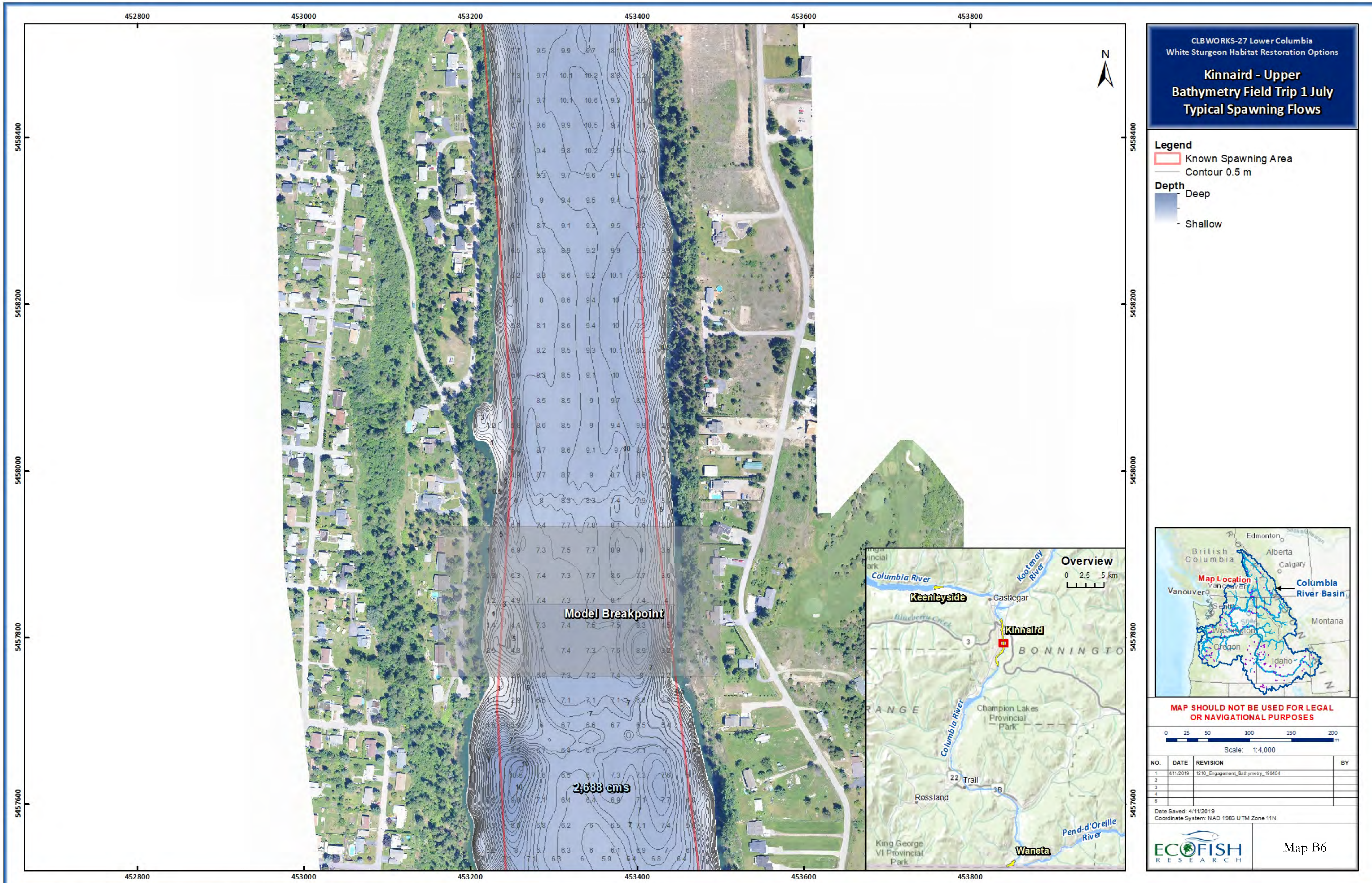

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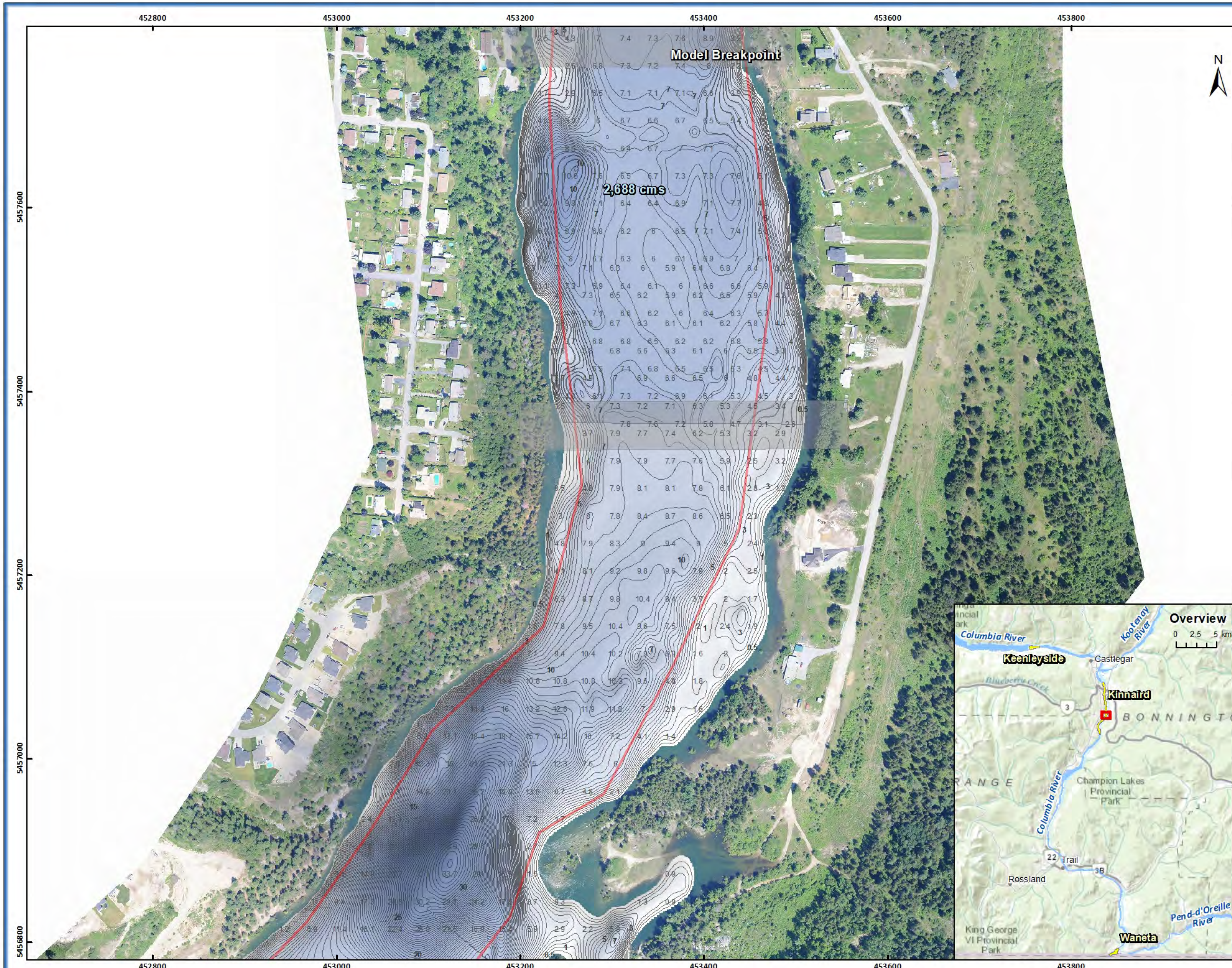

CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Kinnaird - Lower
Bathymetry Field Trip 1 July
Typical Spawning Flows

Legend

- Known Spawning Area
- Contour 0.5 m

Depth

- Deep
- Shallow

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
1	4/11/2019	1210_Engagement_Bathymetry_190404	
2			
3			
4			
5			

Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map B7

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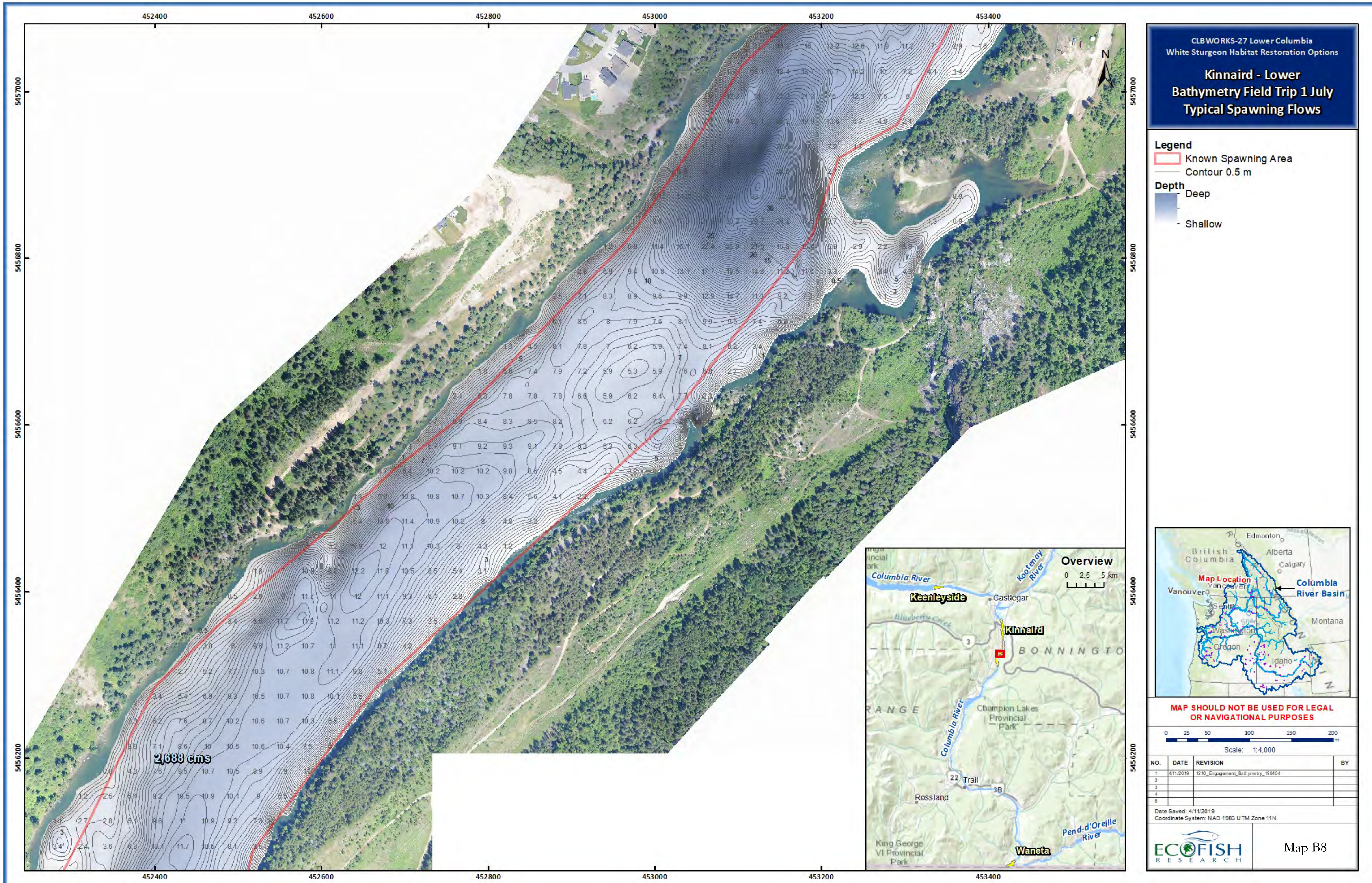

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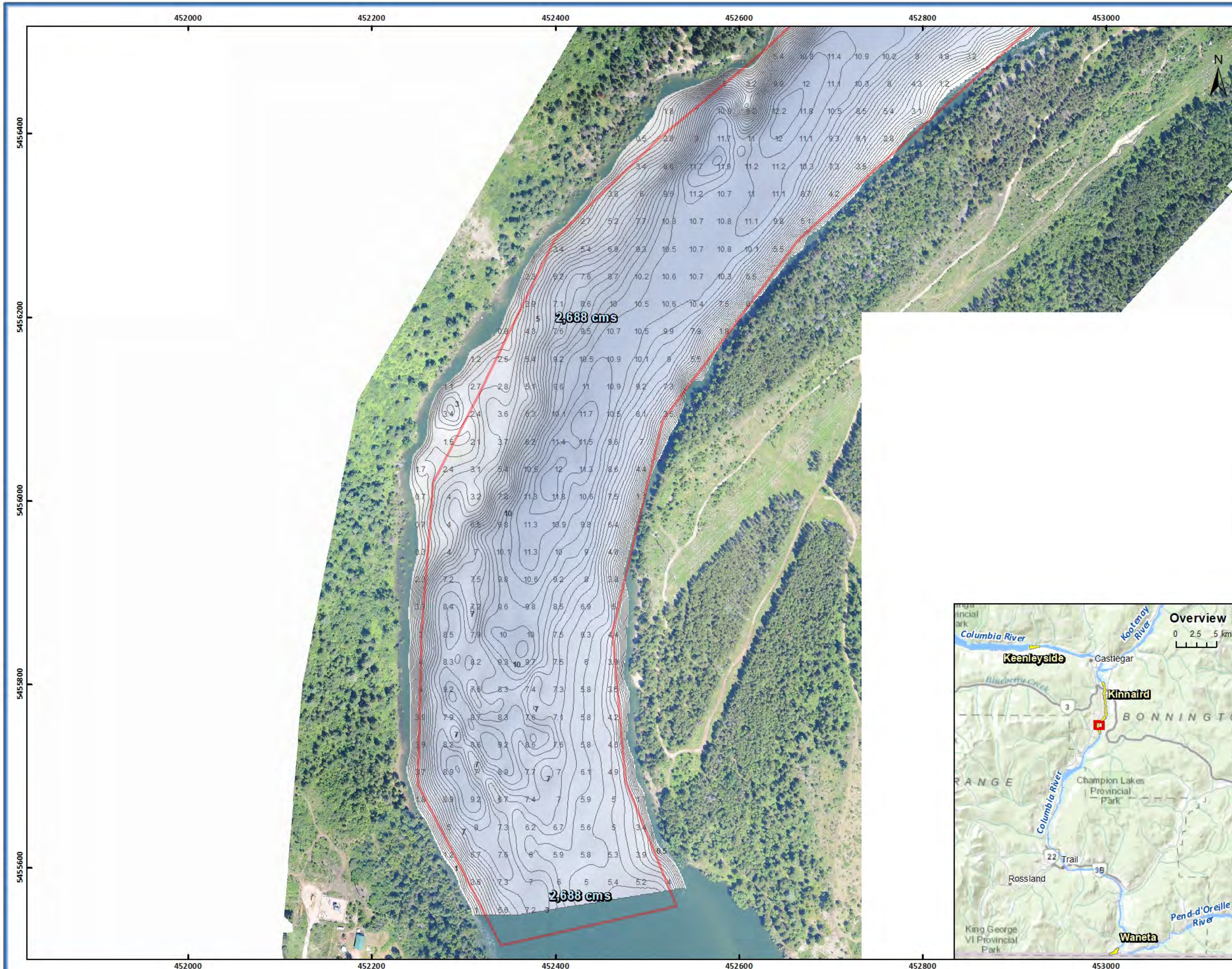

CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Kinnaird - Lower Bathymetry Field Trip 1 July Typical Spawning Flows

N

Legend

Known Spawning Area

Contour 0.5 m

Depth

Deep

Shallow

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
1	4/11/2019	1210_Engagement_Bathymetry_190404	
2			
3			
4			
5			

Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map B9

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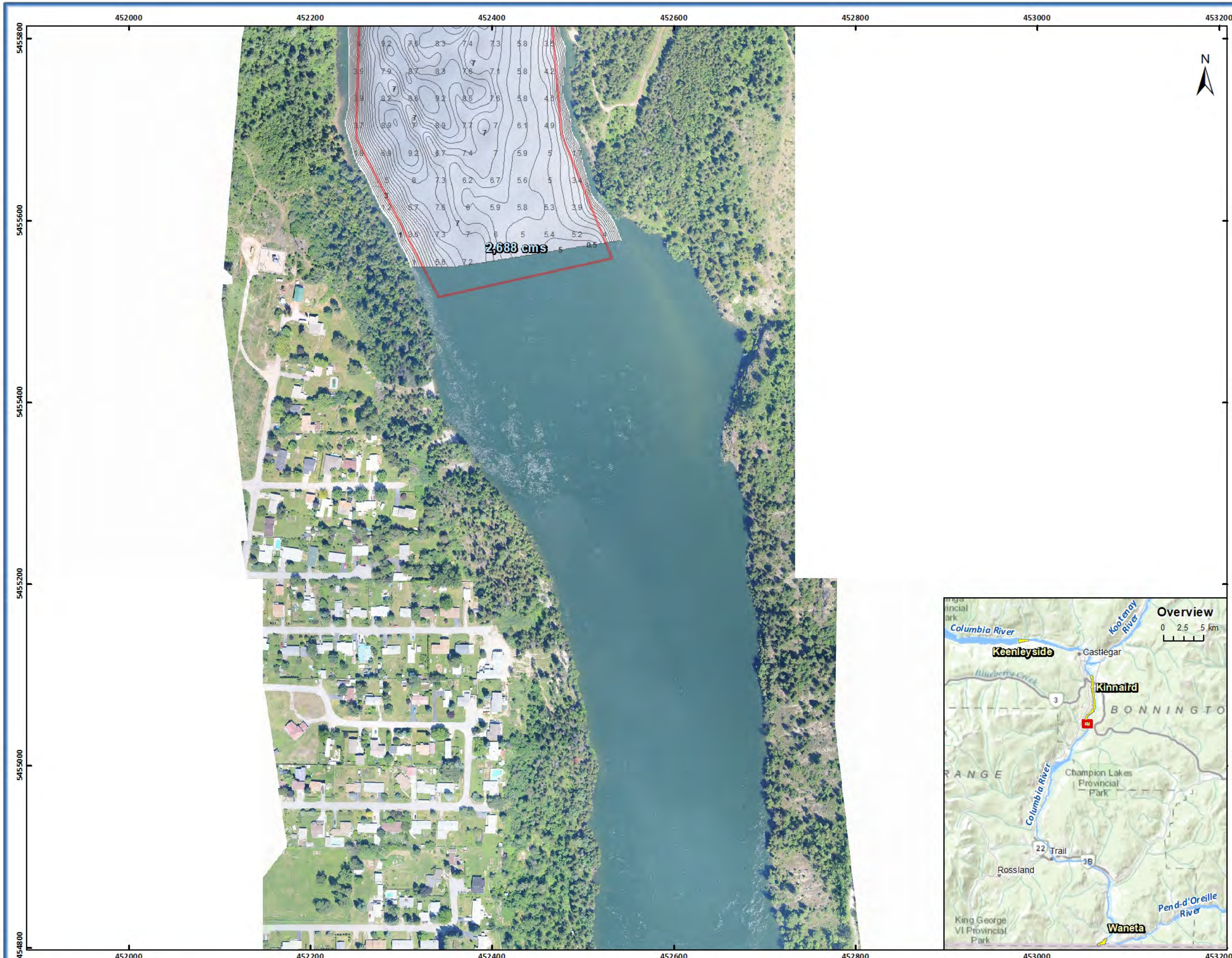


CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Kinnaird - Lower
Bathymetry Field Trip 1 July
Typical Spawning Flows

Legend

Known Spawning Area

Contour 0.5 m

Depth

Deep

Shallow

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

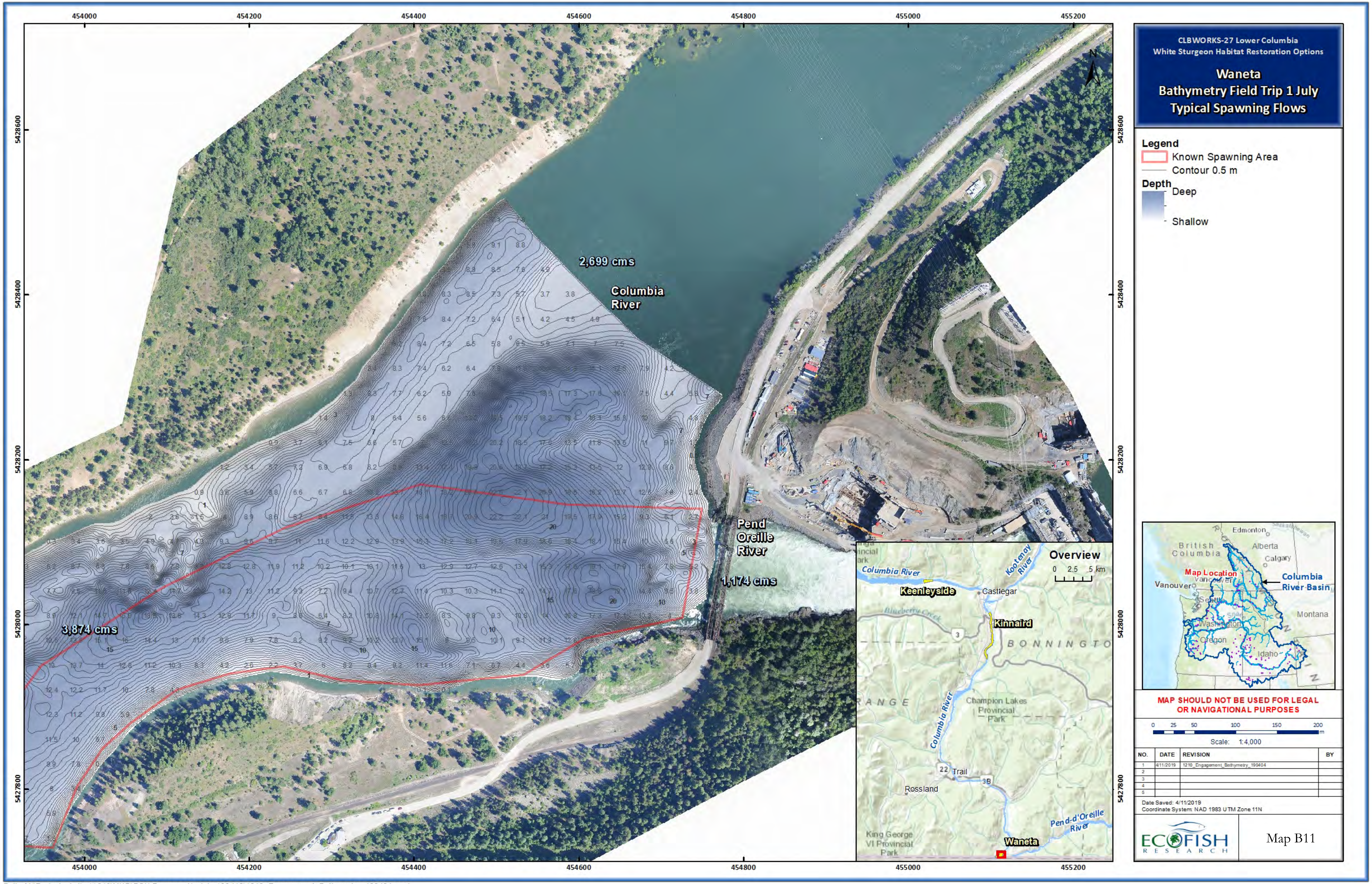
NO.	DATE	REVISION	BY
1	4/11/2019	1210_Engagement_Bathymetry_190404	
2			
3			
4			
5			

Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map B10

Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_Bathymetry_190404.mxd



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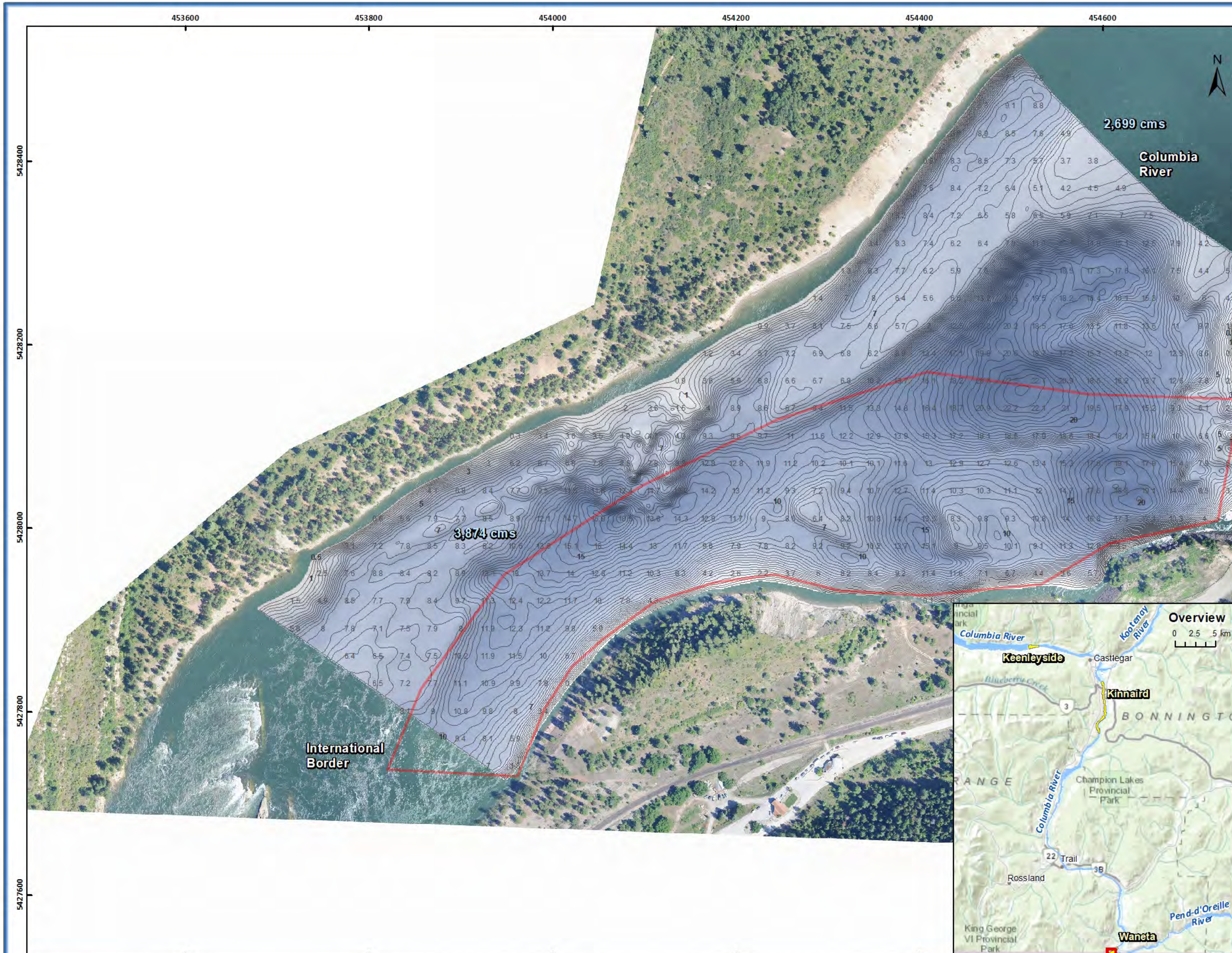


CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Waneta
Bathymetry Field Trip 1 July
Typical Spawning Flows

Legend

Known Spawning Area
Contour 0.5 m

Depth

Deep
Shallow

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
1	4/11/2019	1210_Engagement_Bathymetry_190404	
2			
3			
4			
5			

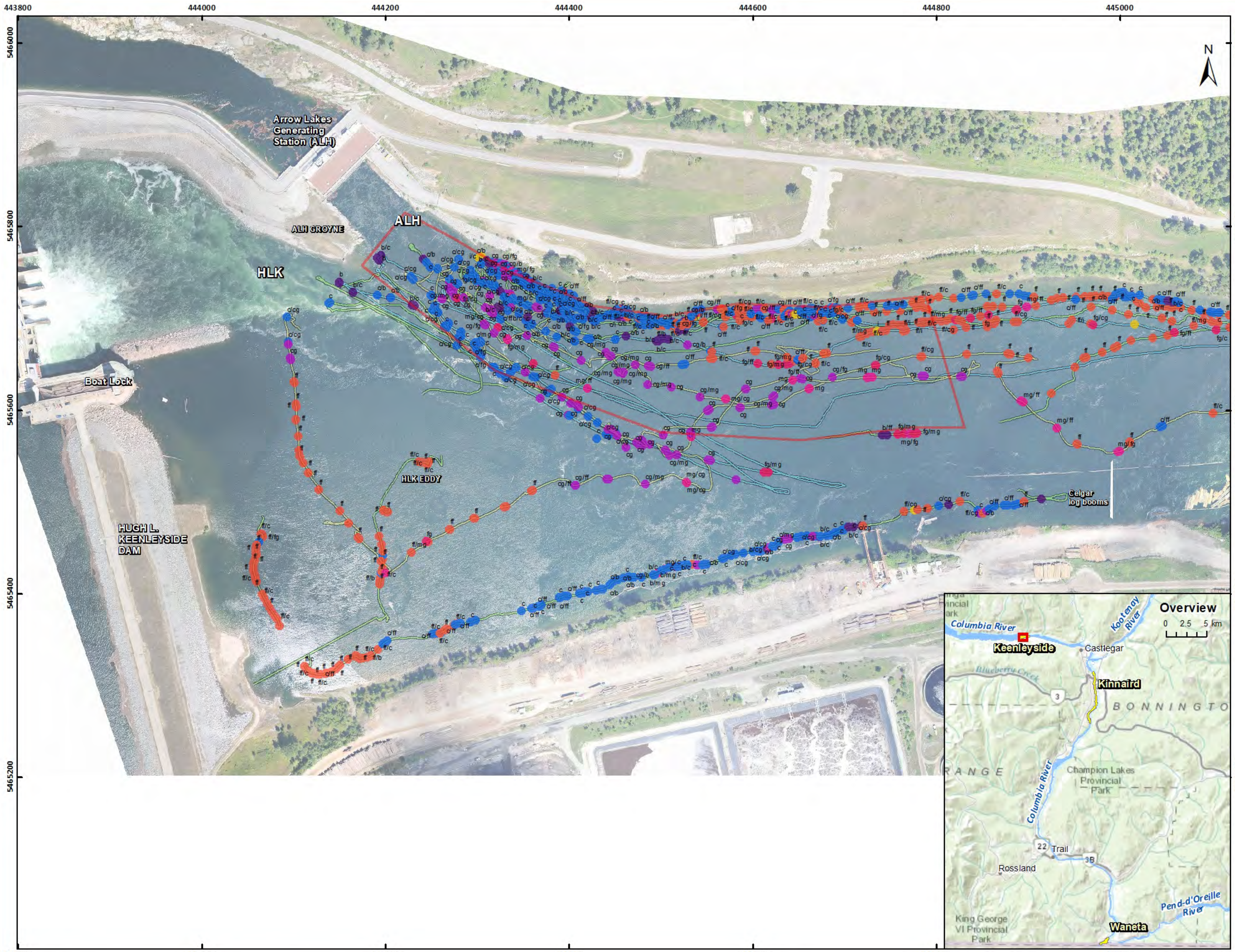
Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map B12

Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_Bathymetry_190404.mxd

Appendix C. Dominant and subdominant substrate classifications



CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Keenleyside Substrate Type

Legend

Known Spawning Area

Dominant Substrate

- Impermeable
- Fines
- Fine Gravel
- Medium Gravel
- Coarse Gravel
- Cobble
- Boulder

Substrate Video Tracks

- Substrate Video (FT3 Nov)
- Substrate Video (FT2 Aug)
- Substrate Video (FT1 Jul)

Substrate Code	Size
(i) Impermeable	-
(b) Boulder	>256 mm
(c) Cobble	>64-256 mm
(cg) Coarse Gravel	>16-64 mm
(mg) Medium Gravel	>4-16 mm
(fg) Fine Gravel	2-4 mm
(ff) Fines	< 2 mm

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

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Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

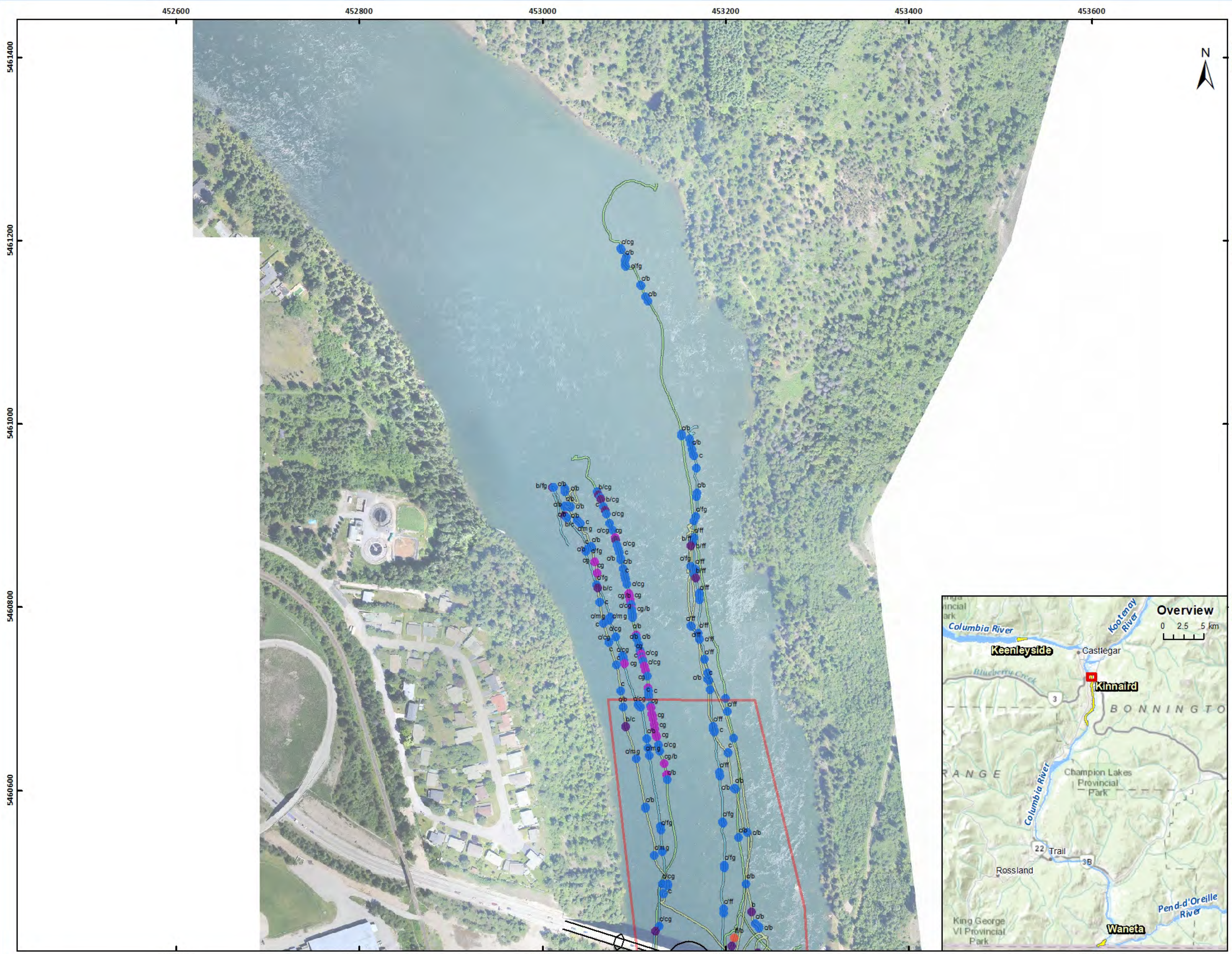
ECOFISH RESEARCH

Map C1

Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_Substrate_190404.mxd

CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Kinnaird - Upper
Substrate Type



Legend

Known Spawning Area

Dominant Substrate

- Impermeable
- Fines
- Fine Gravel
- Medium Gravel
- Coarse Gravel
- Cobble
- Boulder

Substrate Video Tracks

- Substrate Video (FT3 Nov)
- Substrate Video (FT2 Aug)
- Substrate Video (FT1 Jul)

Substrate Code	Size
(i) Impermeable	-
(b) Boulder	>256 mm
(c) Cobble	>64-256 mm
(cg) Coarse Gravel	>16-64 mm
(mg) Medium Gravel	>4-16 mm
(fg) Fine Gravel	2-4 mm
(ff) Fines	< 2 mm

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
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Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map C2

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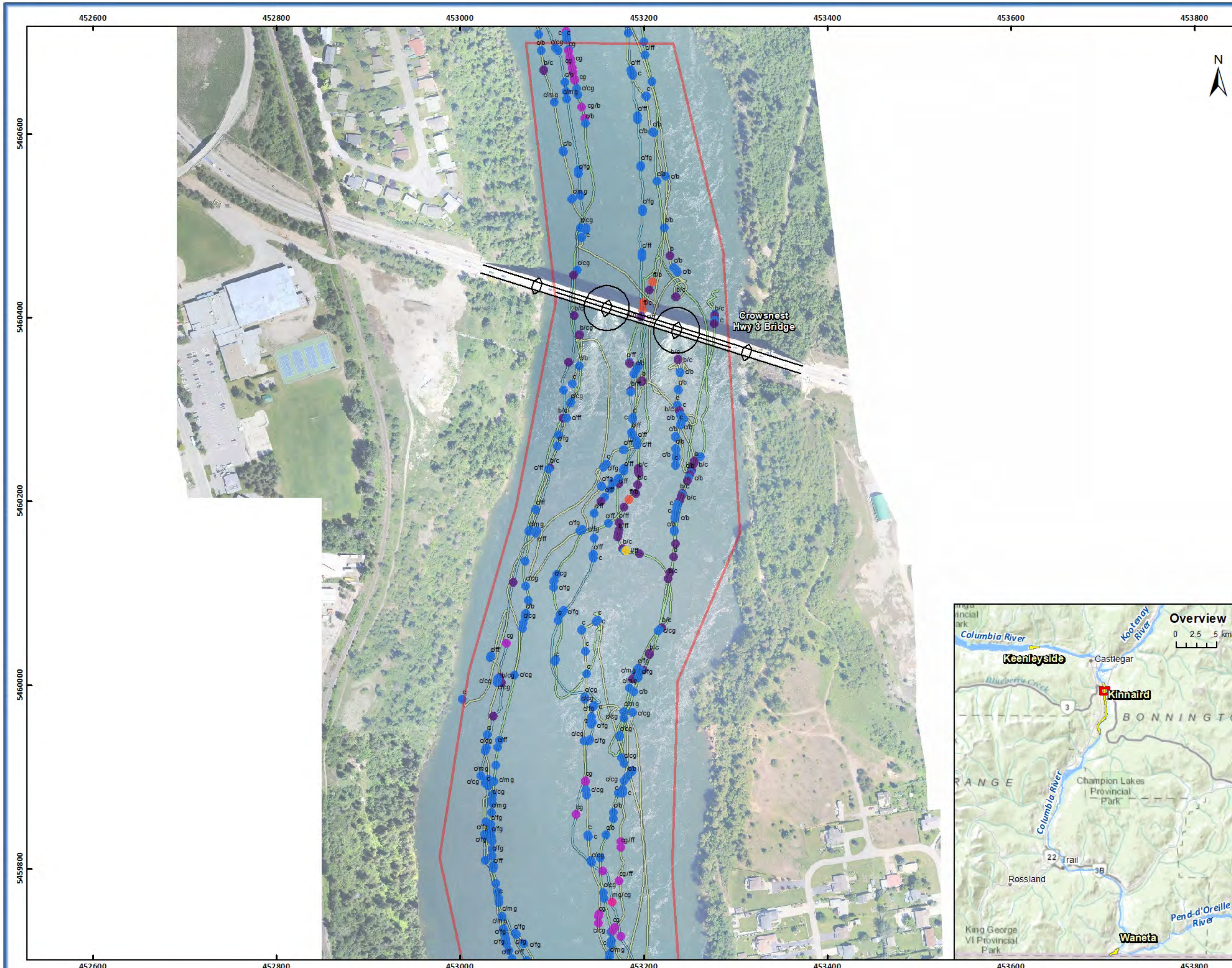

CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Kinnaird - Upper
Substrate Type

Legend

- Known Spawning Area

Dominant Substrate

- Impermeable
- Fines
- Fine Gravel
- Medium Gravel
- Coarse Gravel
- Cobble
- Boulder

Substrate Video Tracks

- Substrate Video (FT3 Nov)
- Substrate Video (FT2 Aug)
- Substrate Video (FT1 Jul)

Substrate Code	Size
(i) Impermeable	-
(b) Boulder	>256 mm
(c) Cobble	>64-256 mm
(cg) Coarse Gravel	>16-64 mm
(mg) Medium Gravel	>4-16 mm
(fg) Fine Gravel	2-4 mm
(ff) Fines	< 2 mm

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
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Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

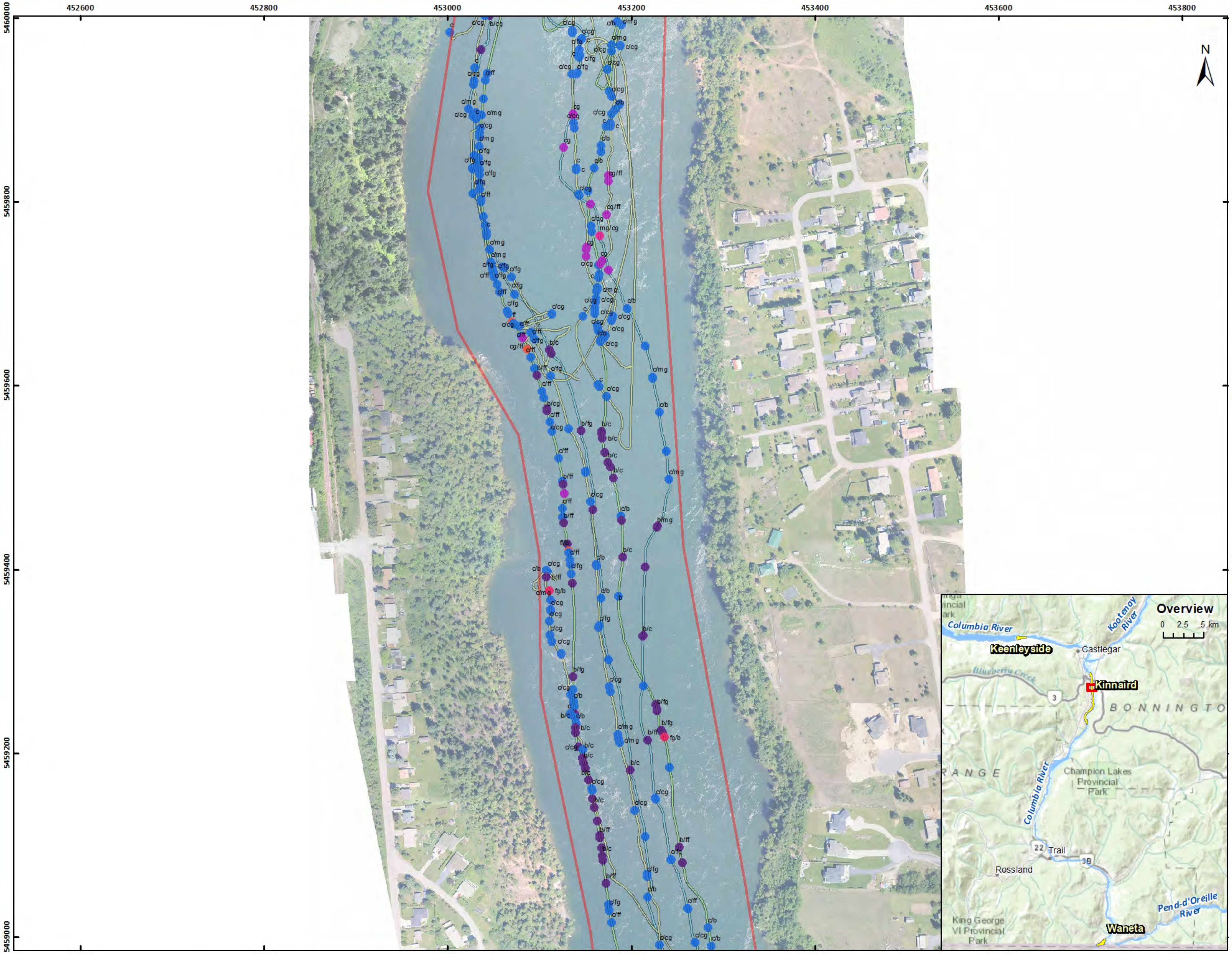
ECOFISH RESEARCH

Map C3

Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_Substrate_190404.mxd

CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Kinnaird - Upper
Substrate Type



Legend

Known Spawning Area

Dominant Substrate

- Impermeable
- Fines
- Fine Gravel
- Medium Gravel
- Coarse Gravel
- Cobble
- Boulder

Substrate Video Tracks

- Substrate Video (FT3 Nov)
- Substrate Video (FT2 Aug)
- Substrate Video (FT1 Jul)

Substrate Code	Size
(i) Impermeable	-
(b) Boulder	>256 mm
(c) Cobble	>64-256 mm
(cg) Coarse Gravel	>16-64 mm
(mg) Medium Gravel	>4-16 mm
(fg) Fine Gravel	2-4 mm
(ff) Fines	< 2 mm

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
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Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map C4

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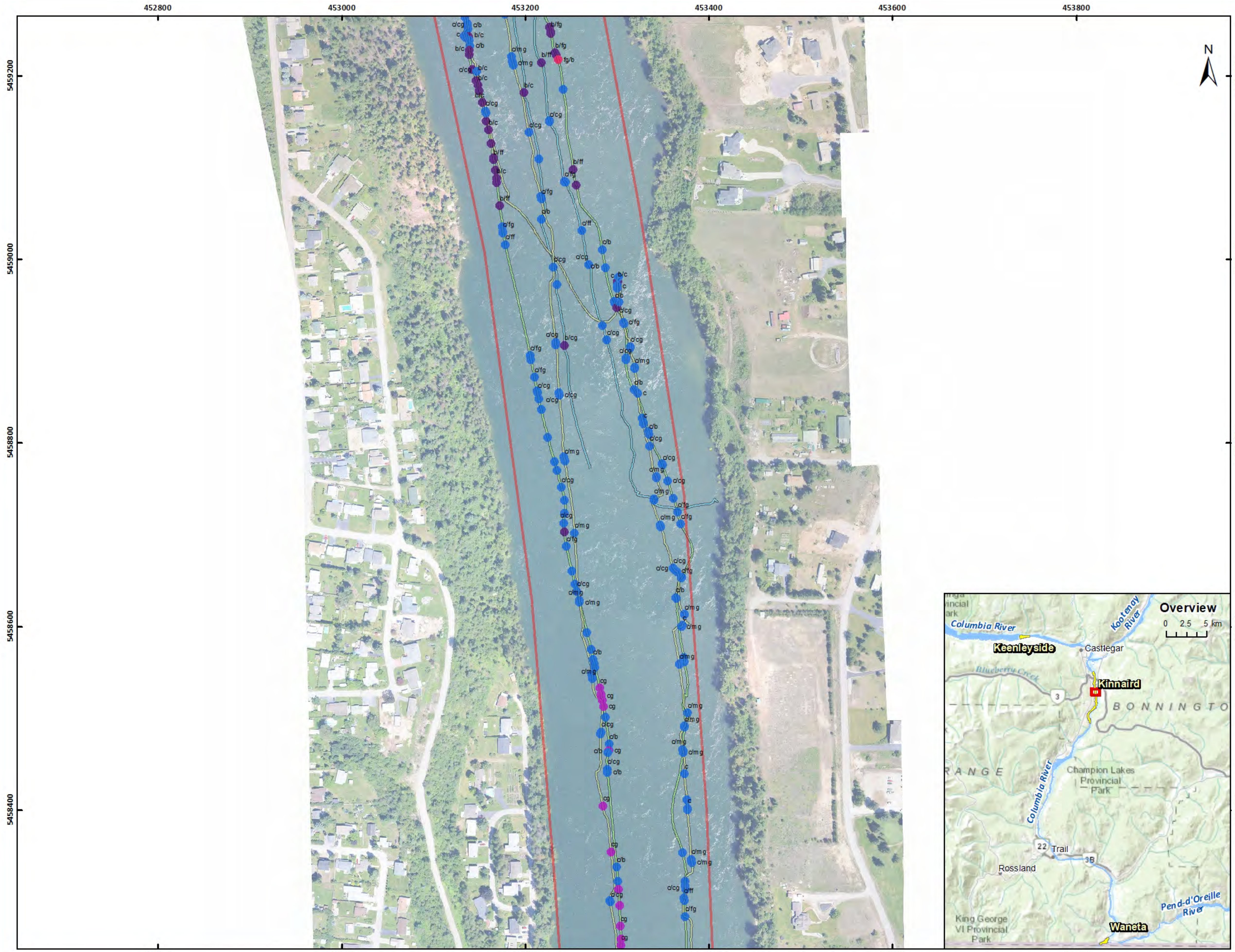

CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Kinnaird - Upper Substrate Type

Legend

Known Spawning Area

Dominant Substrate

- Impermeable
- Fines
- Fine Gravel
- Medium Gravel
- Coarse Gravel
- Cobble
- Boulder

Substrate Video Tracks

- Substrate Video (FT3 Nov)
- Substrate Video (FT2 Aug)
- Substrate Video (FT1 Jul)

Substrate Code	Size
(i) Impermeable	-
(b) Boulder	>256 mm
(c) Cobble	>64-256 mm
(cg) Coarse Gravel	>16-64 mm
(mg) Medium Gravel	>4-16 mm
(fg) Fine Gravel	2-4 mm
(ff) Fines	< 2 mm

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
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Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map C5

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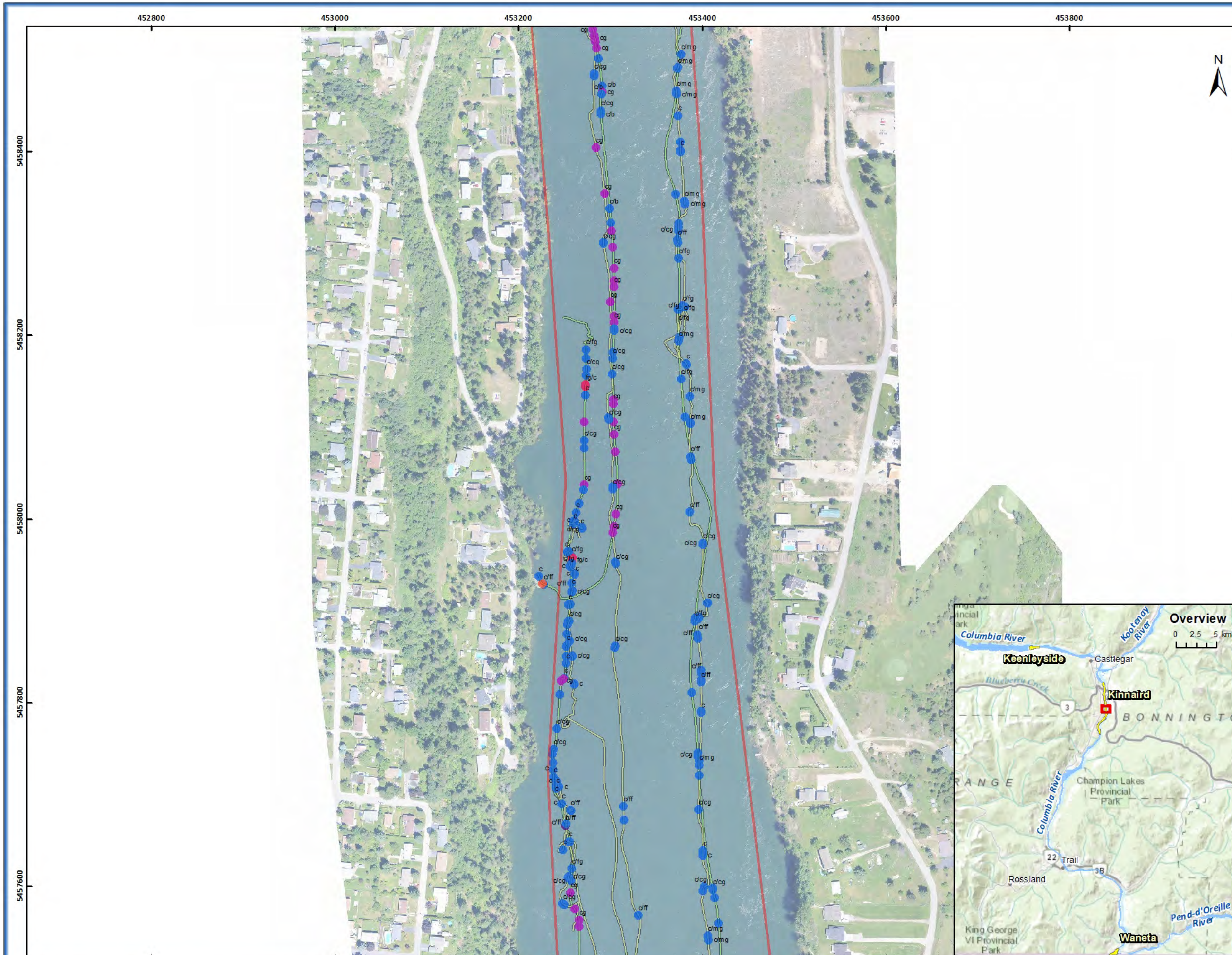

CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Kinnaird - Upper
Substrate Type

Legend

Known Spawning Area

Dominant Substrate

- Impermeable
- Fines
- Fine Gravel
- Medium Gravel
- Coarse Gravel
- Cobble
- Boulder

Substrate Video Tracks

- Substrate Video (FT3 Nov)
- Substrate Video (FT2 Aug)
- Substrate Video (FT1 Jul)

Substrate Code	Size
(i) Impermeable	-
(b) Boulder	>256 mm
(c) Cobble	>64-256 mm
(cg) Coarse Gravel	>16-64 mm
(mg) Medium Gravel	>4-16 mm
(fg) Fine Gravel	2-4 mm
(ff) Fines	< 2 mm

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m
Scale: 1:4,000

NO.	DATE	REVISION	BY
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3			
4			
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Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map C7

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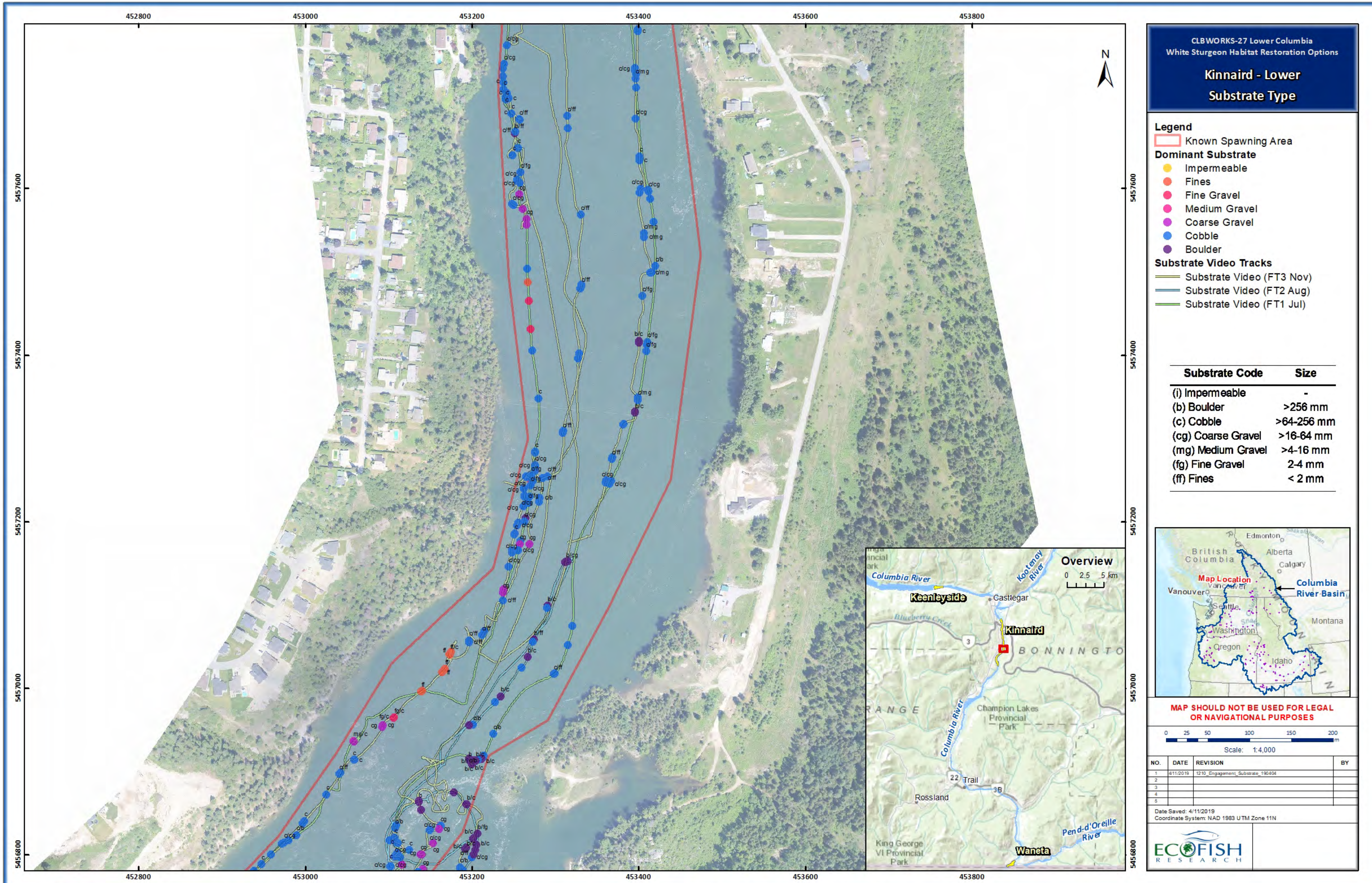

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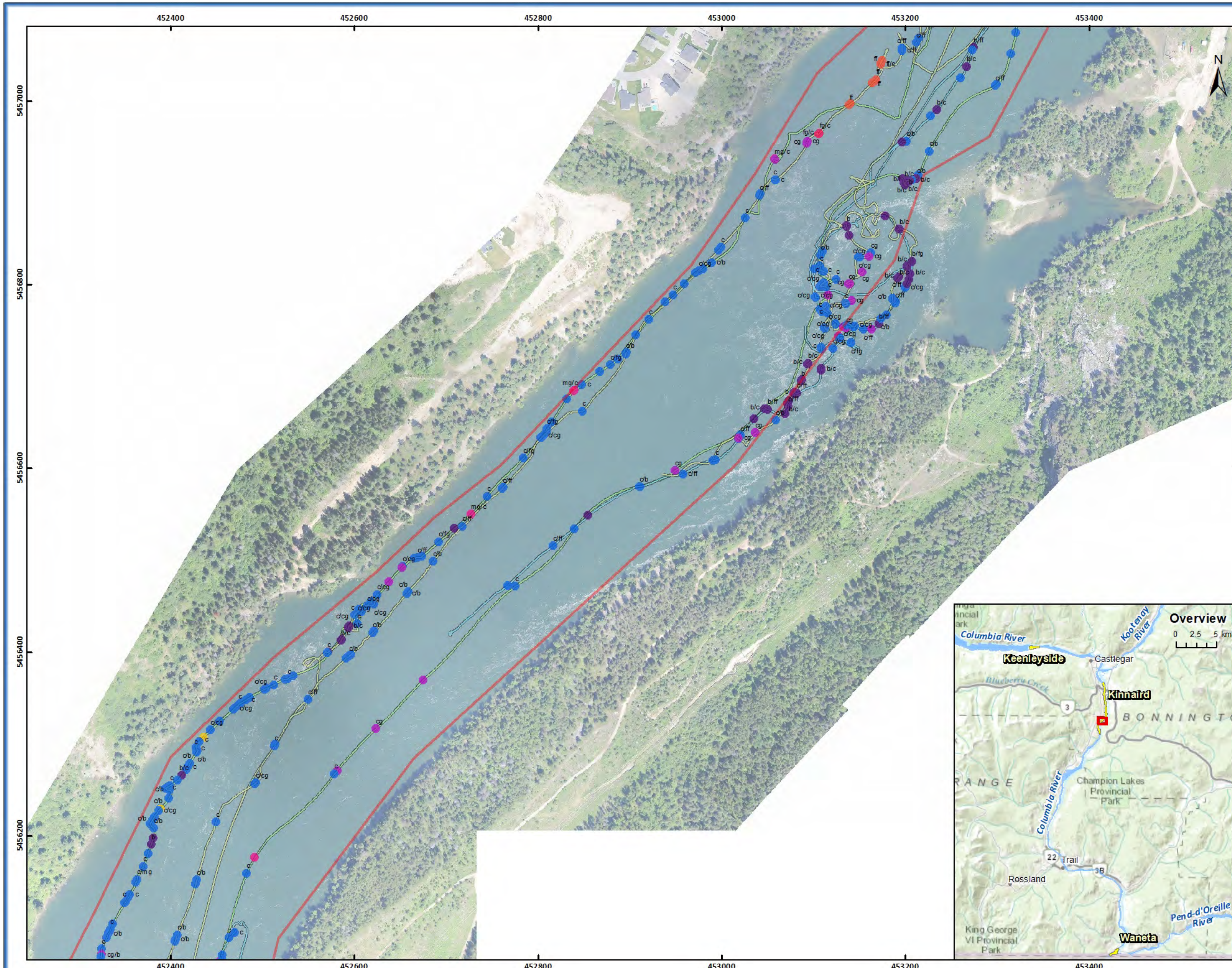

CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Kinnaird - Lower Substrate Type

Legend

Known Spawning Area

Dominant Substrate

- Impermeable
- Fines
- Fine Gravel
- Medium Gravel
- Coarse Gravel
- Cobble
- Boulder

Substrate Video Tracks

- Substrate Video (FT3 Nov)
- Substrate Video (FT2 Aug)
- Substrate Video (FT1 Jul)

Substrate Code	Size
(i) Impermeable	-
(b) Boulder	>256 mm
(c) Cobble	>64-256 mm
(cg) Coarse Gravel	>16-64 mm
(mg) Medium Gravel	>4-16 mm
(fg) Fine Gravel	2-4 mm
(ff) Fines	< 2 mm

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
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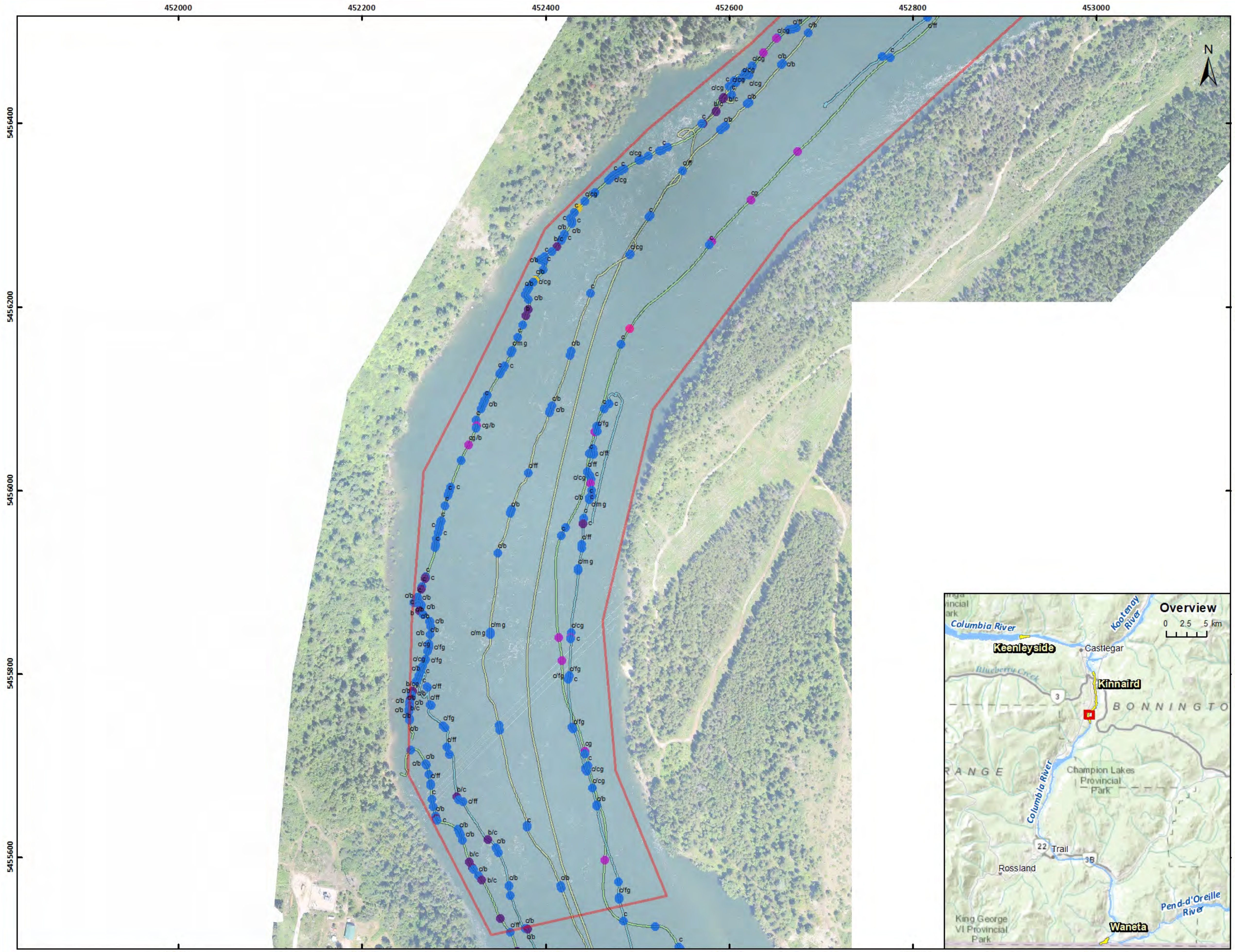
Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map C8

Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_Substrate_190404.mxd



CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Kinnaird - Lower

Substrate Type

Legend

Known Spawning Area

Dominant Substrate

- Impermeable
- Fines
- Fine Gravel
- Medium Gravel
- Coarse Gravel
- Cobble
- Boulder

Substrate Video Tracks

- Substrate Video (FT3 Nov)
- Substrate Video (FT2 Aug)
- Substrate Video (FT1 Jul)

Substrate Code	Size
(i) Impermeable	-
(b) Boulder	>256 mm
(c) Cobble	>64-256 mm
(cg) Coarse Gravel	>16-64 mm
(mg) Medium Gravel	>4-16 mm
(fg) Fine Gravel	2-4 mm
(ff) Fines	< 2 mm

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
1	4/11/2019	1210_Engagement_Substrate_190404	
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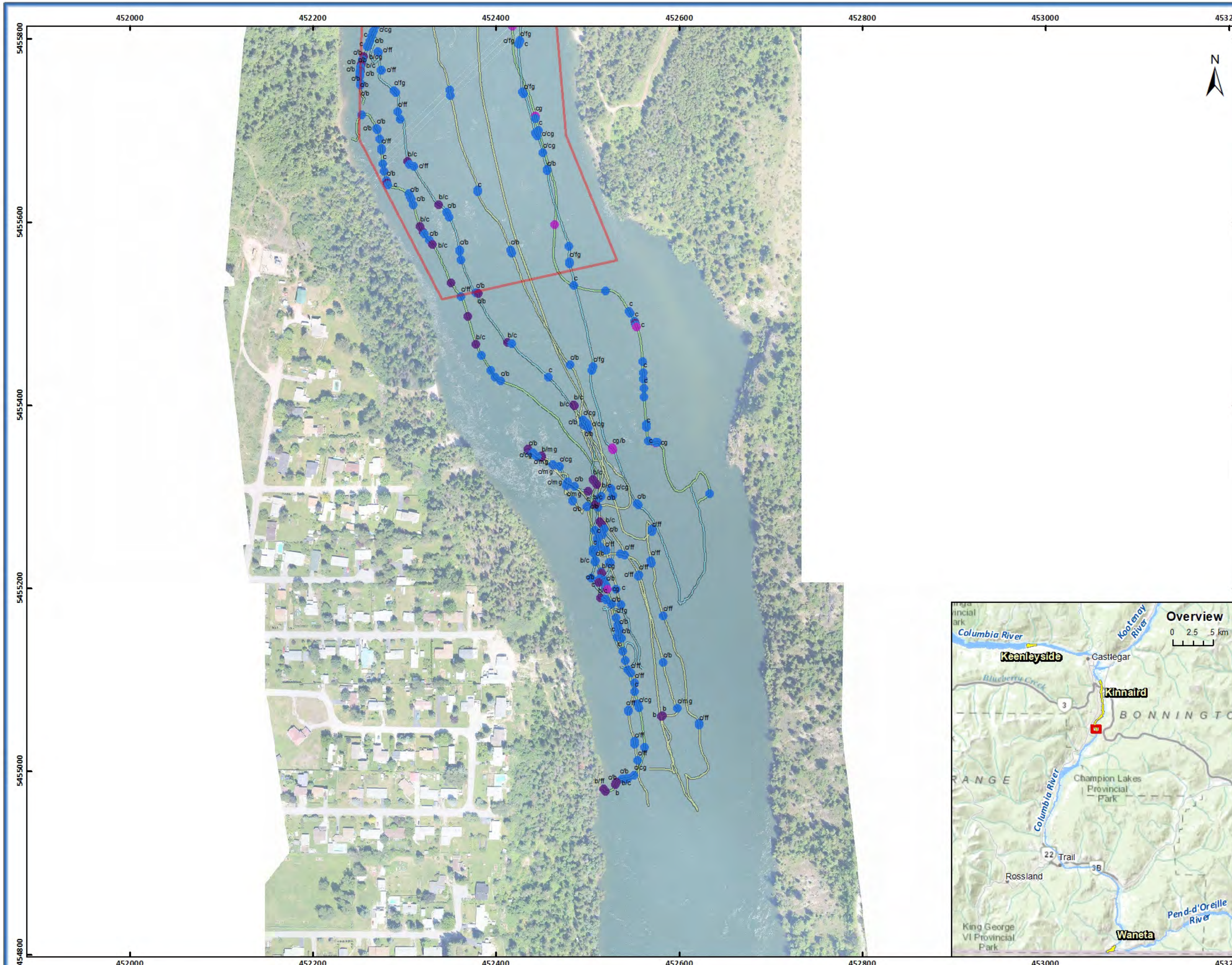
Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map C9

Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_Substrate_190404.mxd



CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Kinnaird - Lower Substrate Type

Legend

Known Spawning Area

Dominant Substrate

- Impermeable
- Fines
- Fine Gravel
- Medium Gravel
- Coarse Gravel
- Cobble
- Boulder

Substrate Video Tracks

- Substrate Video (FT3 Nov)
- Substrate Video (FT2 Aug)
- Substrate Video (FT1 Jul)

Substrate Code	Size
(i) Impermeable	-
(b) Boulder	>256 mm
(c) Cobble	>64-256 mm
(cg) Coarse Gravel	>16-64 mm
(mg) Medium Gravel	>4-16 mm
(fg) Fine Gravel	2-4 mm
(ff) Fines	< 2 mm

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
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Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map C10

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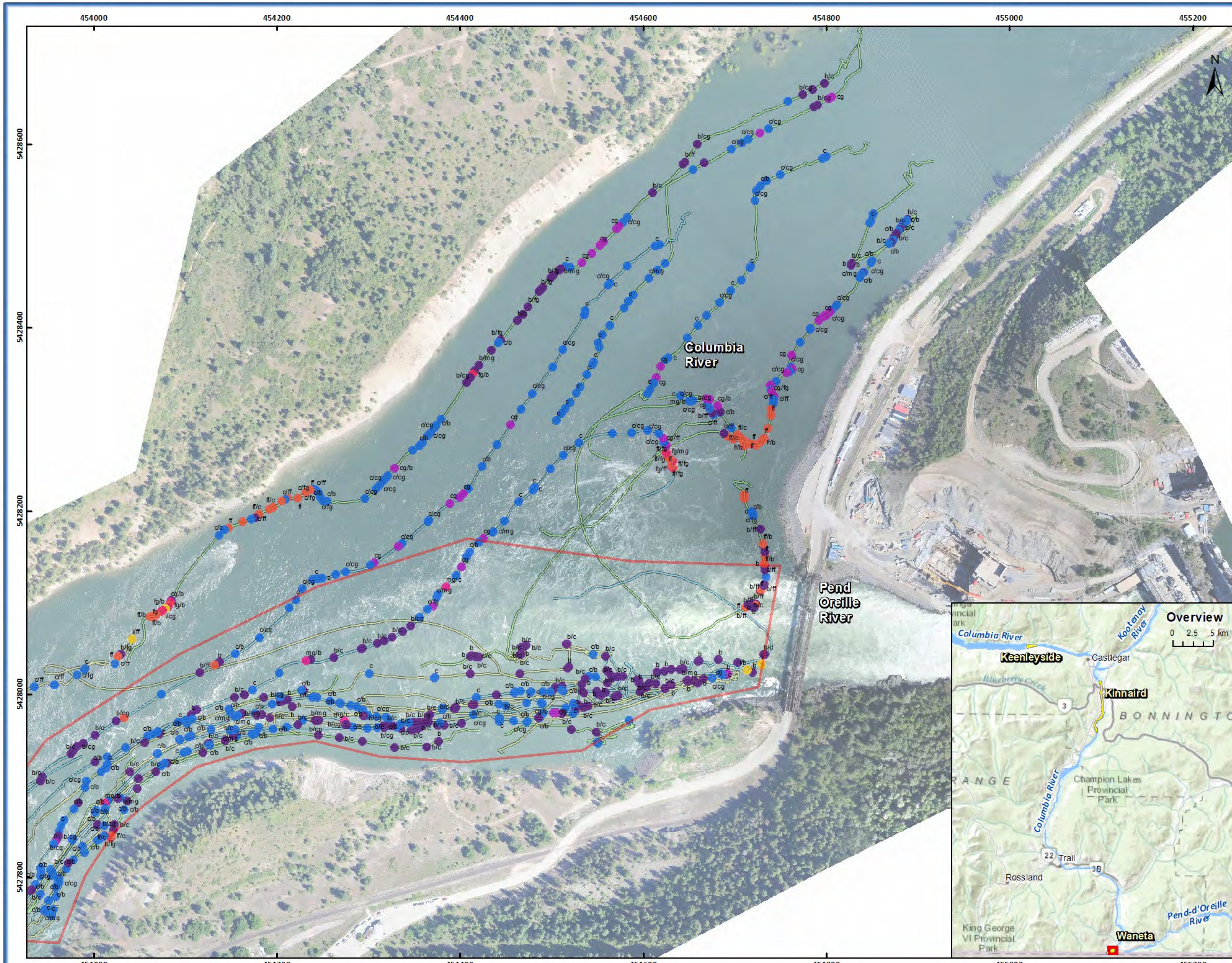

CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Waneta Substrate Type

Legend

Known Spawning Area

Dominant Substrate

- Impermeable
- Fines
- Fine Gravel
- Medium Gravel
- Coarse Gravel
- Cobble
- Boulder

Substrate Video Tracks

- Substrate Video (FT3 Nov)
- Substrate Video (FT2 Aug)
- Substrate Video (FT1 Jul)

Substrate Code	Size
(i) Impermeable	-
(b) Boulder	>256 mm
(c) Cobble	>64-256 mm
(cg) Coarse Gravel	>16-64 mm
(mg) Medium Gravel	>4-16 mm
(fg) Fine Gravel	2-4 mm
(ff) Fines	< 2 mm

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

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Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map C11

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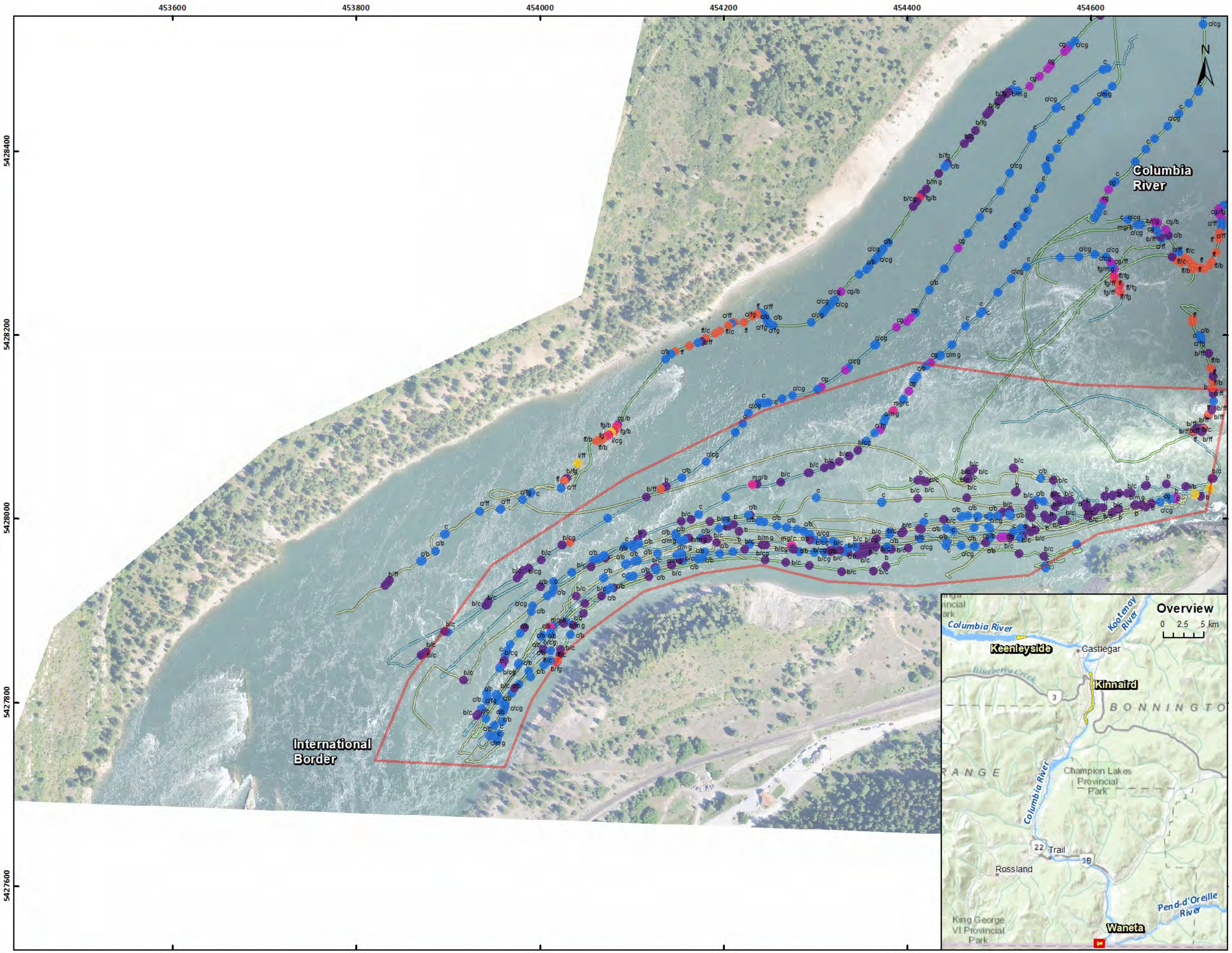

CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Waneta
Substrate Type

Legend

- Known Spawning Area

Dominant Substrate

- Impermeable
- Fines
- Fine Gravel
- Medium Gravel
- Coarse Gravel
- Cobble
- Boulder

Substrate Video Tracks

- Substrate Video (FT3 Nov)
- Substrate Video (FT2 Aug)
- Substrate Video (FT1 Jul)

Substrate Code	Size
(i) Impermeable	-
(b) Boulder	>256 mm
(c) Cobble	>64-256 mm
(cg) Coarse Gravel	>16-64 mm
(mg) Medium Gravel	>4-16 mm
(fg) Fine Gravel	2-4 mm
(ff) Fines	< 2 mm

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

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Scale: 1:4,000

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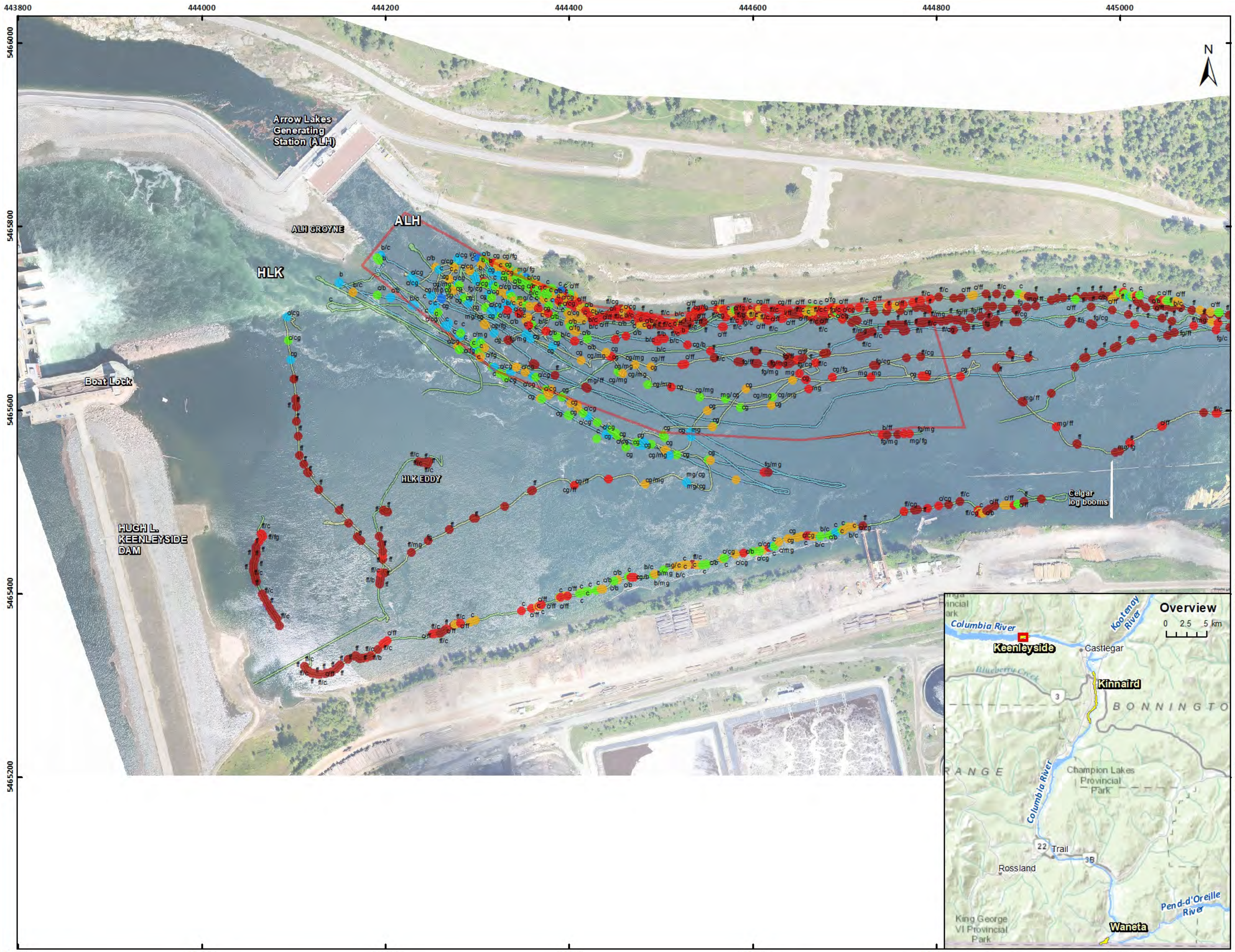
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map C12

Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_Substrate_190404.mxd

Appendix D. Embeddedness classifications



CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Keenleyside Substrate Embeddedness

Legend

Known Spawning Area

Substrate Embeddedness

- e0 (<5%)
- e1 (6-25%)
- e2 (26-50%)
- e3 (51-75%)
- e4 (>75%)
- e5 (Fines)

Substrate Video Tracks

- Substrate Video (FT3 Nov)
- Substrate Video (FT2 Aug)
- Substrate Video (FT1 Jul)

Substrate Code	Size
(i) Impermeable	-
(b) Boulder	>256 mm
(c) Cobble	>64-256 mm
(cg) Coarse Gravel	>16-64 mm
(mg) Medium Gravel	>4-16 mm
(fg) Fine Gravel	2-4 mm
(ff) Fines	< 2 mm

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

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Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map D1

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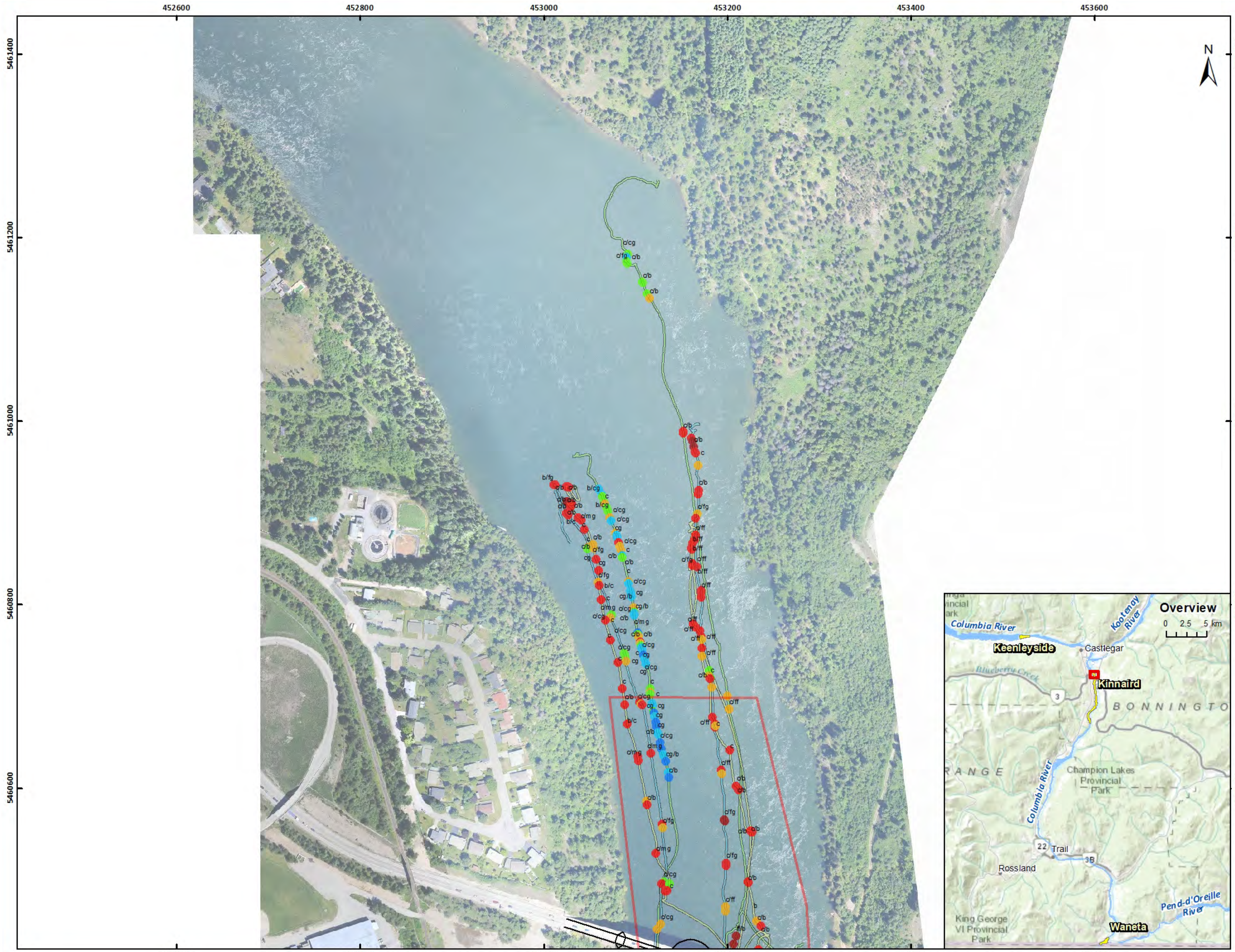

CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Kinnaird - Upper Substrate Embeddedness

Legend

Known Spawning Area

Substrate Embeddedness

- e0 (<5%)
- e1 (6-25%)
- e2 (26-50%)
- e3 (51-75%)
- e4 (>75%)
- e5 (Fines)

Substrate Video Tracks

- Substrate Video (FT3 Nov)
- Substrate Video (FT2 Aug)
- Substrate Video (FT1 Jul)

Substrate Code	Size
(i) Impermeable	-
(b) Boulder	>256 mm
(c) Cobble	>64-256 mm
(cg) Coarse Gravel	>16-64 mm
(mg) Medium Gravel	>4-16 mm
(fg) Fine Gravel	2-4 mm
(ff) Fines	< 2 mm

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

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Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map D2

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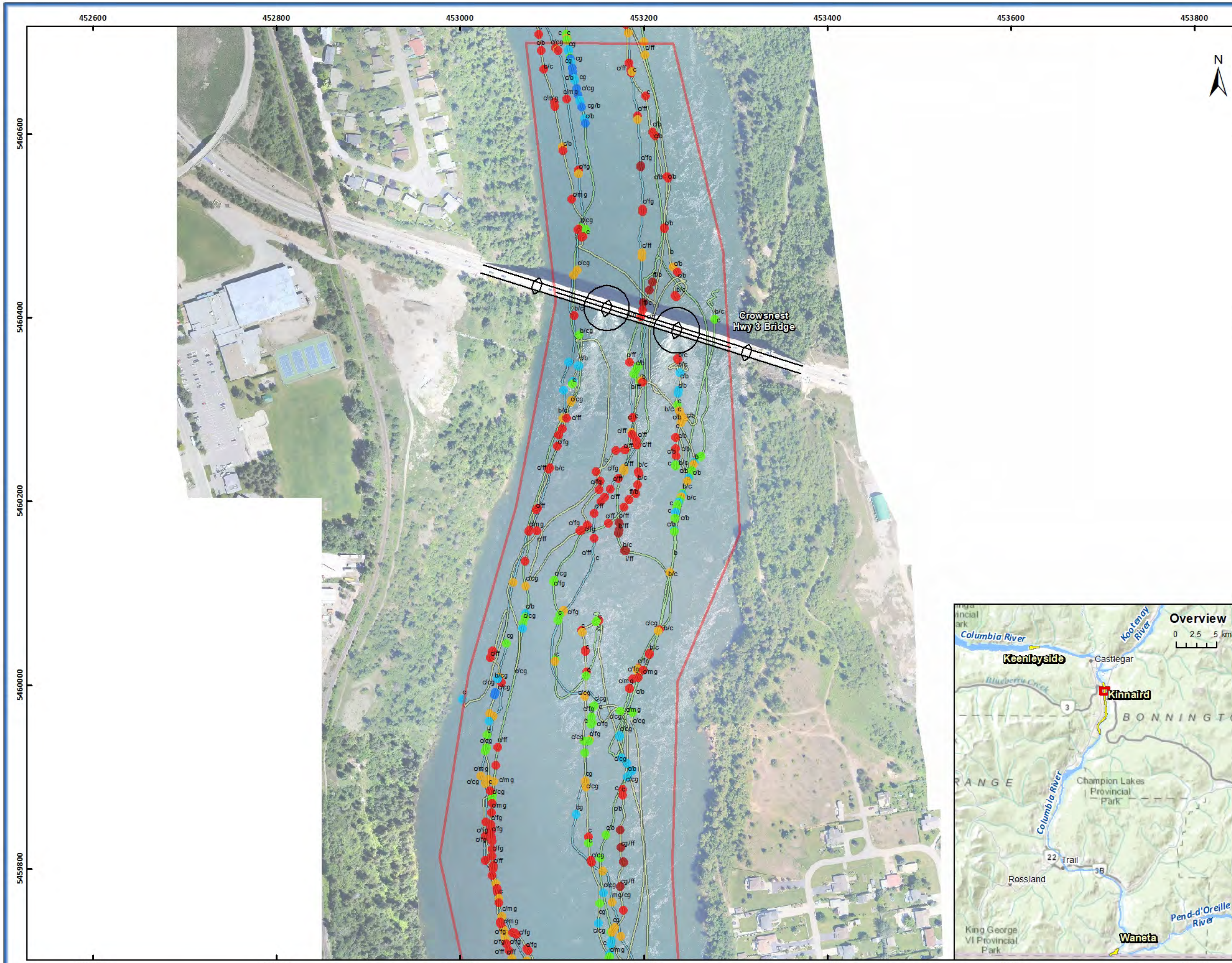

CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Kinnaird - Upper
Substrate Embeddedness

Legend

Known Spawning Area

Substrate Embeddedness

- e0 (<5%)
- e1 (6-25%)
- e2 (26-50%)
- e3 (51-75%)
- e4 (>75%)
- e5 (Fines)

Substrate Video Tracks

- Substrate Video (FT3 Nov)
- Substrate Video (FT2 Aug)
- Substrate Video (FT1 Jul)

Substrate Code	Size
(i) Impermeable	-
(b) Boulder	>256 mm
(c) Cobble	>64-256 mm
(cg) Coarse Gravel	>16-64 mm
(mg) Medium Gravel	>4-16 mm
(fg) Fine Gravel	2-4 mm
(ff) Fines	< 2 mm

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
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Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map D3

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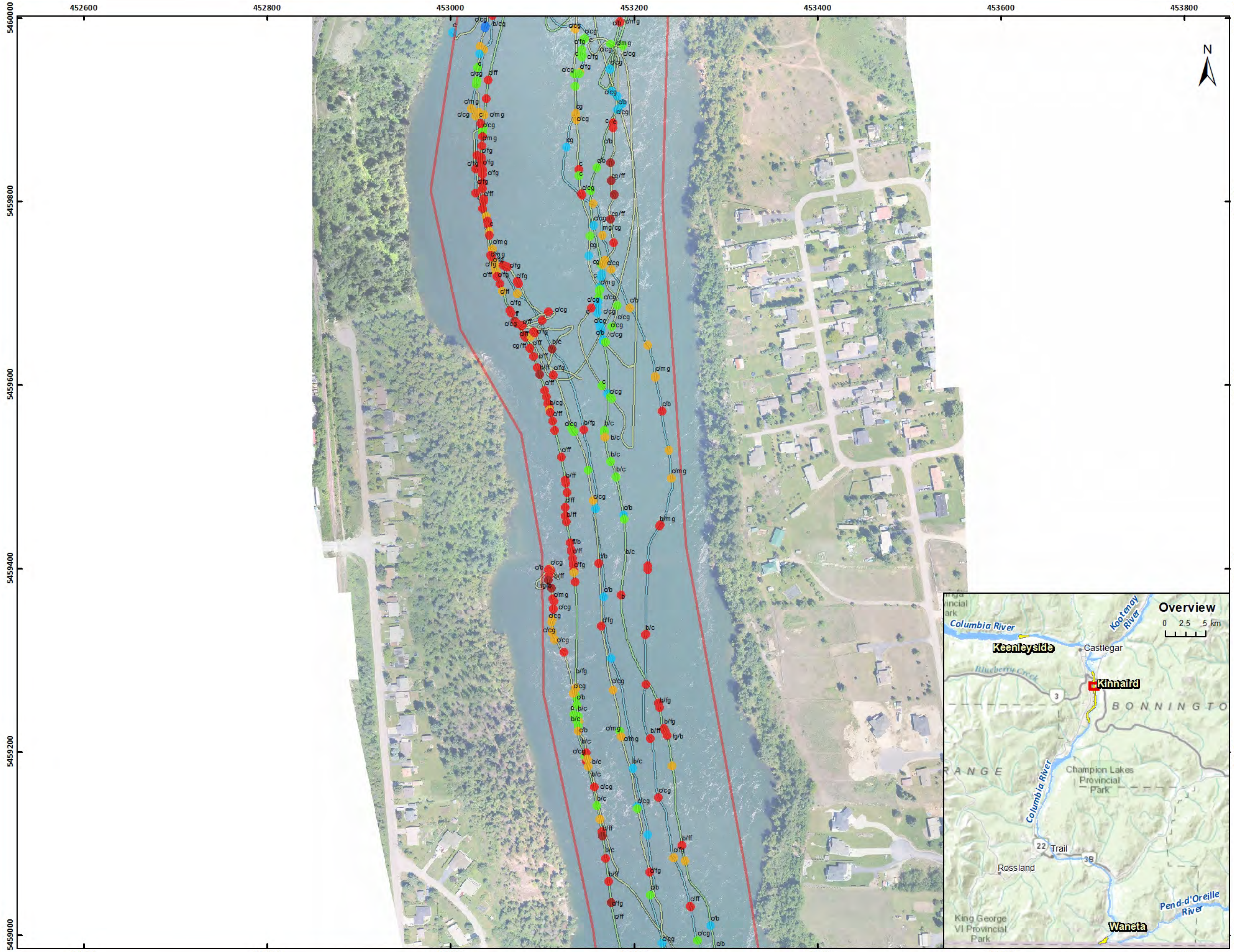

CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Kinnaird - Upper Substrate Embeddedness

Legend

Known Spawning Area

Substrate Embeddedness

- e0 (<5%)
- e1 (6-25%)
- e2 (26-50%)
- e3 (51-75%)
- e4 (>75%)
- e5 (Fines)

Substrate Video Tracks

- Substrate Video (FT3 Nov)
- Substrate Video (FT2 Aug)
- Substrate Video (FT1 Jul)

Substrate Code	Size
(i) Impermeable	-
(b) Boulder	>256 mm
(c) Cobble	>64-256 mm
(cg) Coarse Gravel	>16-64 mm
(mg) Medium Gravel	>4-16 mm
(fg) Fine Gravel	2-4 mm
(ff) Fines	< 2 mm

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
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Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map D4

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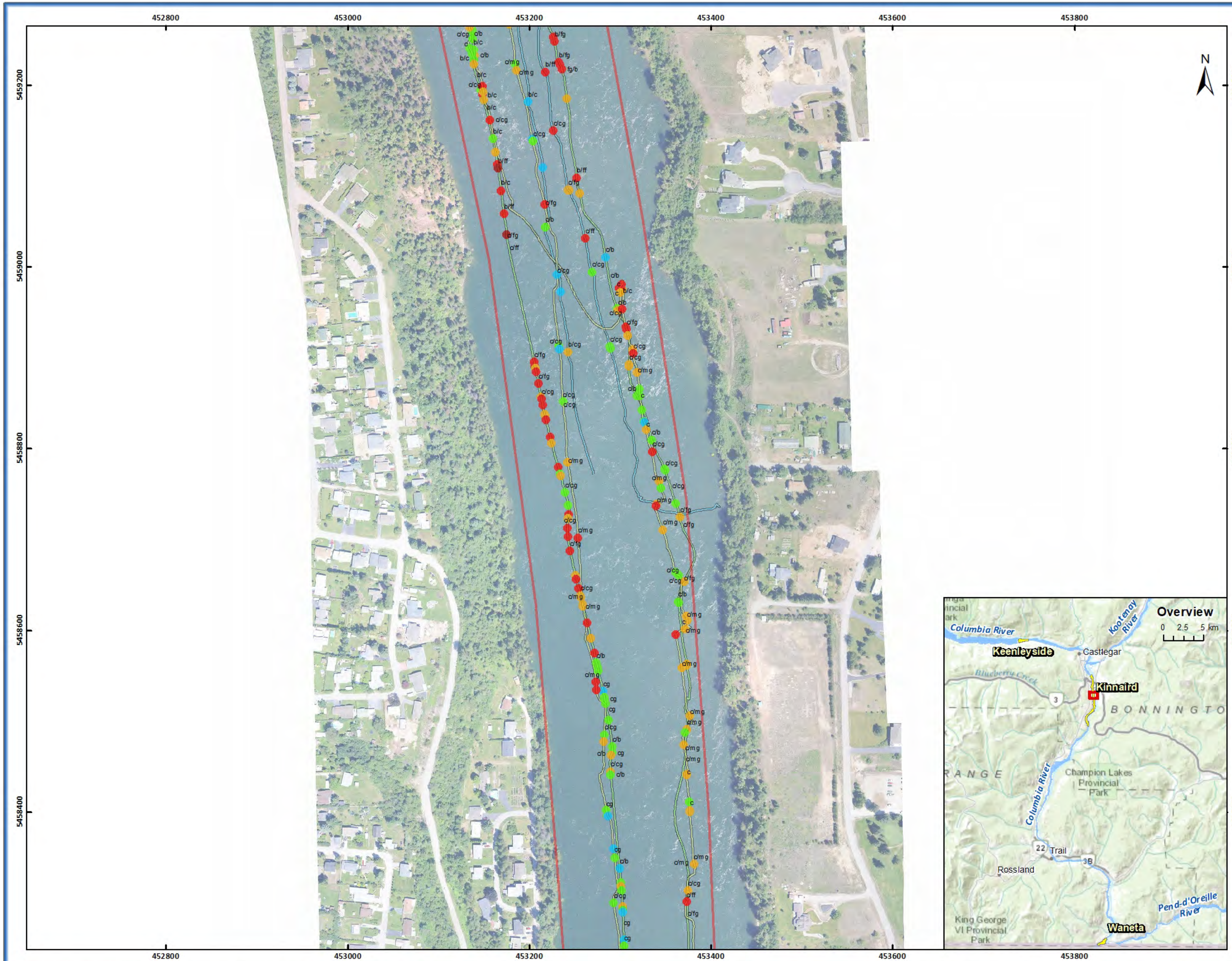

CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Kinnaird - Upper
Substrate Embeddedness

Legend

Known Spawning Area

Substrate Embeddedness

- e0 (<5%)
- e1 (6-25%)
- e2 (26-50%)
- e3 (51-75%)
- e4 (>75%)
- e5 (Fines)

Substrate Video Tracks

- Substrate Video (FT3 Nov)
- Substrate Video (FT2 Aug)
- Substrate Video (FT1 Jul)

Substrate Code	Size
(i) Impermeable	-
(b) Boulder	>256 mm
(c) Cobble	>64-256 mm
(cg) Coarse Gravel	>16-64 mm
(mg) Medium Gravel	>4-16 mm
(fg) Fine Gravel	2-4 mm
(ff) Fines	< 2 mm

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
1	4/11/2019	1210_Engagement_Embeddedness_190404	
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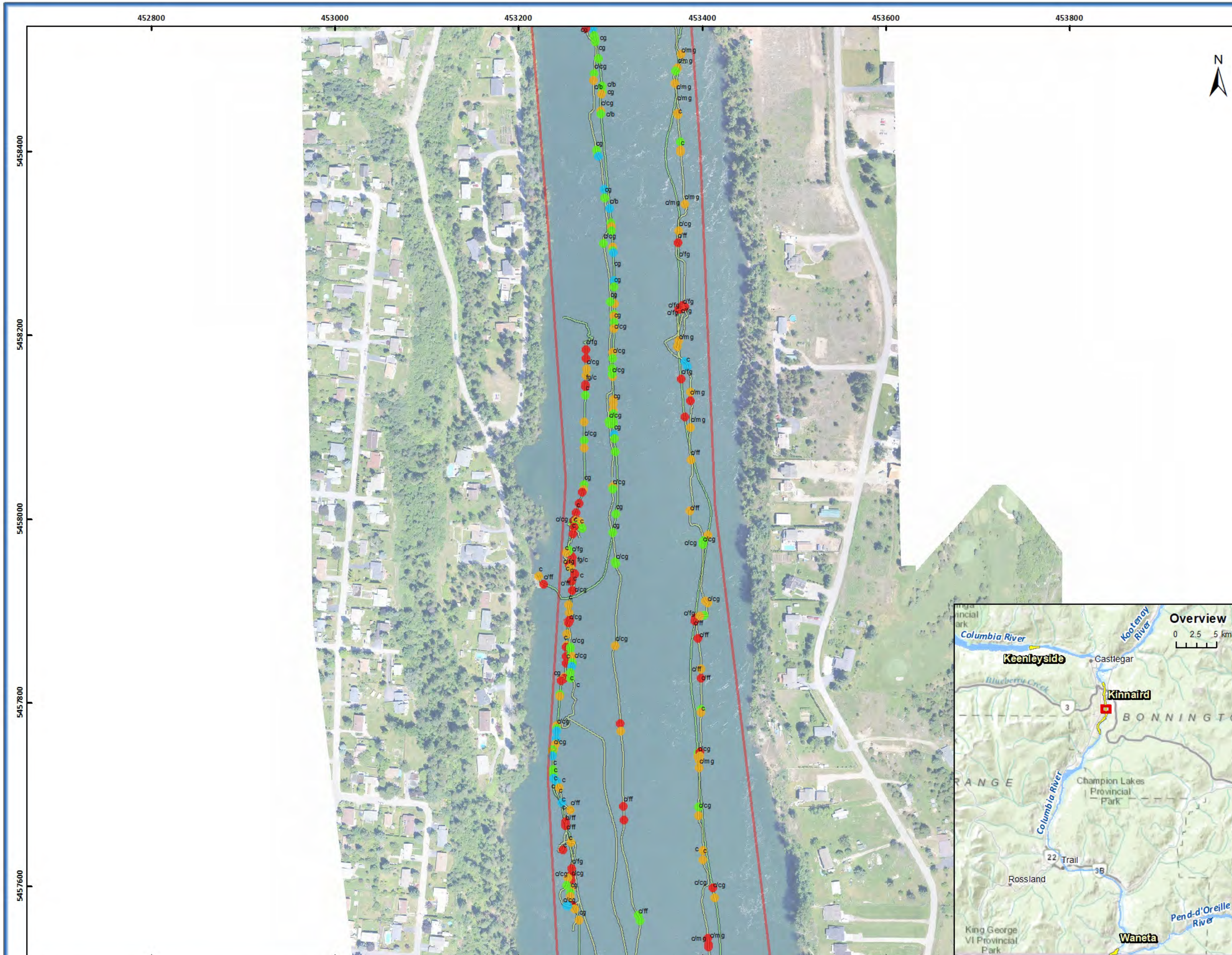
Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map D5

Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_Embeddedness_190404.mxd



CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Kinnaird - Upper
Substrate Embeddedness

Legend

Known Spawning Area

Substrate Embeddedness

- e0 (<5%)
- e1 (6-25%)
- e2 (26-50%)
- e3 (51-75%)
- e4 (>75%)
- e5 (Fines)

Substrate Video Tracks

- Substrate Video (FT3 Nov)
- Substrate Video (FT2 Aug)
- Substrate Video (FT1 Jul)

Substrate Code	Size
(i) Impermeable	-
(b) Boulder	>256 mm
(c) Cobble	>64-256 mm
(cg) Coarse Gravel	>16-64 mm
(mg) Medium Gravel	>4-16 mm
(fg) Fine Gravel	2-4 mm
(ff) Fines	< 2 mm

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

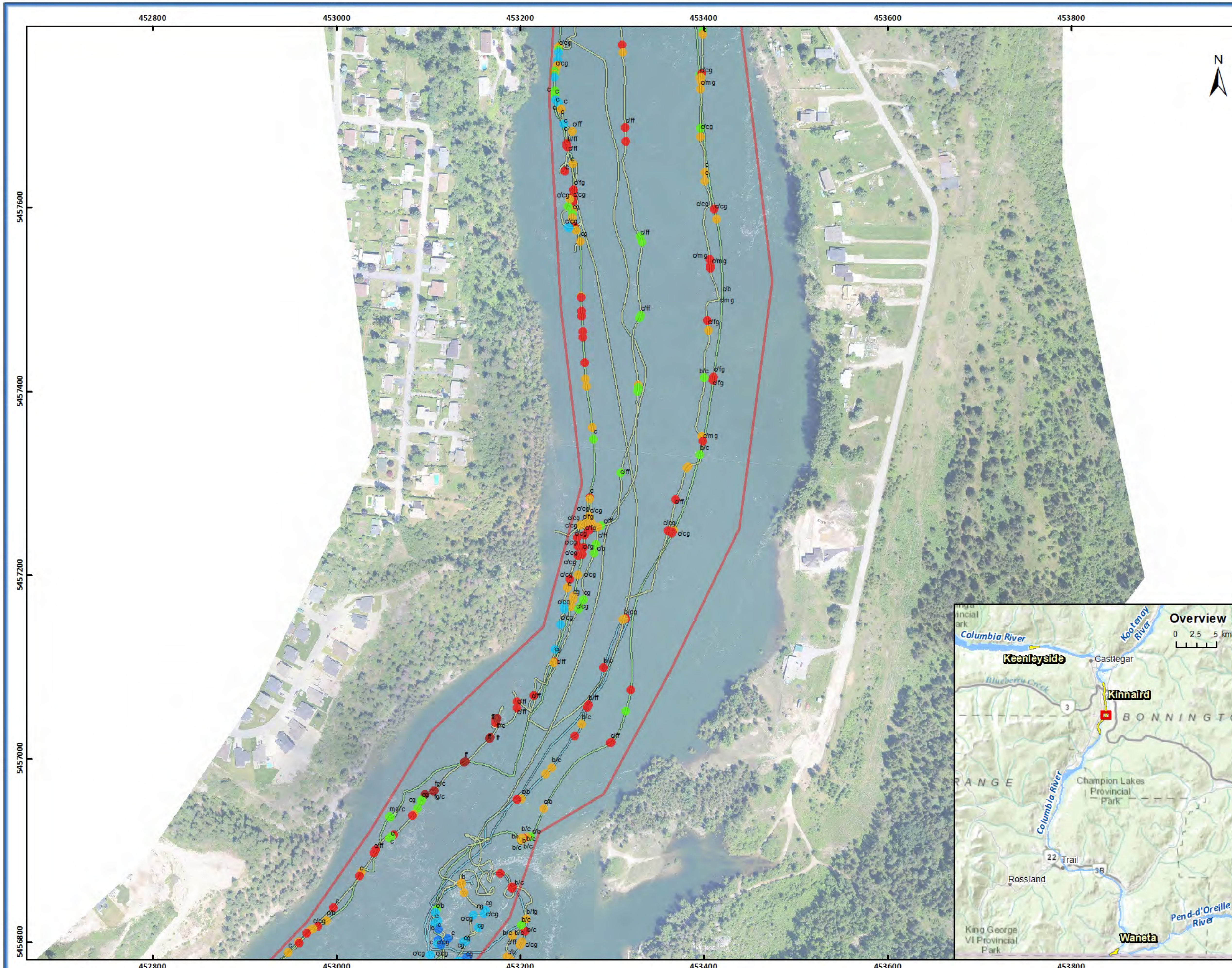
NO.	DATE	REVISION	BY
1	4/11/2019	1210_Engagement_Embeddedness_190404	
2			
3			
4			
5			

Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map D6

Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_Embeddedness_190404.mxd



CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Kinnaird - Lower
Substrate Embeddedness

Legend

Known Spawning Area

Substrate Embeddedness

- e0 (<5%)
- e1 (6-25%)
- e2 (26-50%)
- e3 (51-75%)
- e4 (>75%)
- e5 (Fines)

Substrate Video Tracks

- Substrate Video (FT3 Nov)
- Substrate Video (FT2 Aug)
- Substrate Video (FT1 Jul)

Substrate Code	Size
(i) Impermeable	-
(b) Boulder	>256 mm
(c) Cobble	>64-256 mm
(cg) Coarse Gravel	>16-64 mm
(mg) Medium Gravel	>4-16 mm
(fg) Fine Gravel	2-4 mm
(ff) Fines	< 2 mm

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

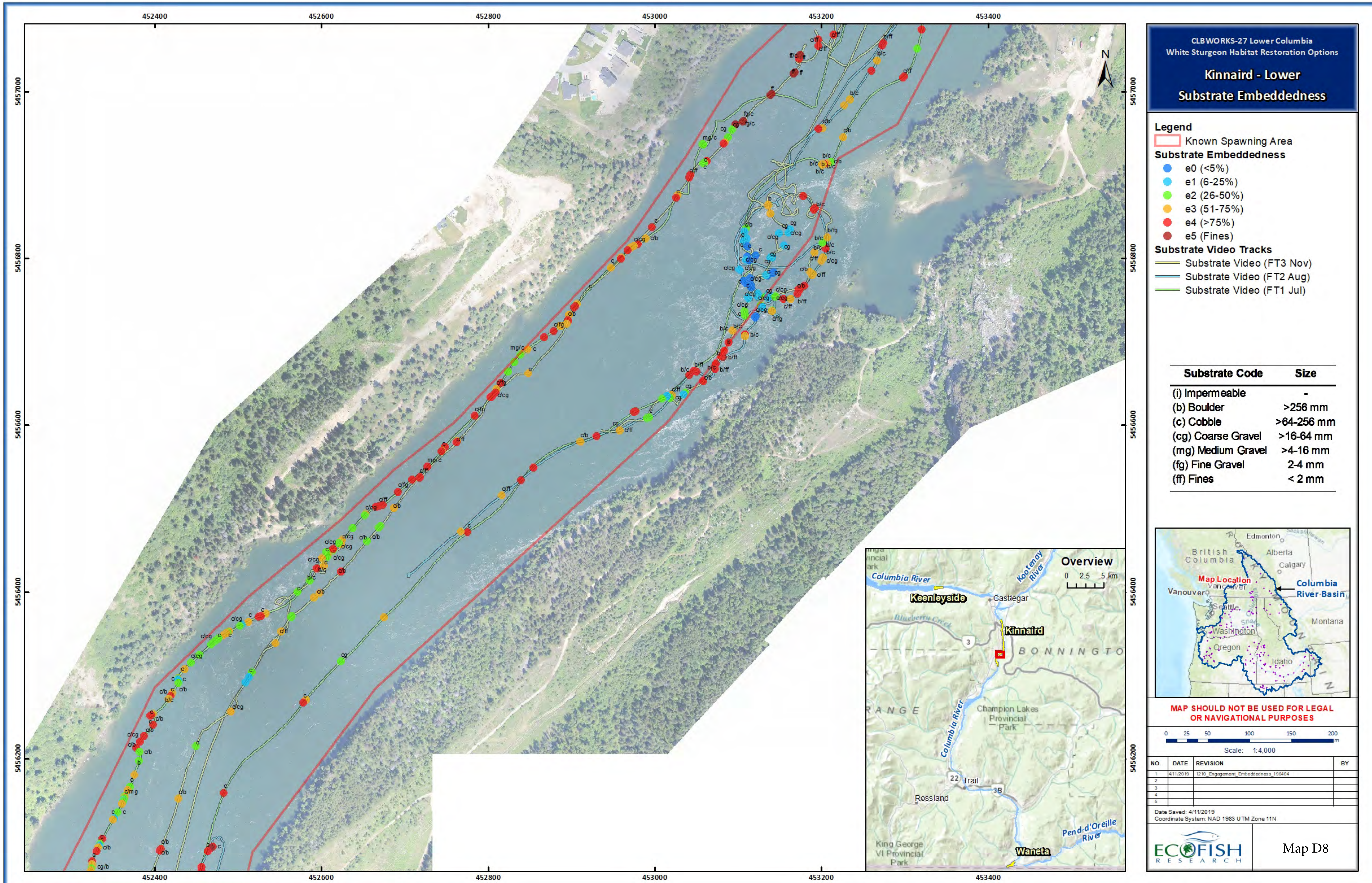
NO.	DATE	REVISION	BY
1	4/11/2019	1210_Engagement_Embeddedness_190404	
2			
3			
4			
5			

Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map D7

Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_Embeddedness_190404.mxd



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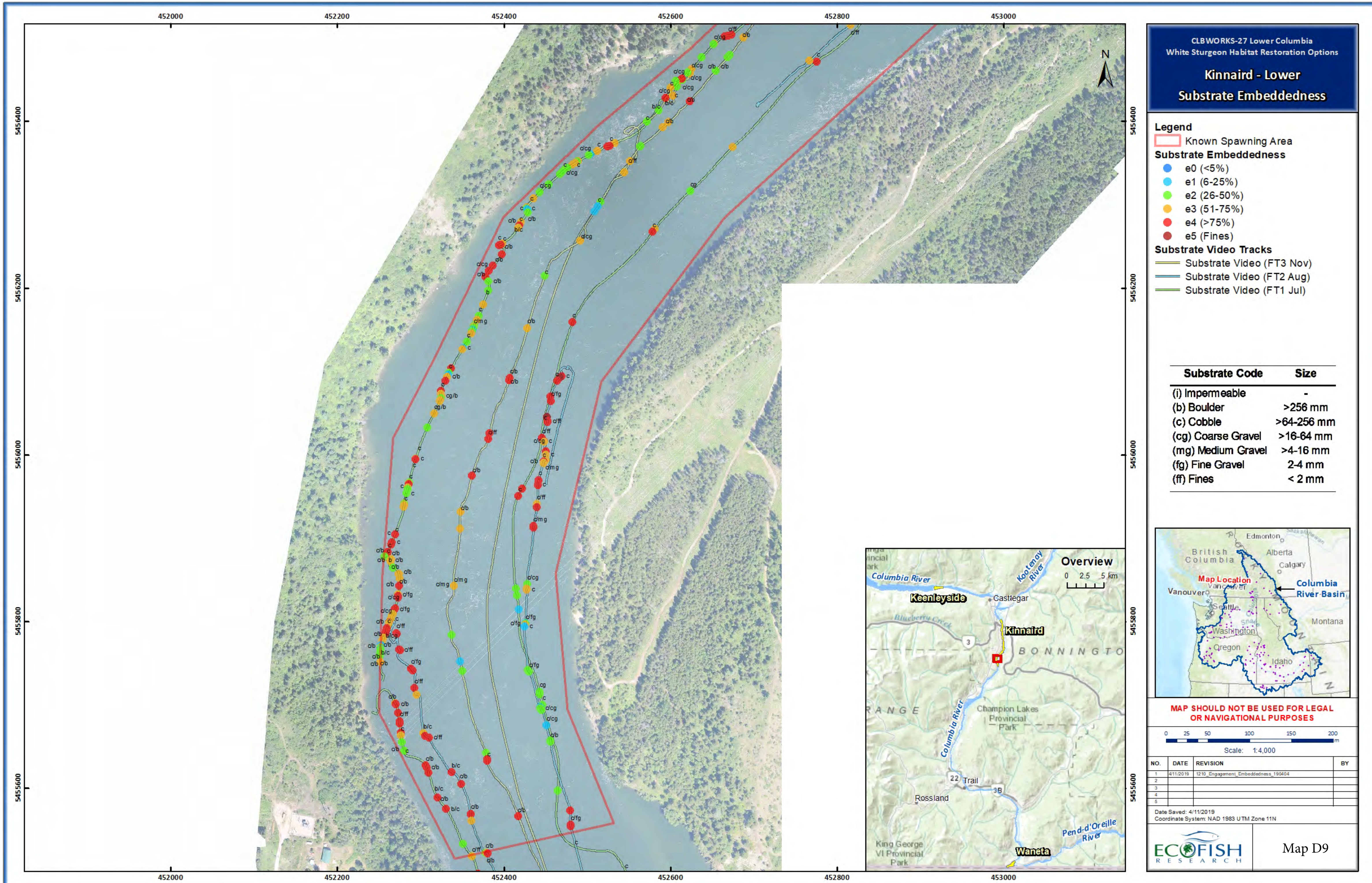

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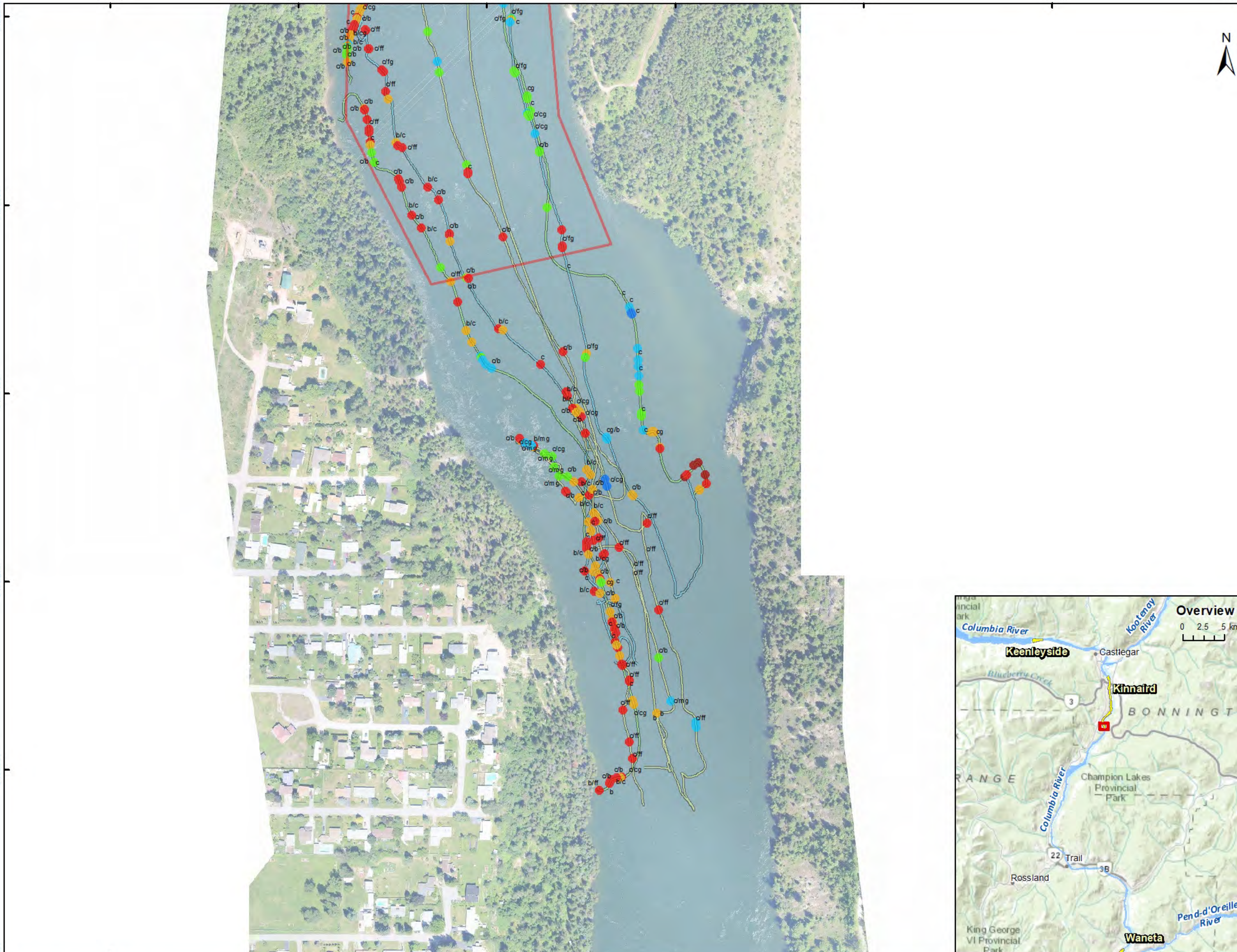


CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Kinnaird - Lower Substrate Embeddedness

Legend

Known Spawning Area

Substrate Embeddedness

- e0 (<5%)
- e1 (6-25%)
- e2 (26-50%)
- e3 (51-75%)
- e4 (>75%)
- e5 (Fines)

Substrate Video Tracks

- Substrate Video (FT3 Nov)
- Substrate Video (FT2 Aug)
- Substrate Video (FT1 Jul)

Substrate Code	Size
(i) Impermeable	-
(b) Boulder	>256 mm
(c) Cobble	>64-256 mm
(cg) Coarse Gravel	>16-64 mm
(mg) Medium Gravel	>4-16 mm
(fg) Fine Gravel	2-4 mm
(ff) Fines	< 2 mm

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

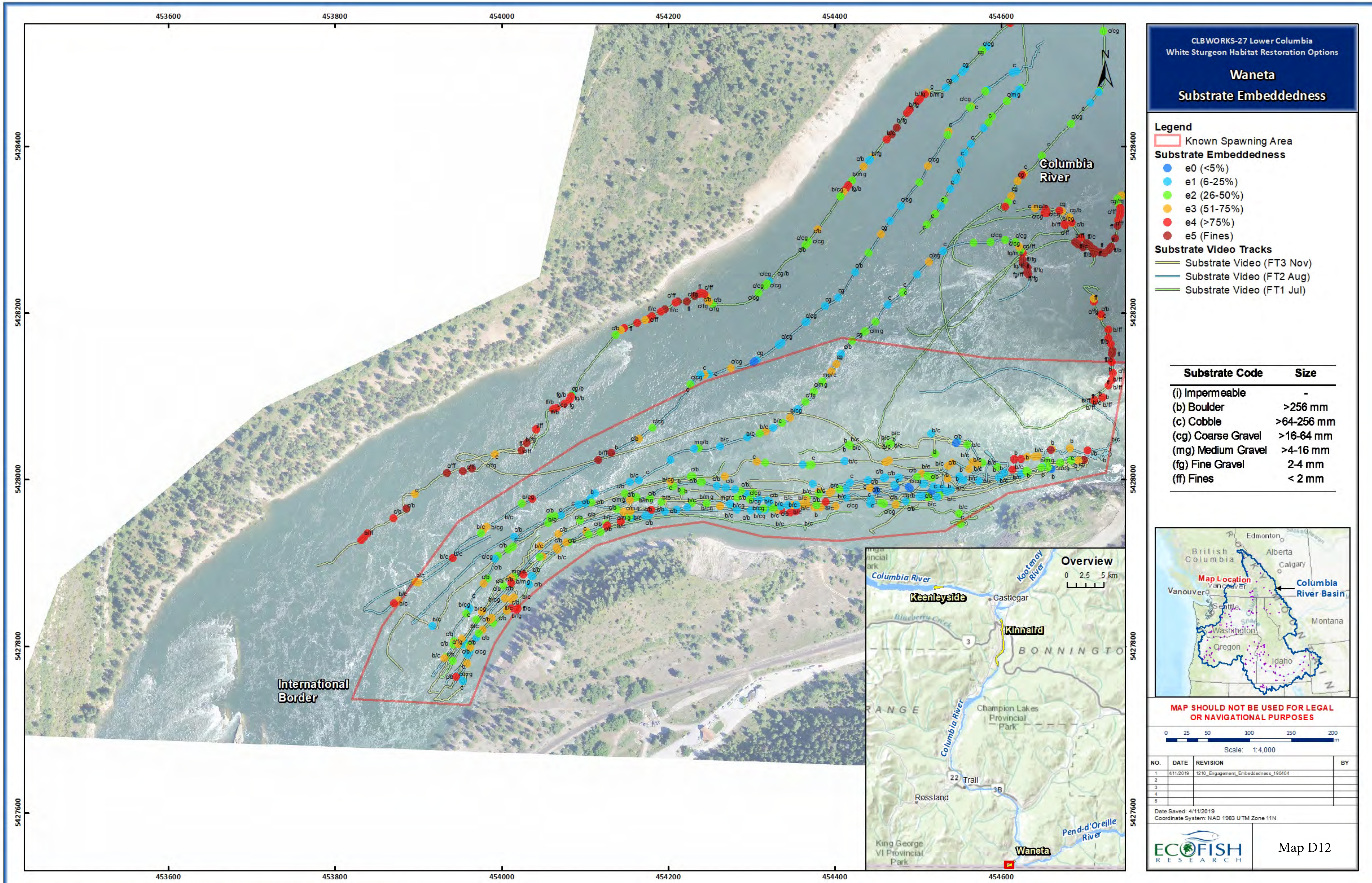
NO.	DATE	REVISION	BY
1	4/11/2019	1210_Engagement_Embeddedness_190404	
2			
3			
4			
5			

Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map D10

Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_Embeddedness_190404.mxd



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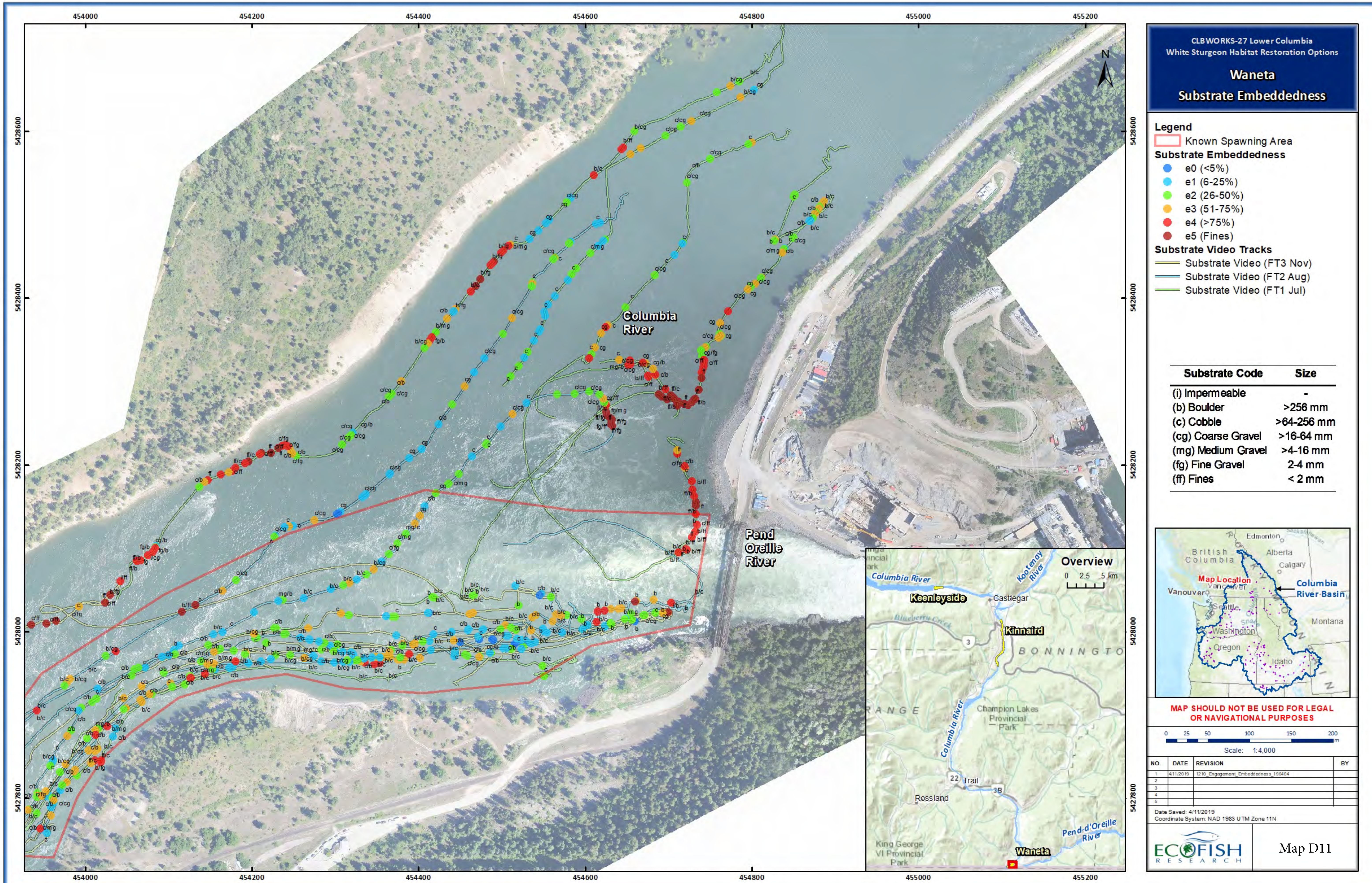
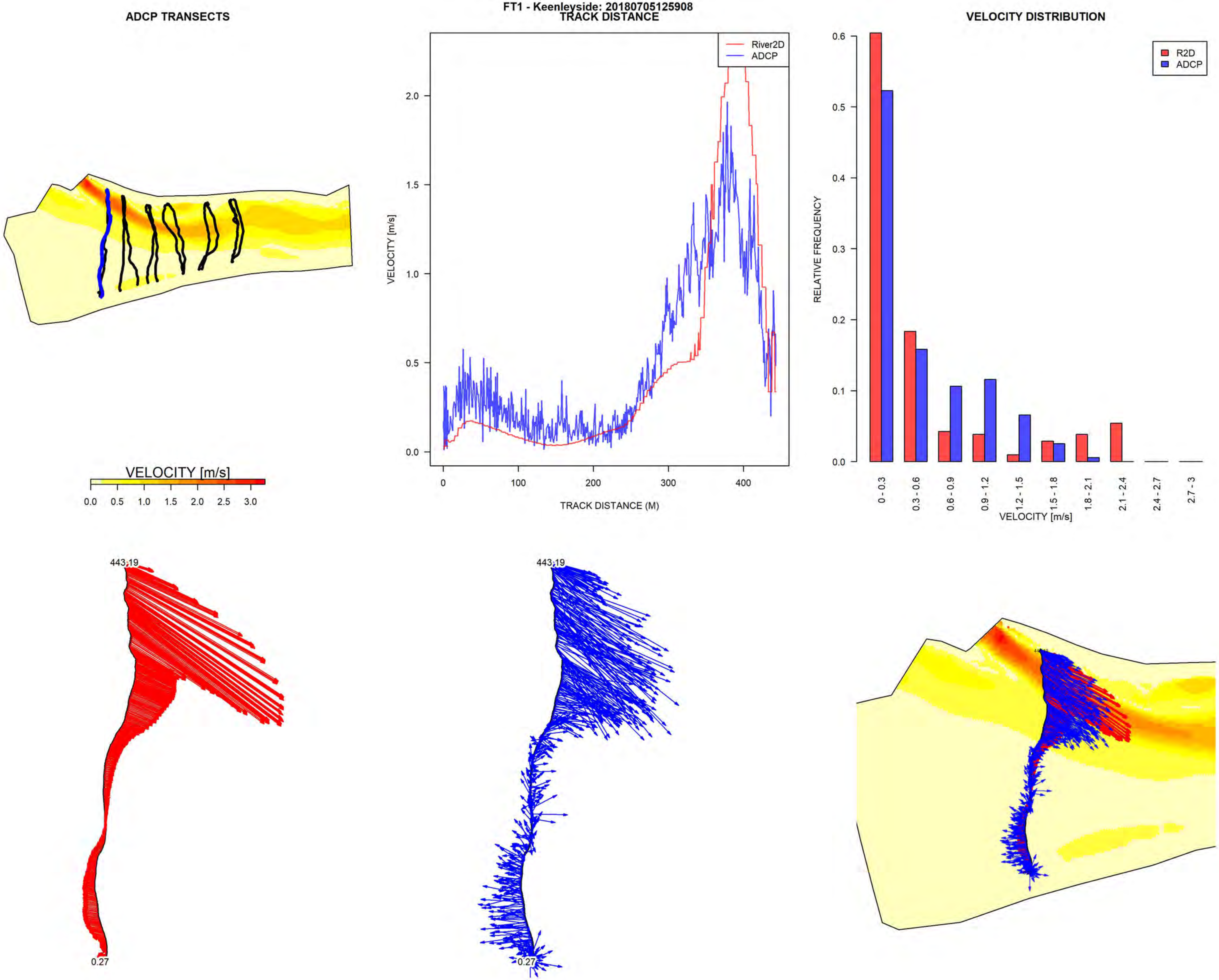


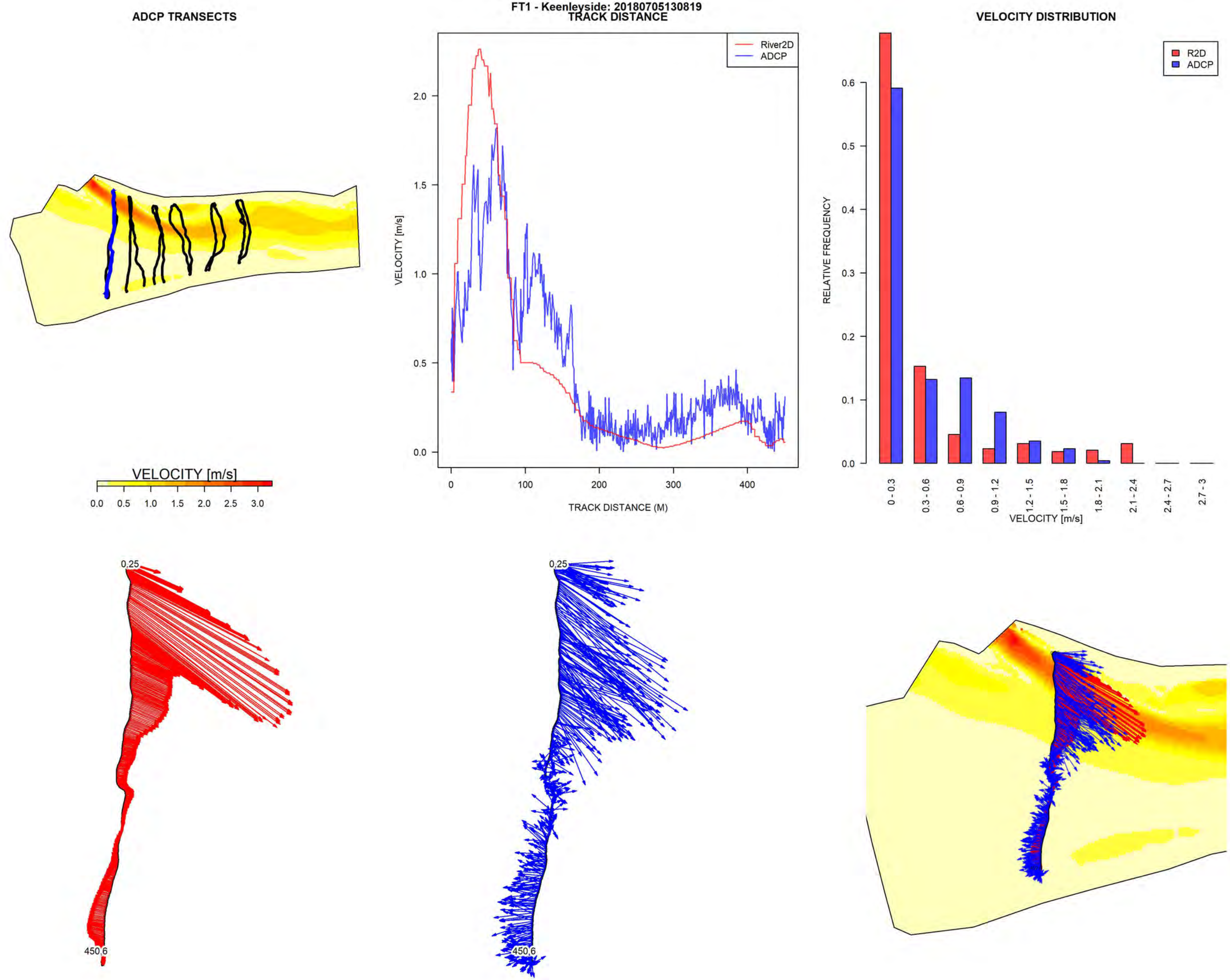
Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_Embeddedness_190404.mxd

Appendix E. Hydrodynamic model calibration and validation results

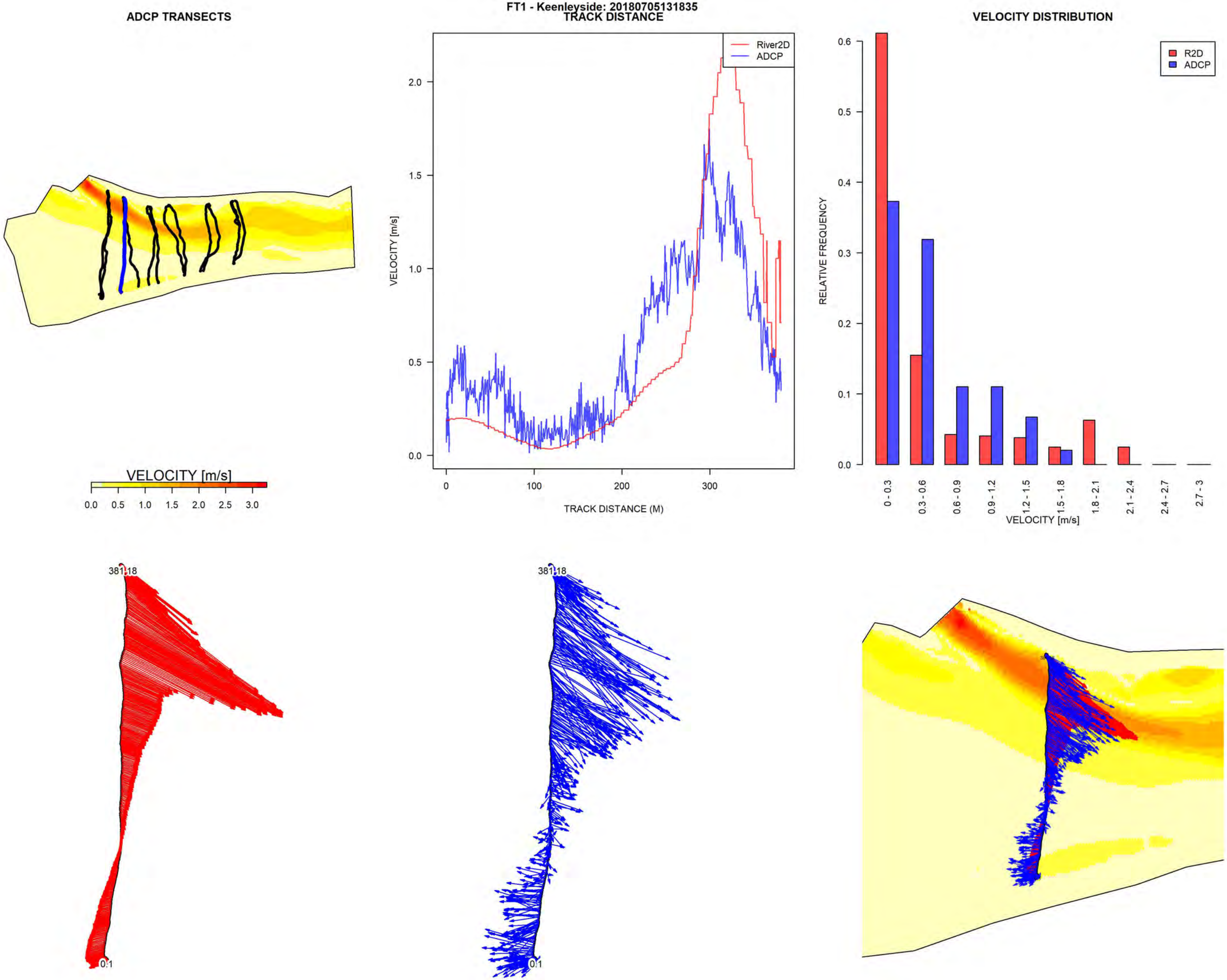
FT1 - Keenleyside: 20180705125908



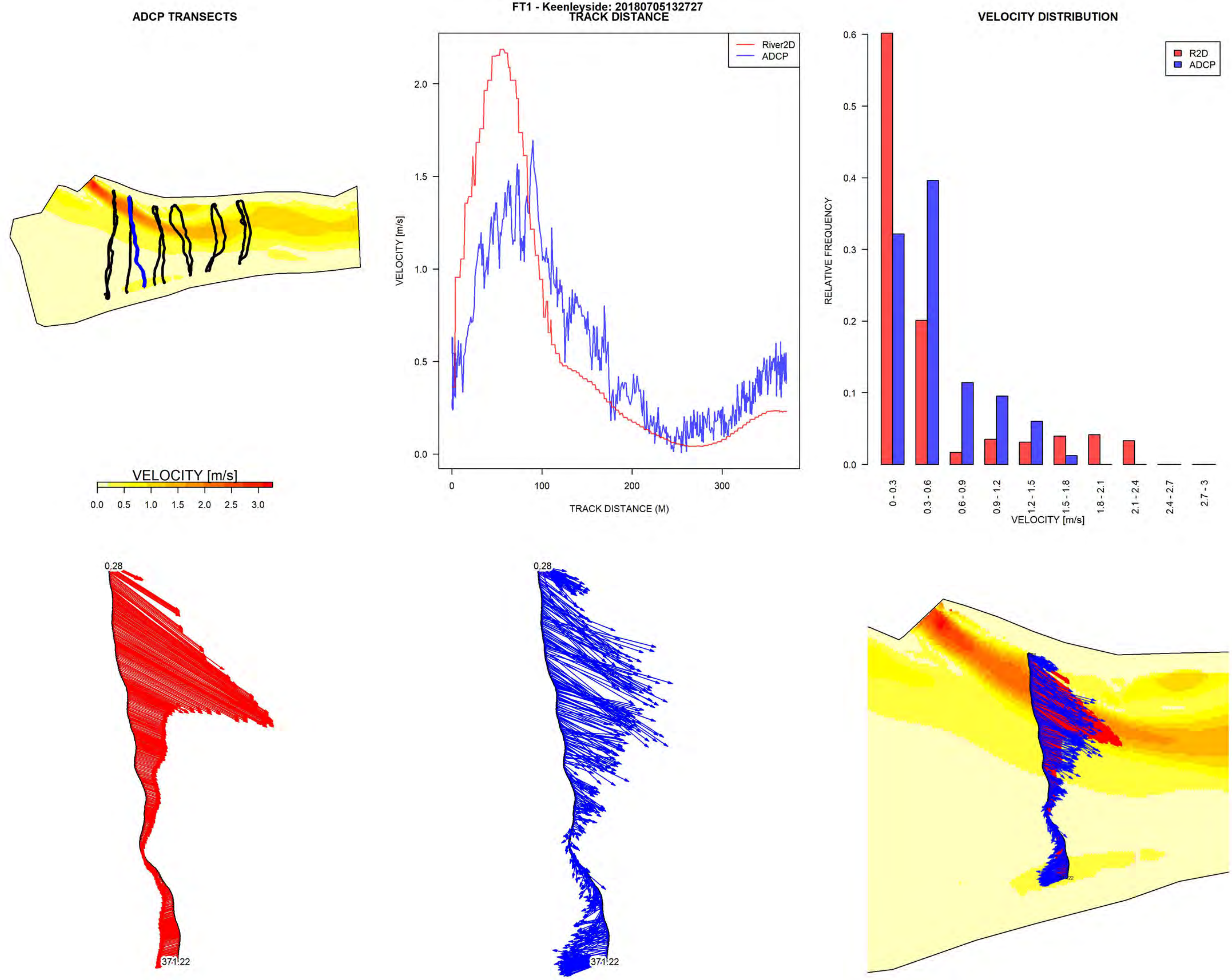
FT1 - Keenleyside: 20180705130819



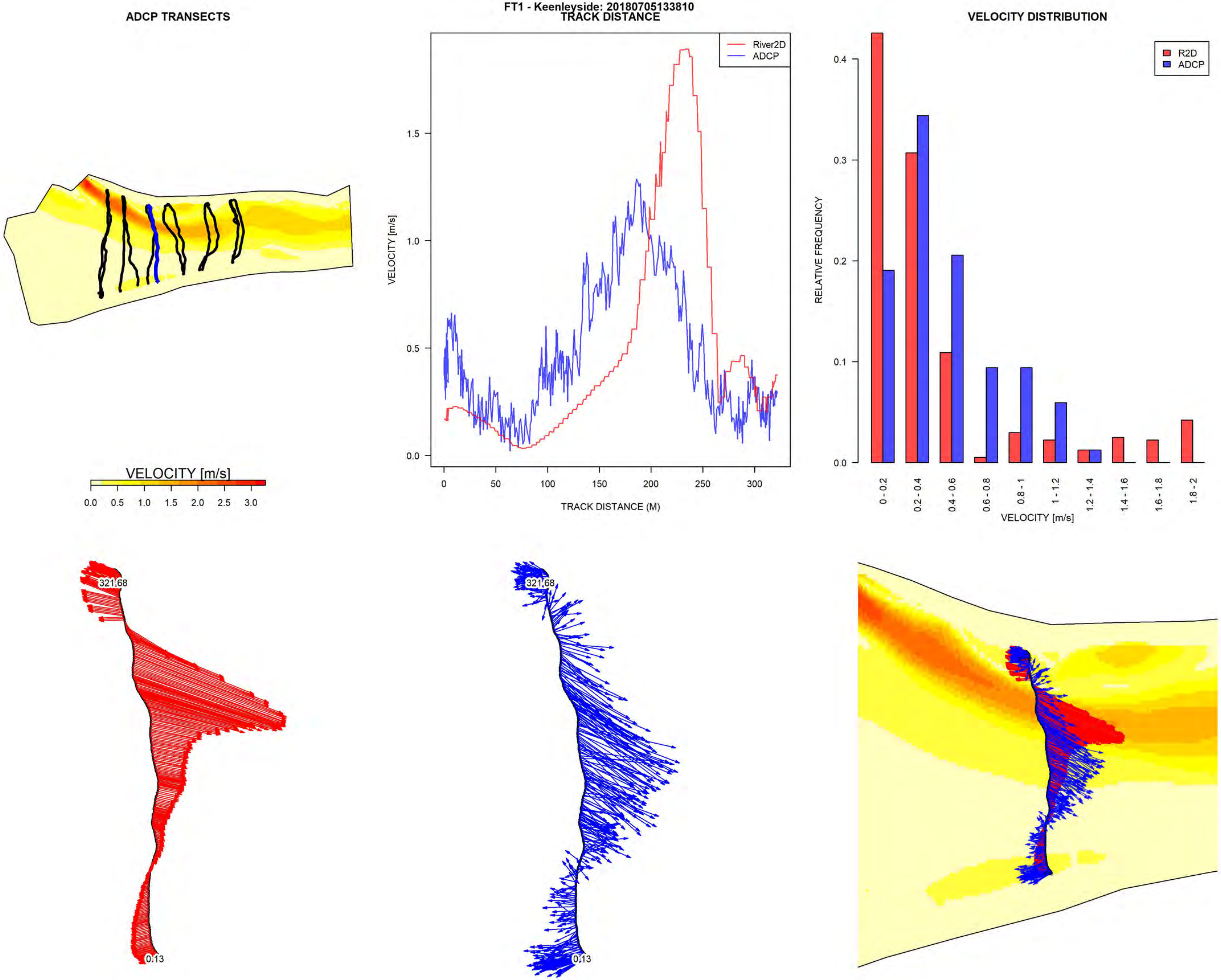
FT1 - Keenleyside: 20180705131835



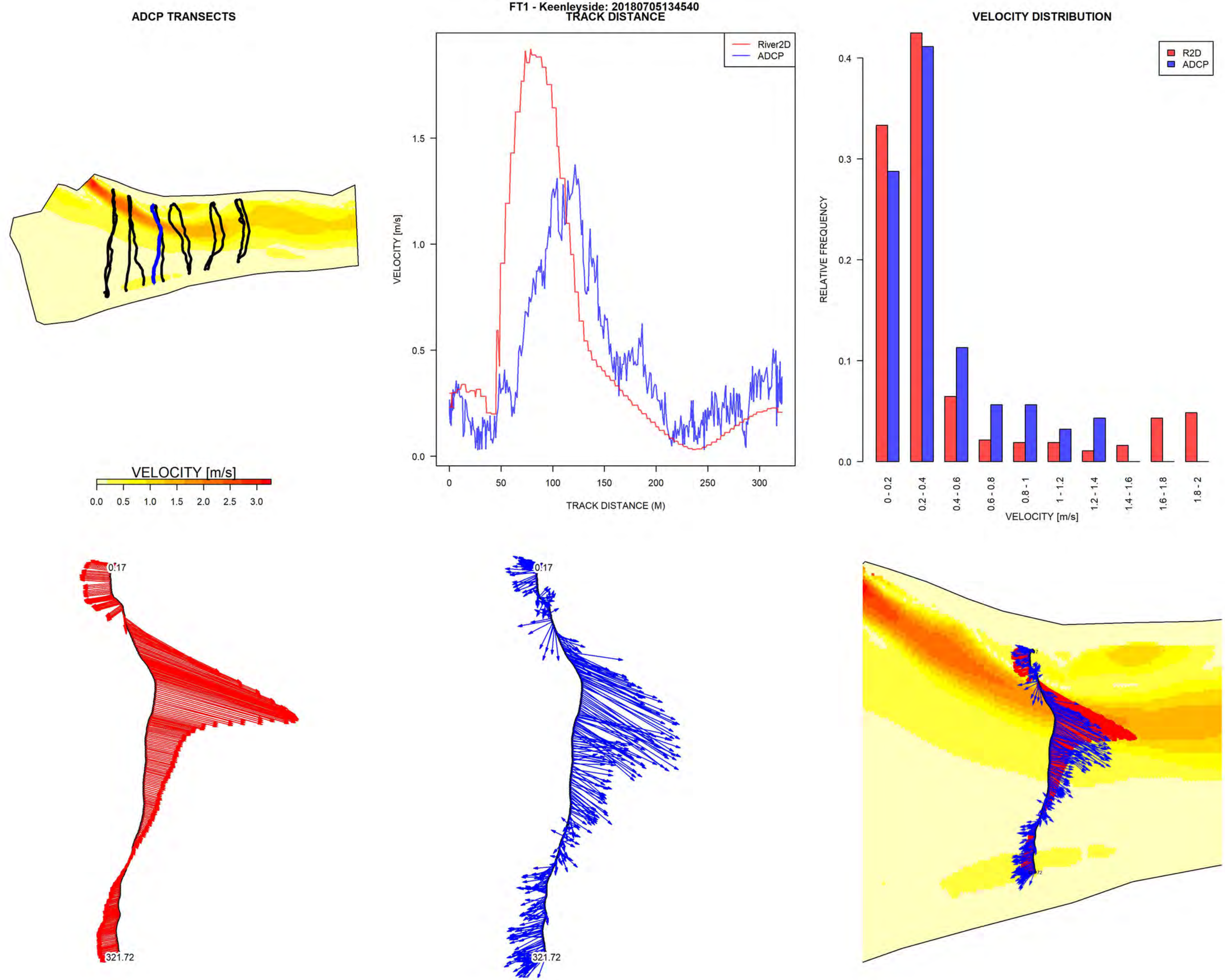
FT1 - Keenleyside: 20180705132727

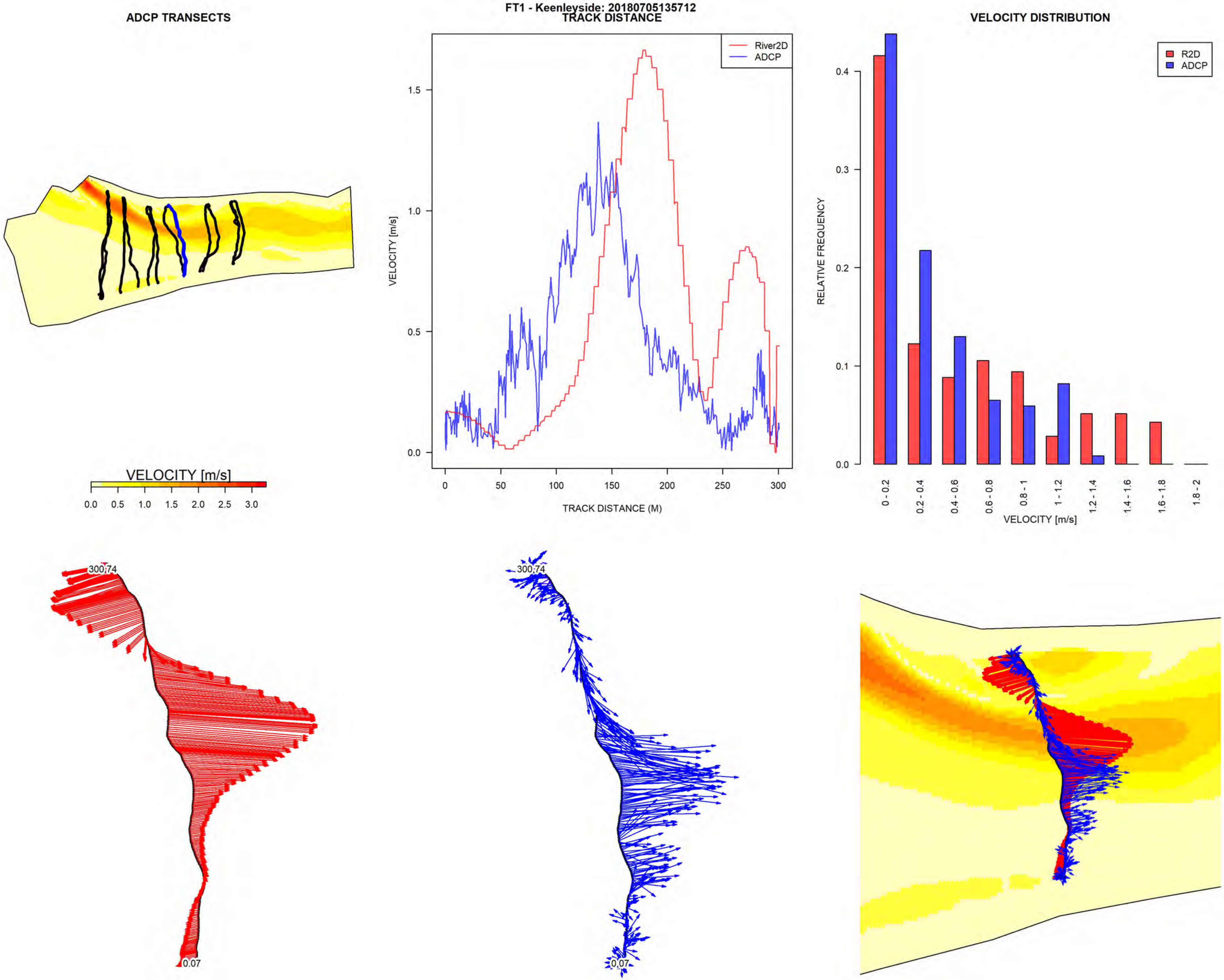


FT1 - Keenleyside: 20180705133810



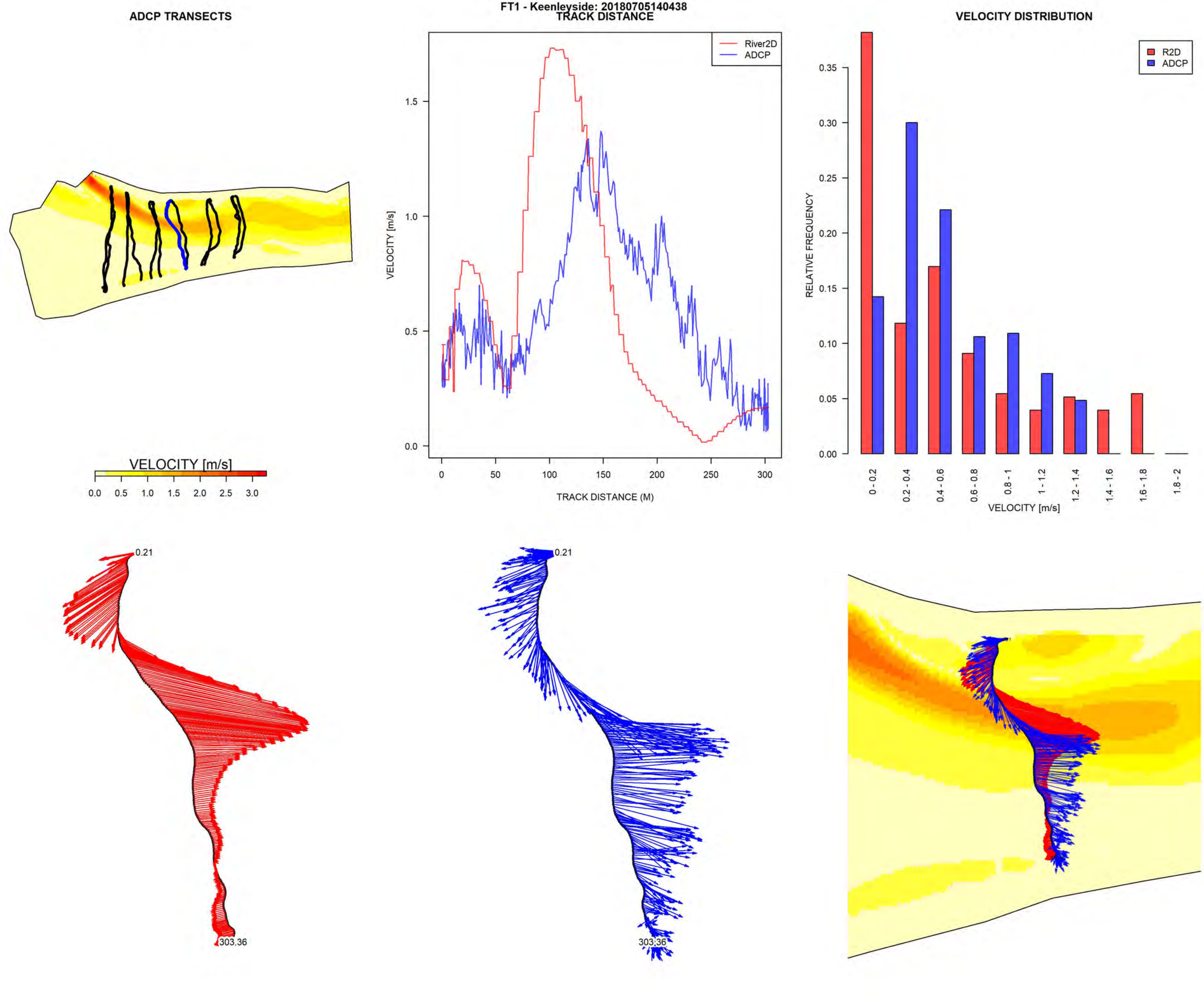
FT1 - Keenleyside: 20180705134540



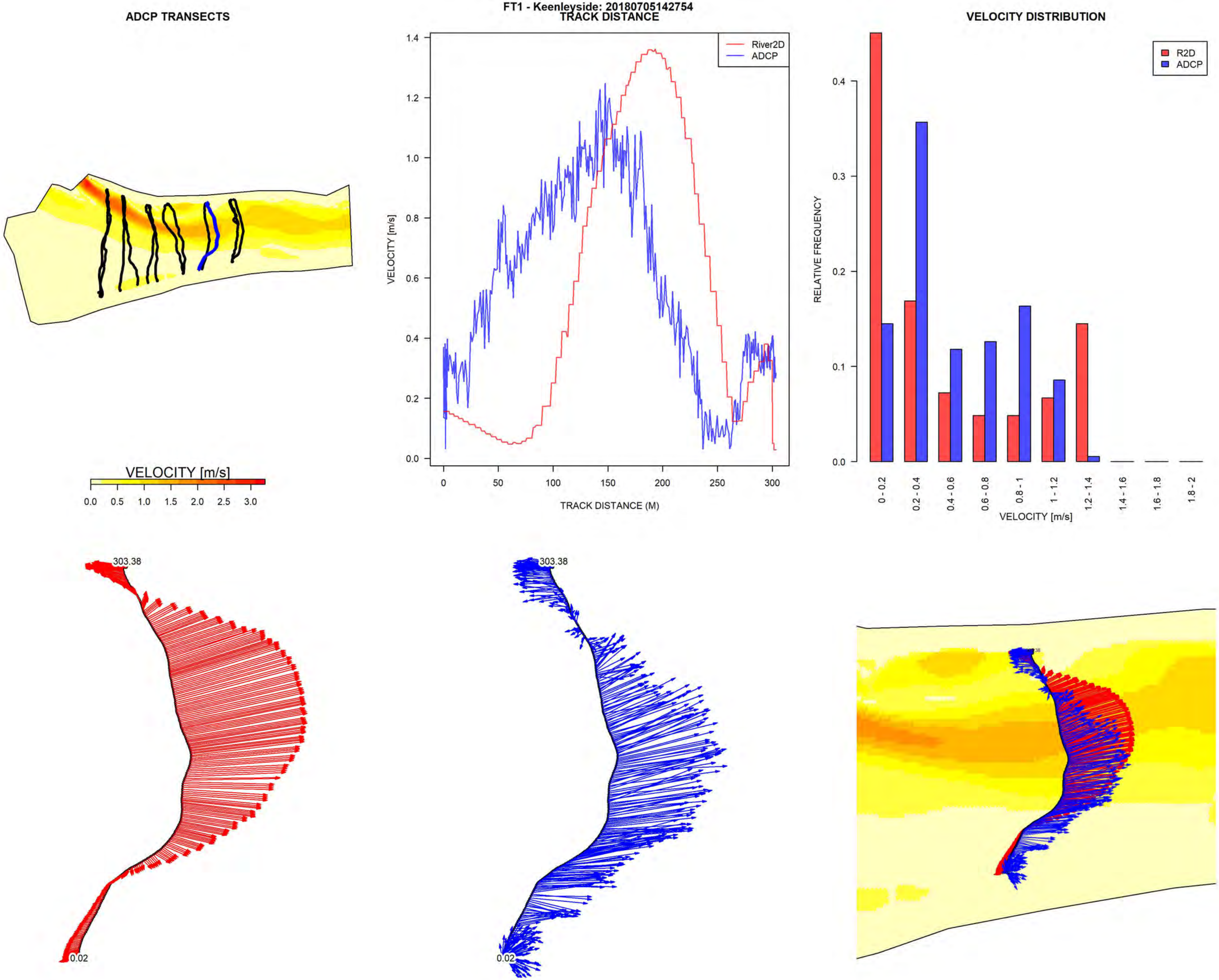


FT1 - Keenleyside: 20180705135712
ADCP TRANSECTS
VELOCITY [m/s]
0.0 0.5 1.0 1.5 2.0 2.5 3.0
TRACK DISTANCE
River2D
ADCP
VELOCITY [m/s]
TRACK DISTANCE (M)
VELOCITY DISTRIBUTION
R2D
ADCP
RELATIVE FREQUENCY
0 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 1
1 - 1.2
1.2 - 1.4
1.4 - 1.6
1.6 - 1.8
1.8 - 2
VELOCITY [m/s]
300.74
0.07
300.74
0.07

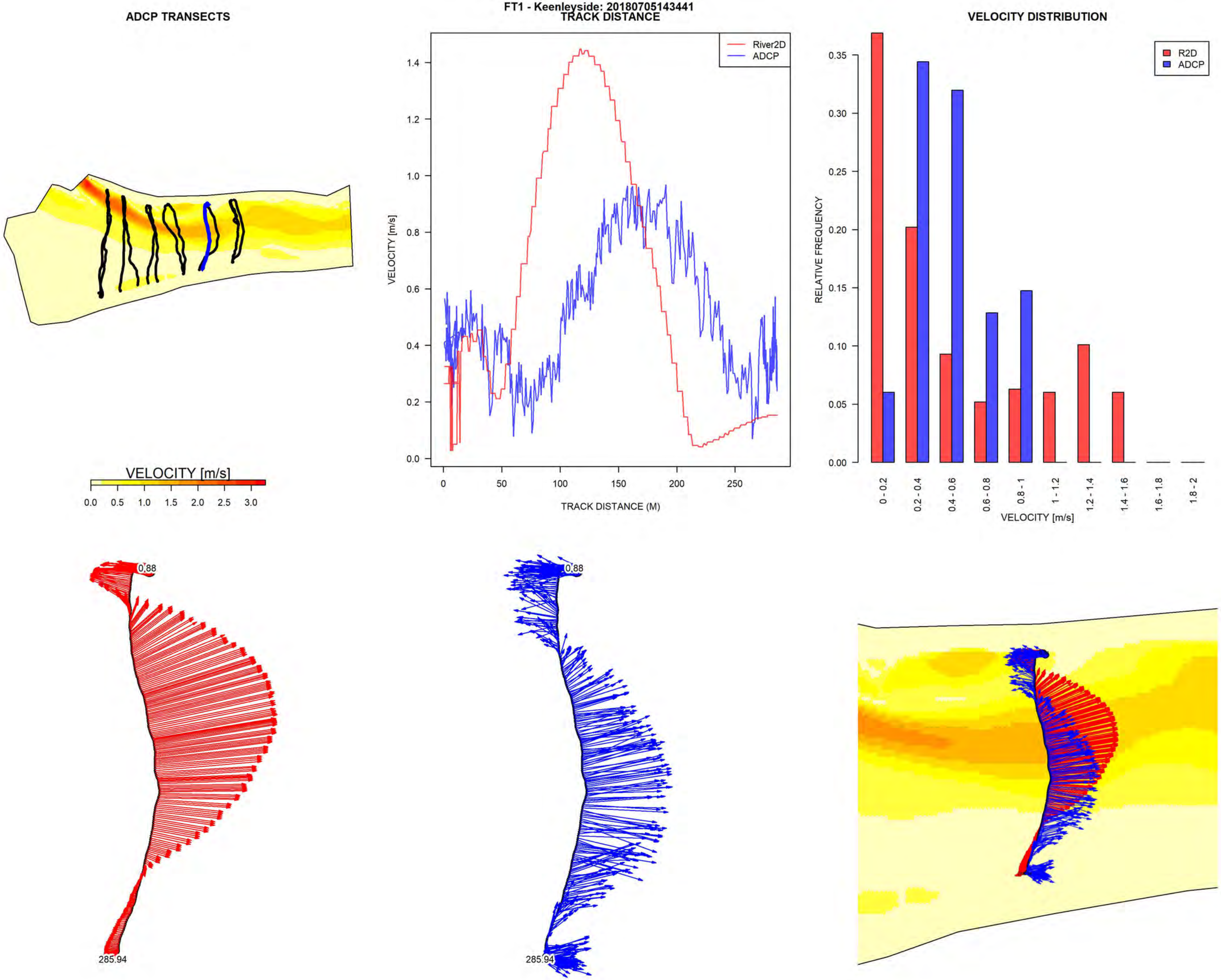
FT1 - Keenleyside: 20180705140438

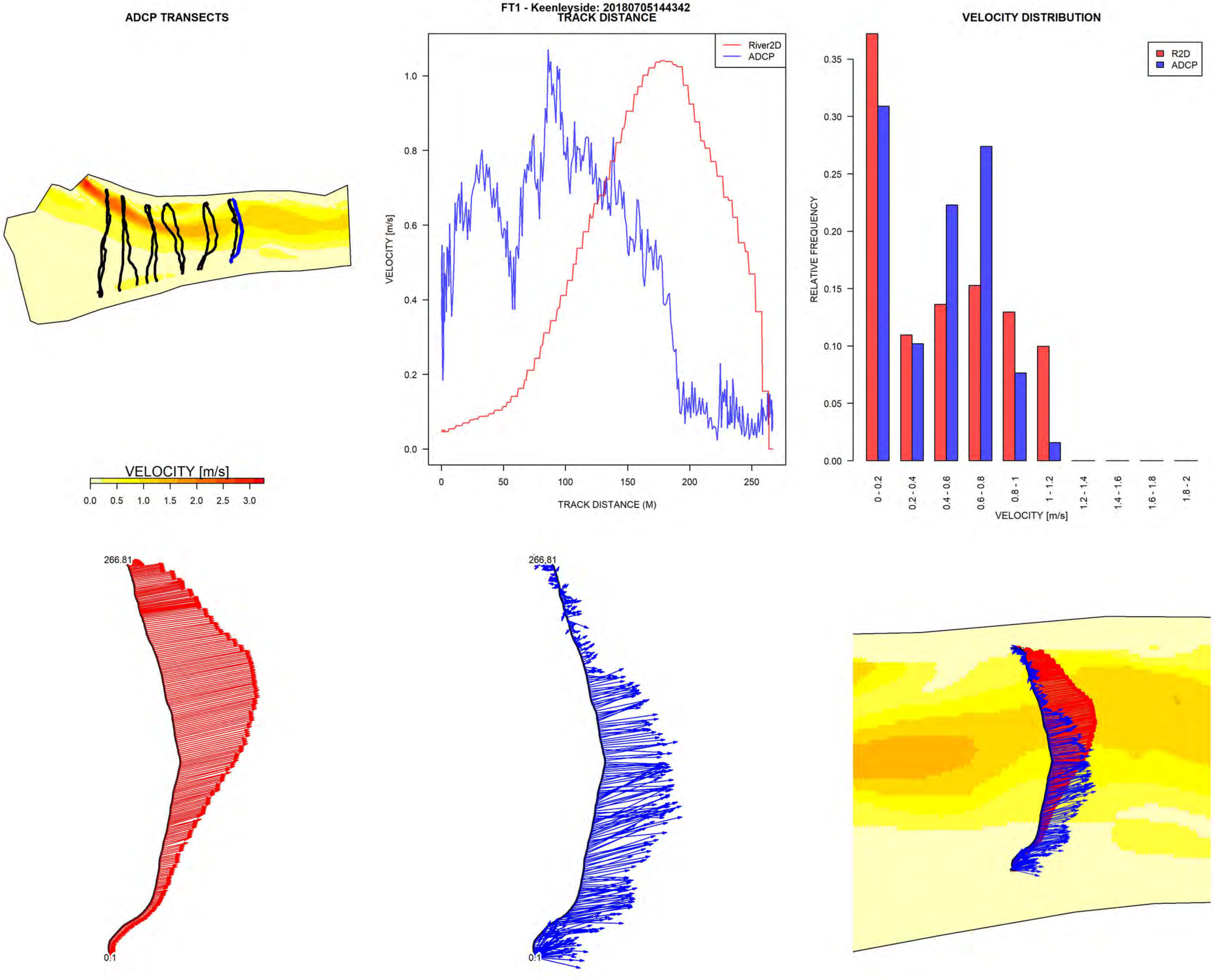


FT1 - Keenleyside: 20180705142754



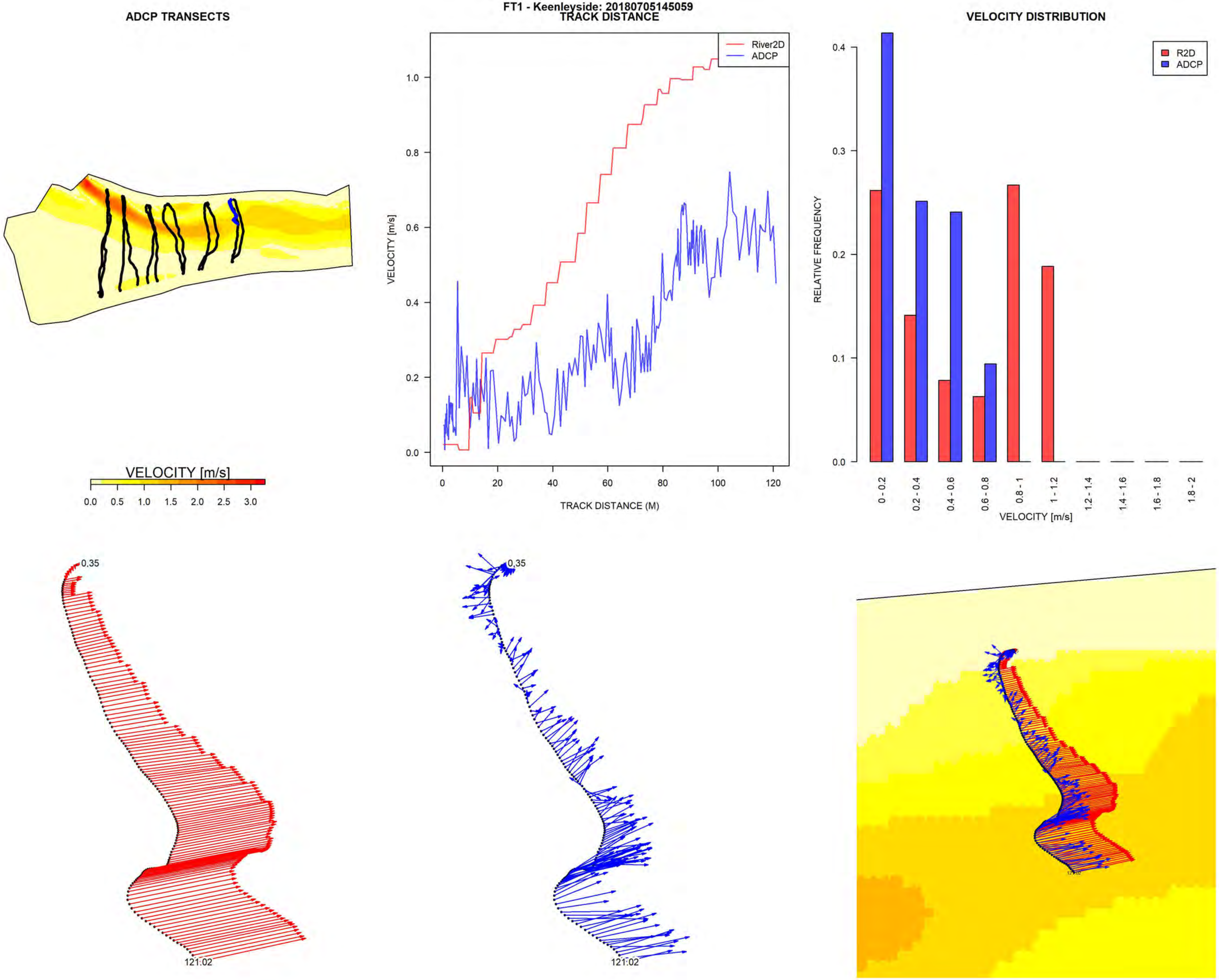
FT1 - Keenleyside: 20180705143441



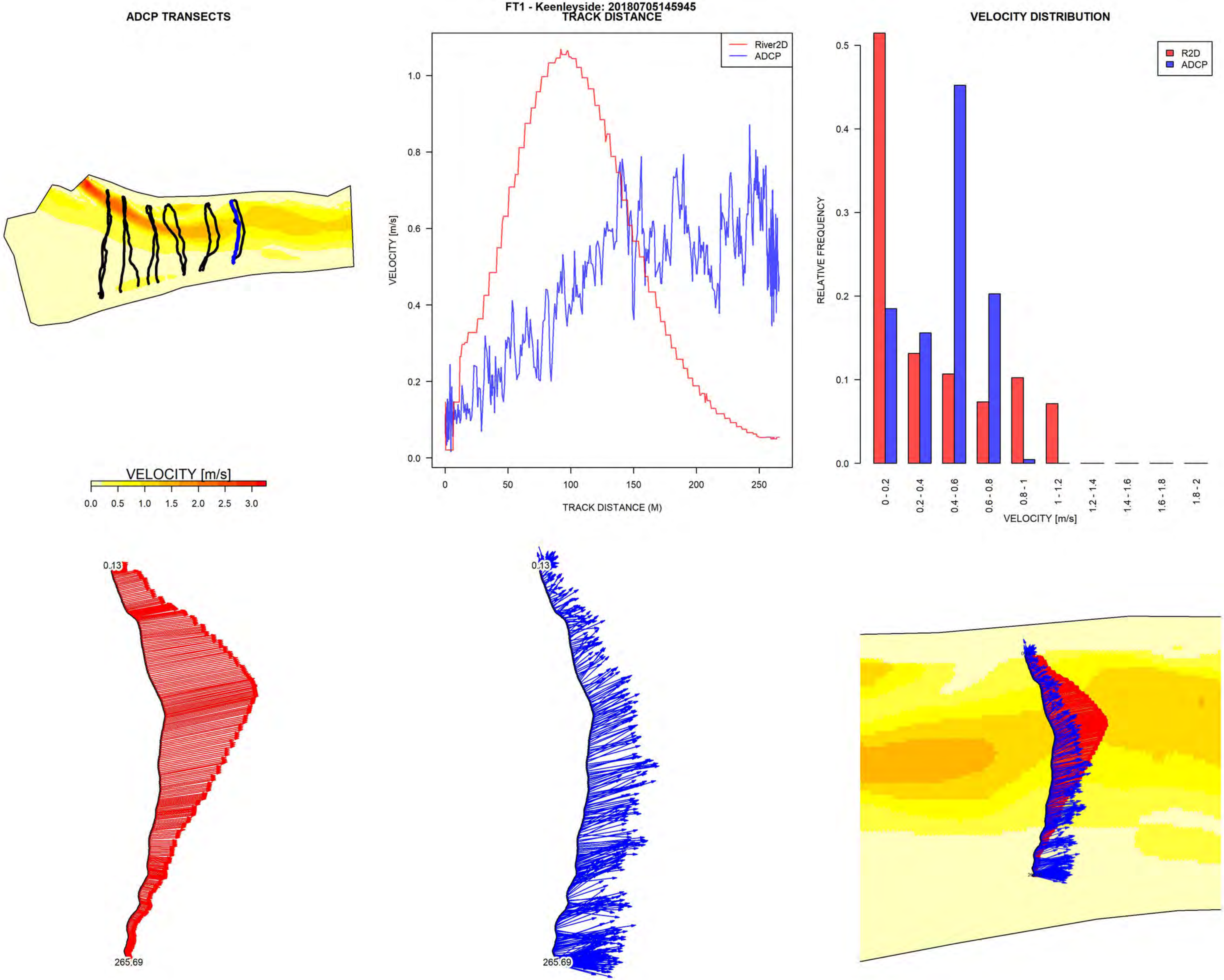


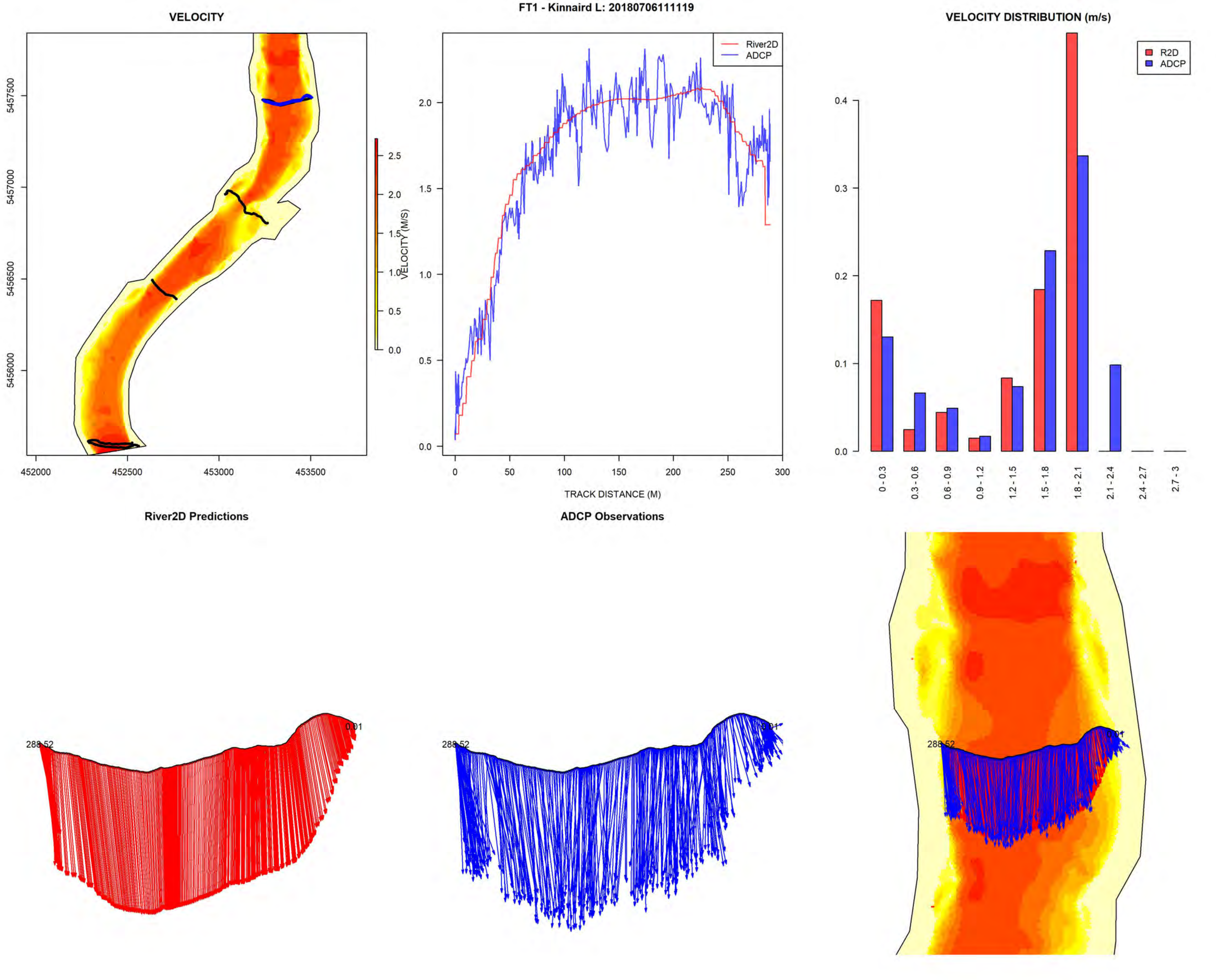
FT1 - Keenleyside: 20180705144342
ADCP TRANSECTS
VELOCITY [m/s]
0.0 0.5 1.0 1.5 2.0 2.5 3.0
TRACK DISTANCE
River2D
ADCP
VELOCITY [m/s]
TRACK DISTANCE (M)
0.0 0.2 0.4 0.6 0.8 1.0
0 50 100 150 200 250
VELOCITY DISTRIBUTION
R2D
ADCP
RELATIVE FREQUENCY
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35
0 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 1
1 - 1.2
1.2 - 1.4
1.4 - 1.6
1.6 - 1.8
1.8 - 2
VELOCITY [m/s]
266.81
0.1
266.81
0.1

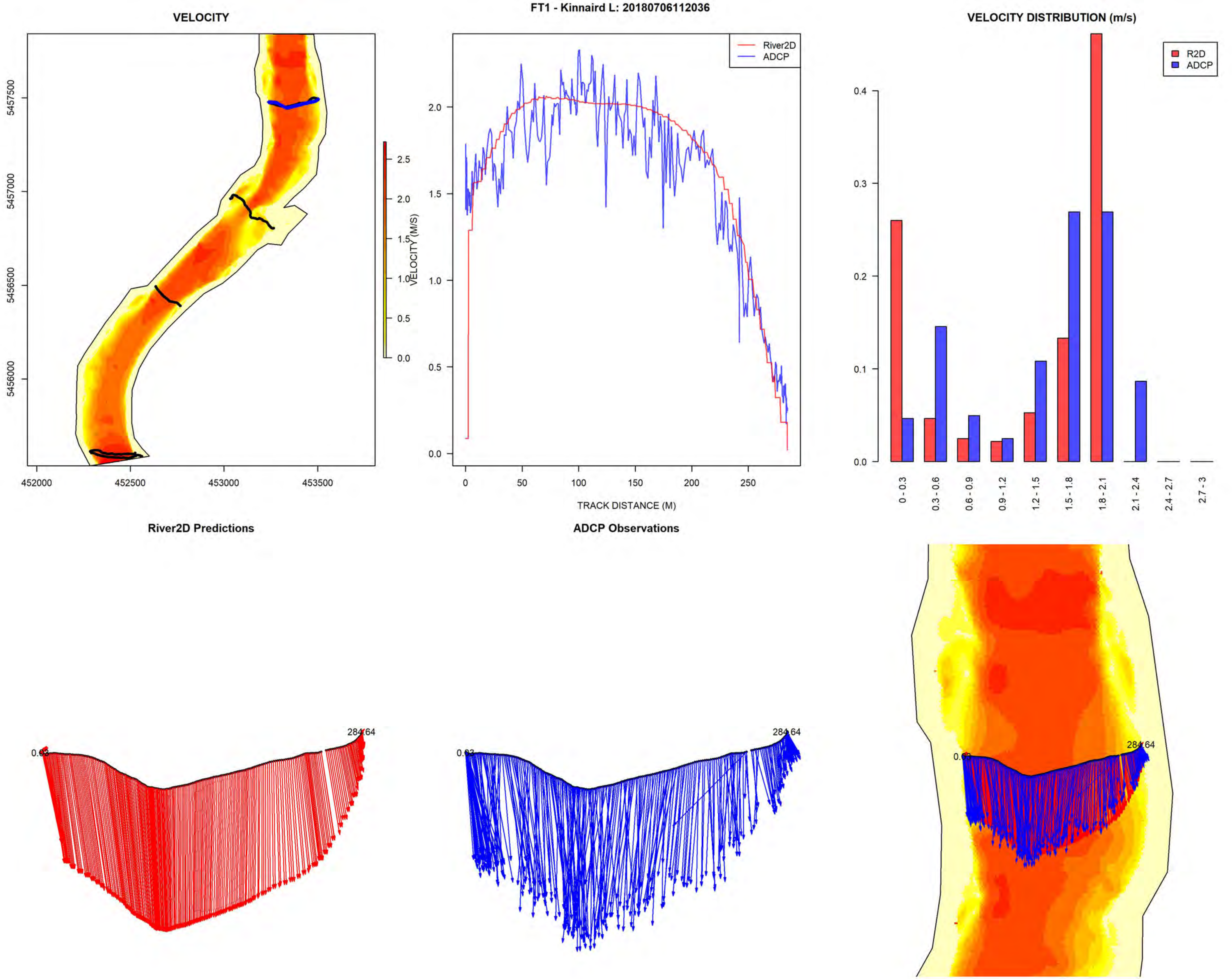
FT1 - Keenleyside: 20180705145059



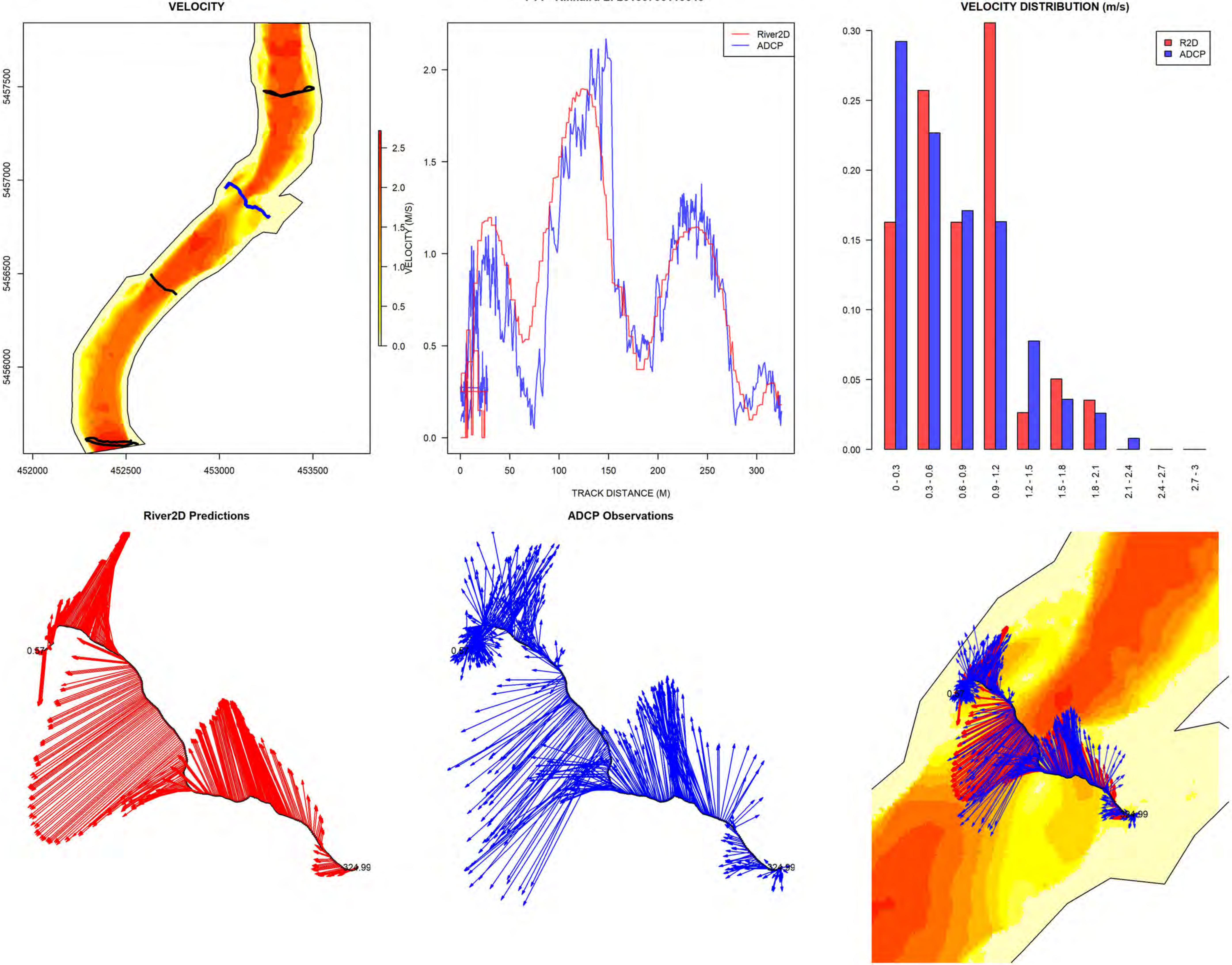
FT1 - Keenleyside: 20180705145945

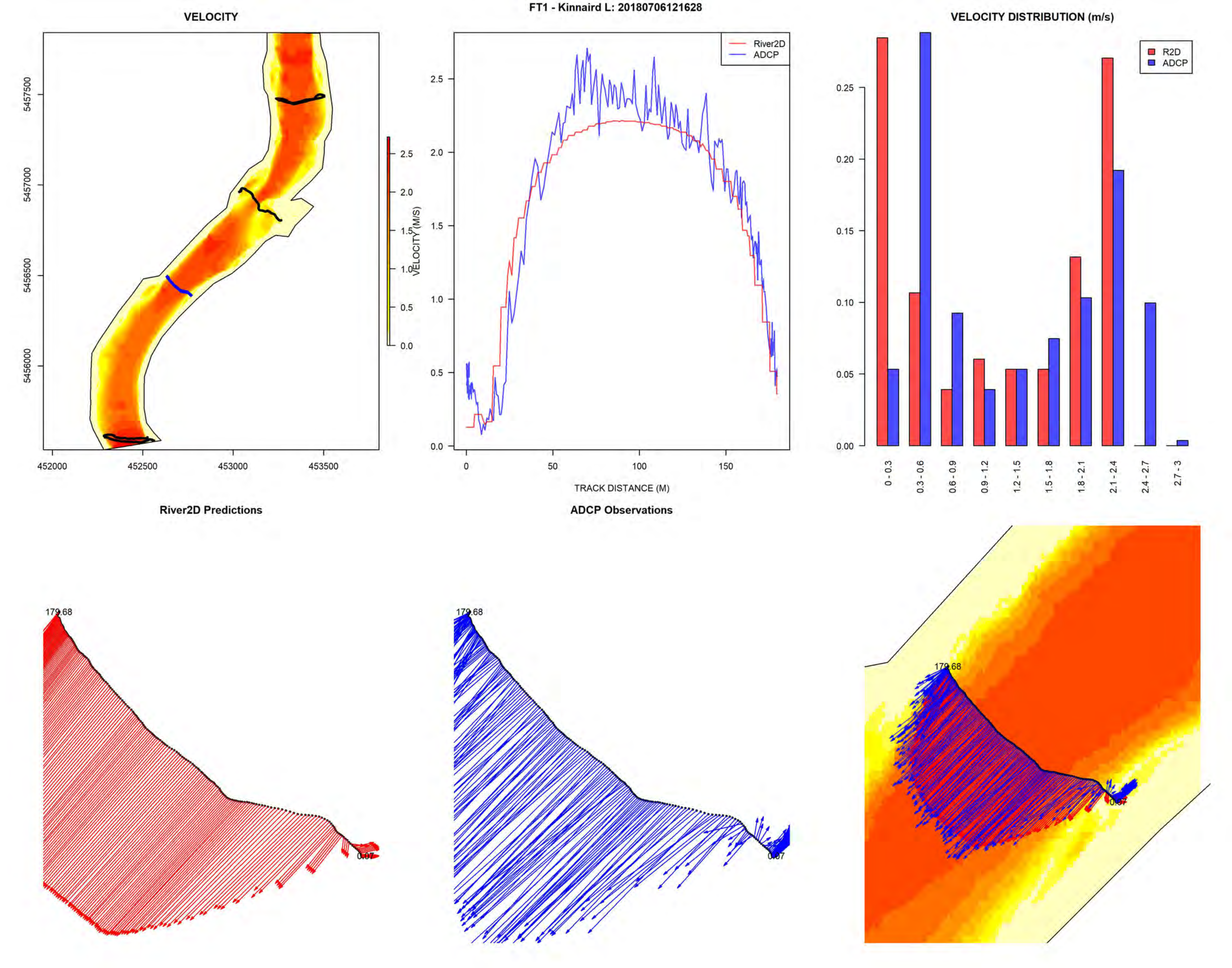


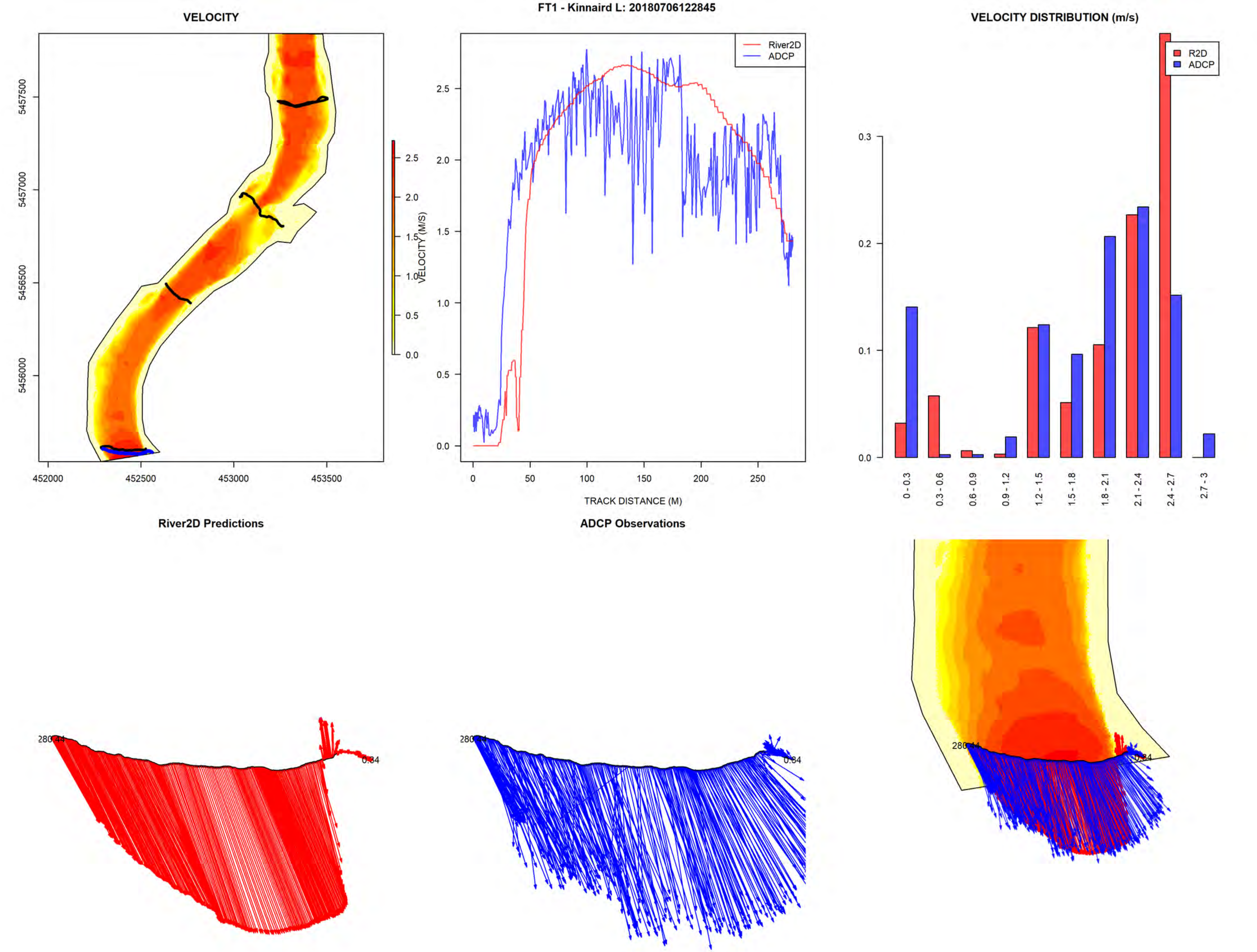

FT1 - Kinnaird L: 20180706111119
VELOCITY
VELOCITY (M/S)
2.5
2.0
1.5
1.0
0.5
0.0
5457500
5457000
5456500
5456000
452000
452500
453000
453500
River2D
ADCP
TRACK DISTANCE (M)
0
50
100
150
200
250
300
VELOCITY DISTRIBUTION (m/s)
R2D
ADCP
0.4
0.3
0.2
0.1
0.0
0 - 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
2.4 - 2.7
2.7 - 3
River2D Predictions
ADCP Observations
288.52
0.01


FT1 - Kinnaird L: 20180706112036
VELOCITY
5457500
5457000
5456500
5456000
452000
452500
453000
453500
VELOCITY (M/S)
2.5
2.0
1.5
1.0
0.5
0.0
River2D
ADCP
TRACK DISTANCE (M)
0
50
100
150
200
250
VELOCITY DISTRIBUTION (m/s)
R2D
ADCP
0.4
0.3
0.2
0.1
0.0
0 - 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
2.4 - 2.7
2.7 - 3
River2D Predictions
ADCP Observations
0.63
284.64

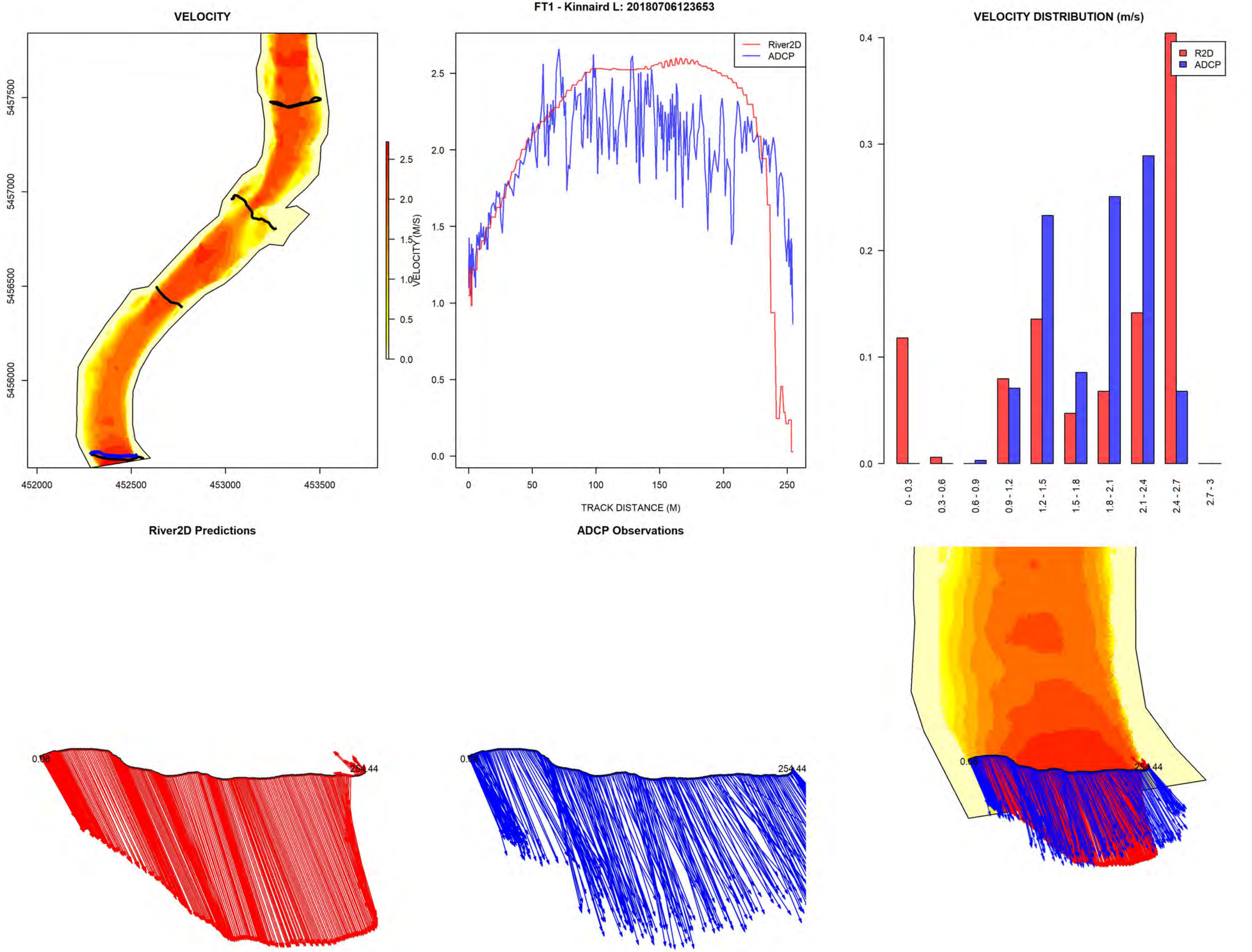
FT1 - Kinnaird L: 20180706115645

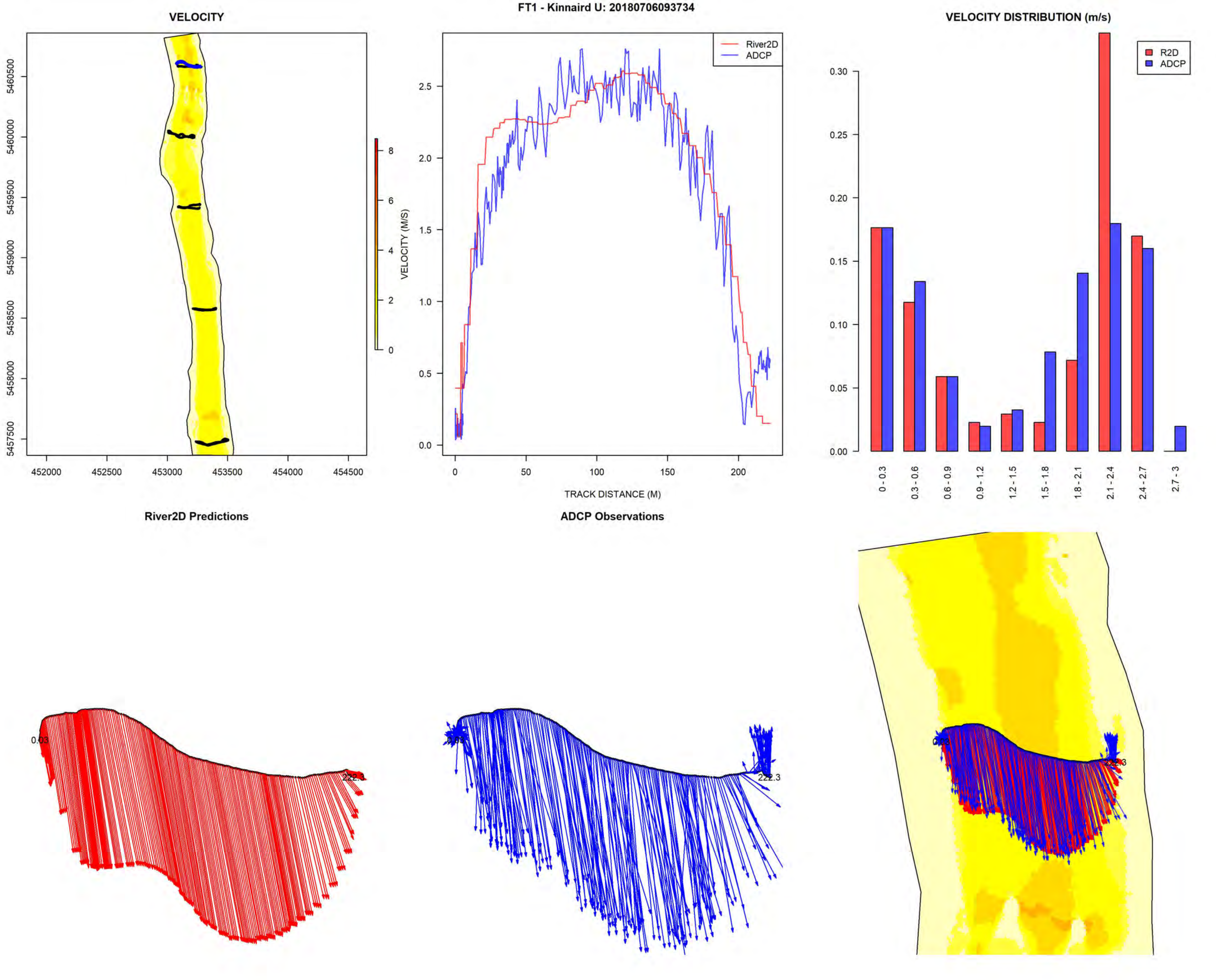


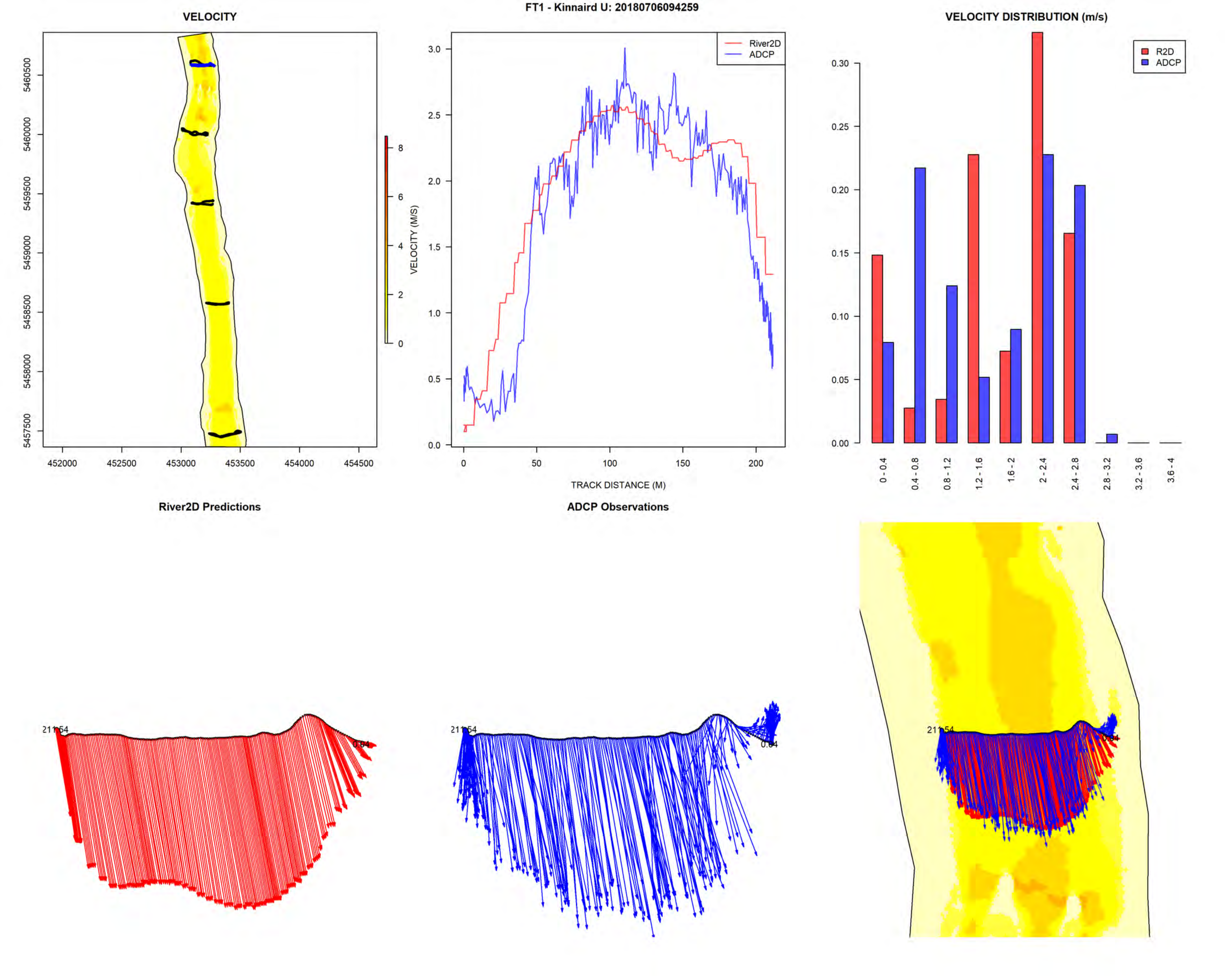

FT1 - Kinnaird L: 20180706121628
VELOCITY
VELOCITY (M/S)
2.5
2.0
1.5
1.0
0.5
0.0
5457500
5457000
5456500
5456000
452000
452500
453000
453500
River2D
ADCP
TRACK DISTANCE (M)
0
50
100
150
VELOCITY DISTRIBUTION (m/s)
R2D
ADCP
0.25
0.20
0.15
0.10
0.05
0.00
0 - 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
2.4 - 2.7
2.7 - 3
River2D Predictions
ADCP Observations
179.68
0.07


FT1 - Kinnaird L: 20180706122845
VELOCITY
5457500
5457000
5456500
5456000
452000
452500
453000
453500
VELOCITY (M/S)
0.0
0.5
1.0
1.5
2.0
2.5
River2D
ADCP
TRACK DISTANCE (M)
0
50
100
150
200
250
VELOCITY DISTRIBUTION (m/s)
R2D
ADCP
0.0
0.1
0.2
0.3
0 - 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
2.4 - 2.7
2.7 - 3
River2D Predictions
280.44
0.84
ADCP Observations

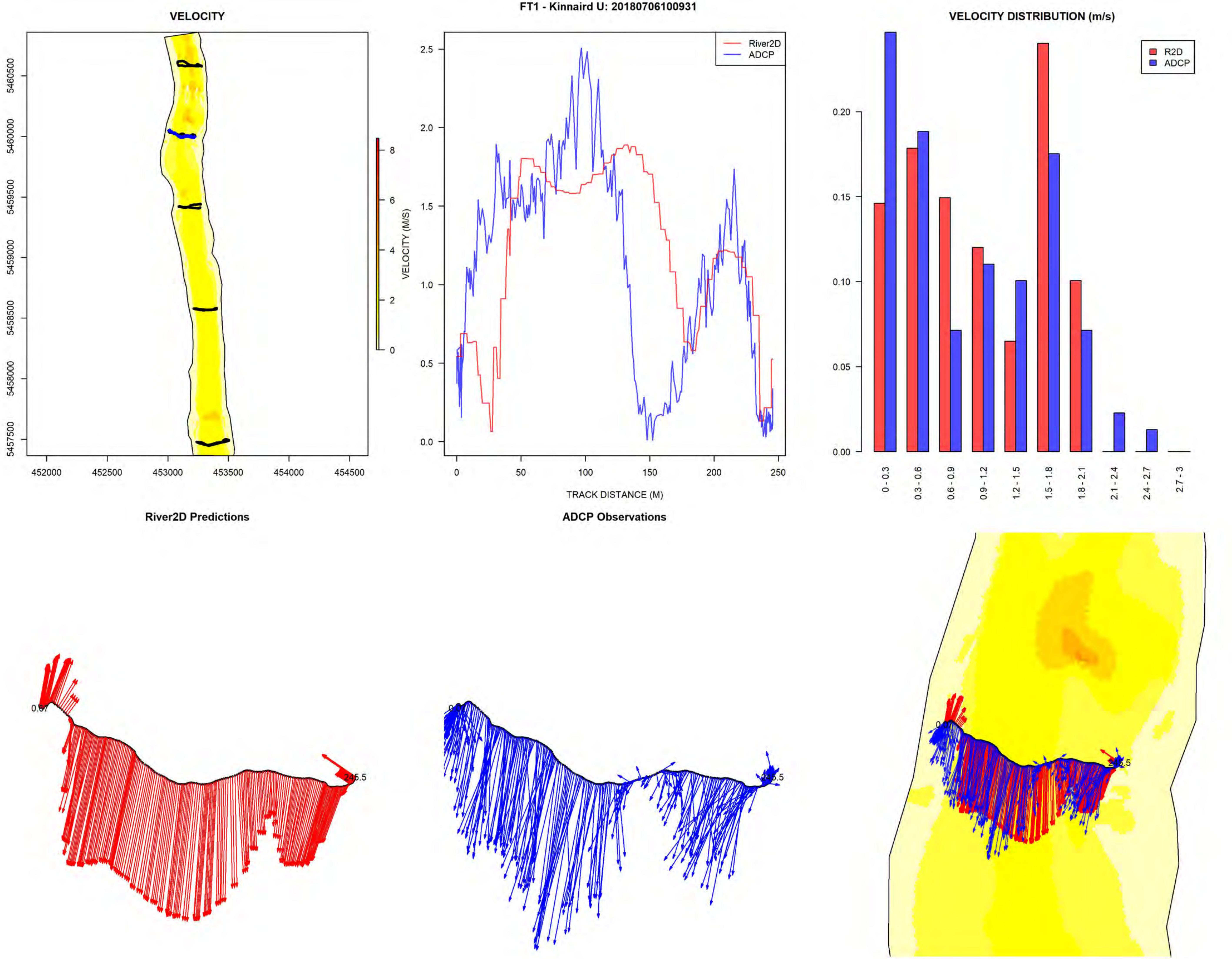
FT1 - Kinnaird L: 20180706123653

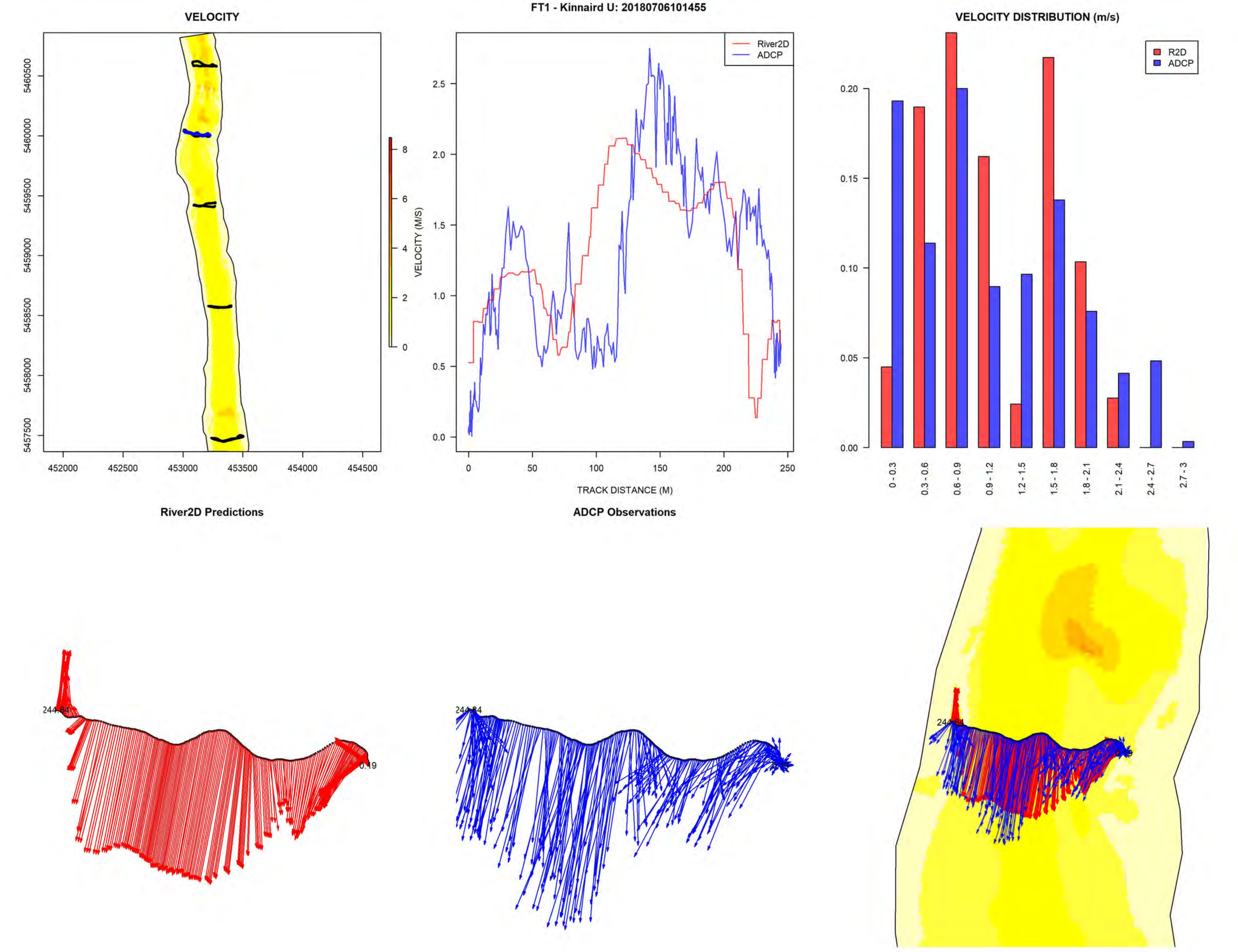



FT1 - Kinnaird U: 20180706093734
VELOCITY
VELOCITY (M/S)
VELOCITY DISTRIBUTION (m/s)
River2D
ADCP
R2D
TRACK DISTANCE (M)
River2D Predictions
ADCP Observations
0.03
222.3

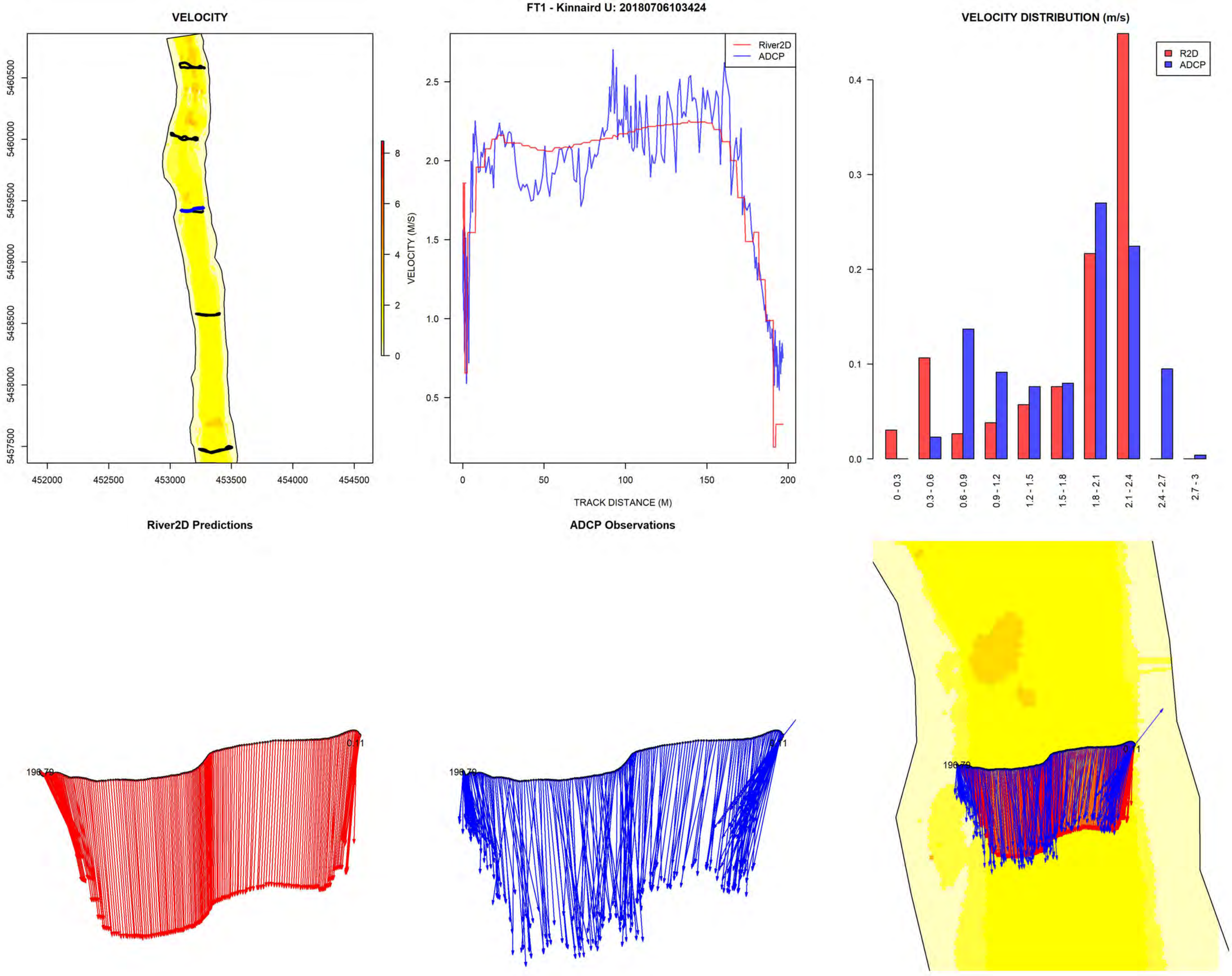

FT1 - Kinnaird U: 20180706094259
VELOCITY
452000
452500
453000
453500
454000
454500
5457500
5458000
5458500
5459000
5459500
5460000
5460500
0
2
4
6
8
VELOCITY (M/S)
TRACK DISTANCE (M)
River2D
ADCP
VELOCITY DISTRIBUTION (m/s)
R2D
ADCP
0 - 0.4
0.4 - 0.8
0.8 - 1.2
1.2 - 1.6
1.6 - 2
2 - 2.4
2.4 - 2.8
2.8 - 3.2
3.2 - 3.6
3.6 - 4
River2D Predictions
ADCP Observations
211.54
0.04

FT1 - Kinnaird U: 20180706100931





FT1 - Kinnaird U: 20180706101455
VELOCITY
5460500
5460000
5459500
5459000
5458500
5458000
5457500
452000
452500
453000
453500
454000
454500
VELOCITY (M/S)
0
2
4
6
8
River2D
ADCP
TRACK DISTANCE (M)
0.0
0.5
1.0
1.5
2.0
2.5
0
50
100
150
200
250
VELOCITY DISTRIBUTION (m/s)
R2D
ADCP
0.00
0.05
0.10
0.15
0.20
0 - 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
2.4 - 2.7
2.7 - 3
River2D Predictions
244.84
0.19
ADCP Observations
244.84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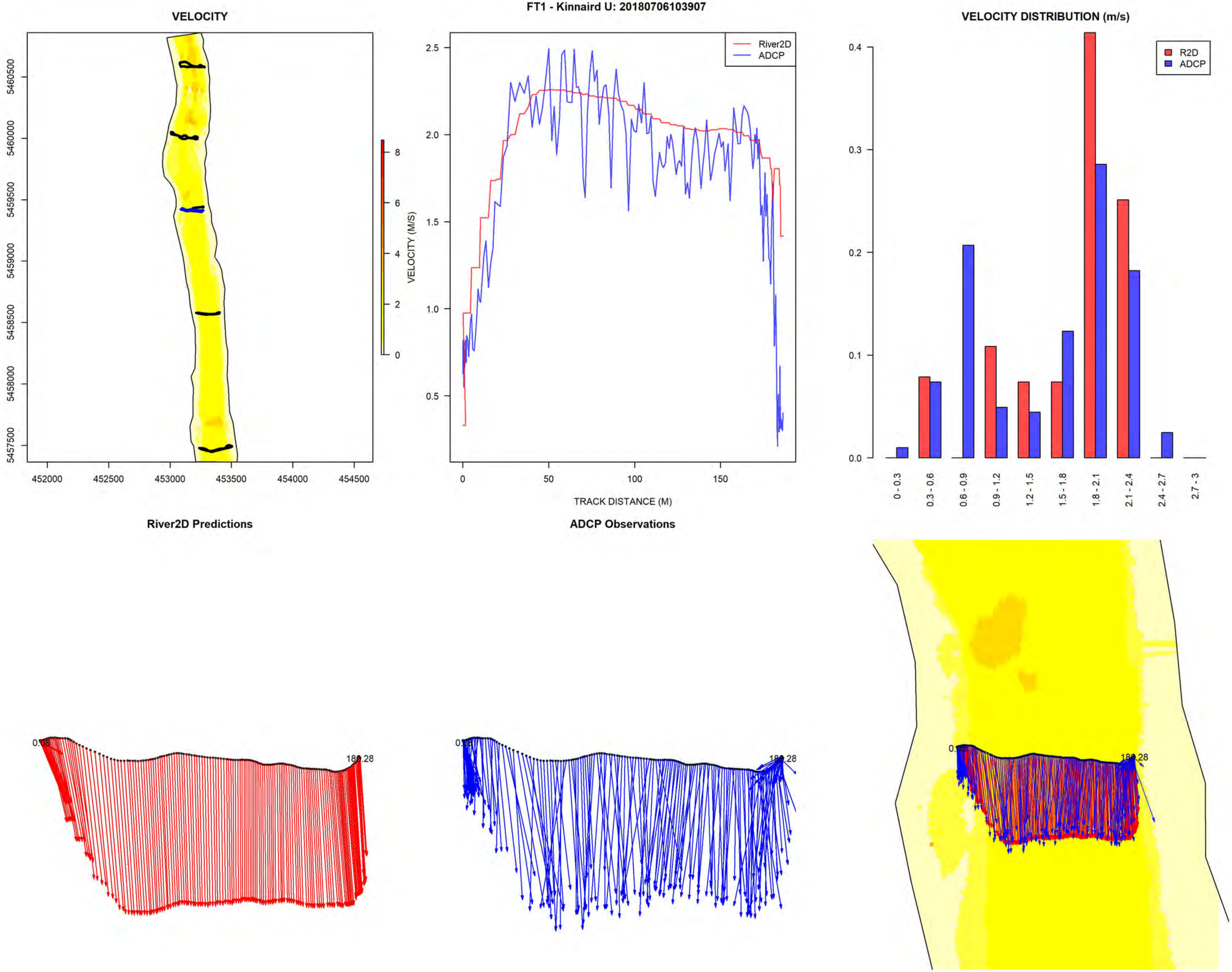
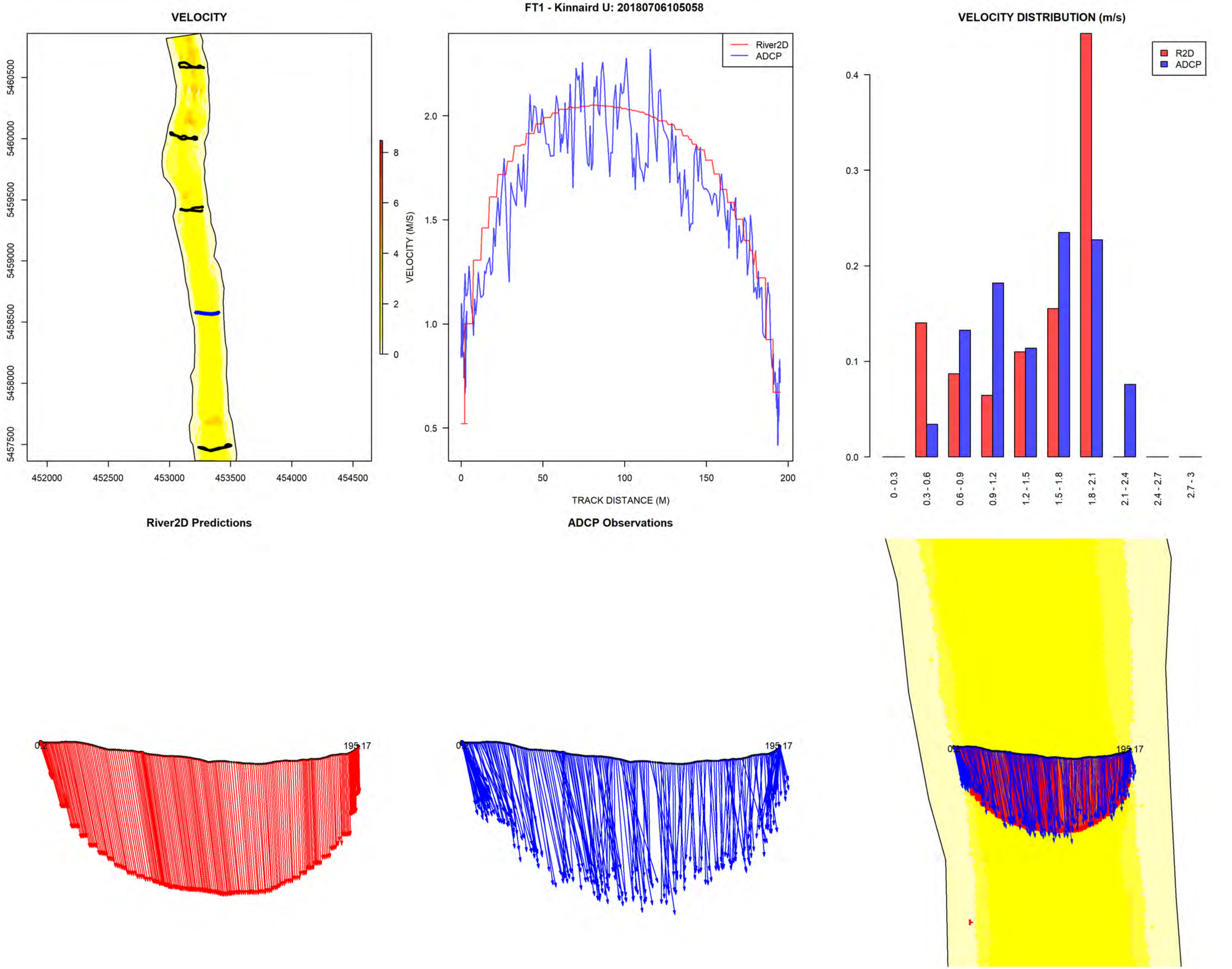
VELOCITY
5460500
5460000
5459500
5459000
5458500
5458000
5457500
452000
452500
453000
453500
454000
454500
VELOCITY (M/S)
0
2
4
6
8
River2D
ADCP
0.5
1.0
1.5
2.0
2.5
0
50
100
150
200
TRACK DISTANCE (M)
VELOCITY DISTRIBUTION (m/s)
R2D
ADCP
0.0
0.1
0.2
0.3
0.4
0 - 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
2.4 - 2.7
2.7 - 3
River2D Predictions
ADCP Observations
196.79
0.11

FT1 - Kinnaird U: 20180706103907

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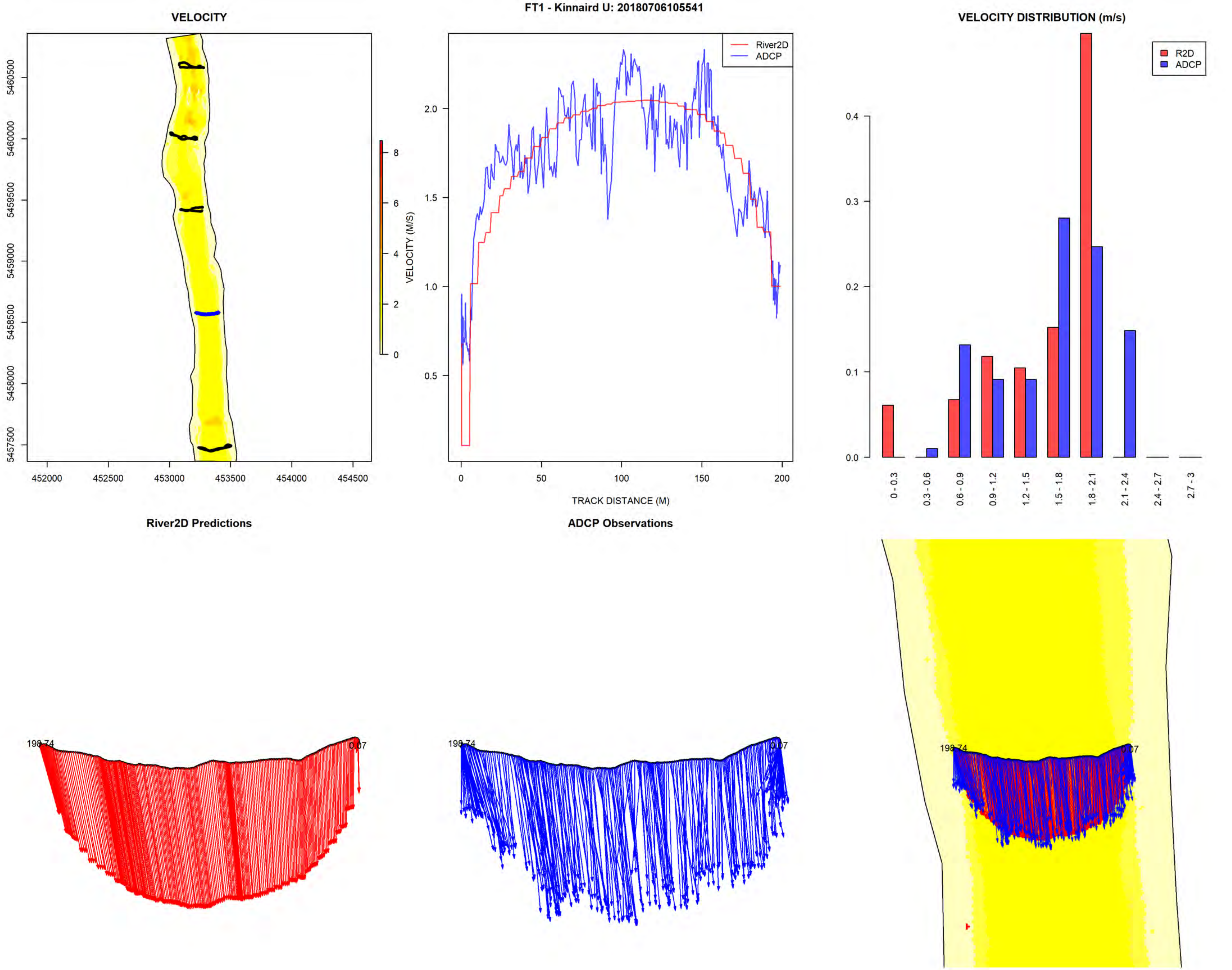
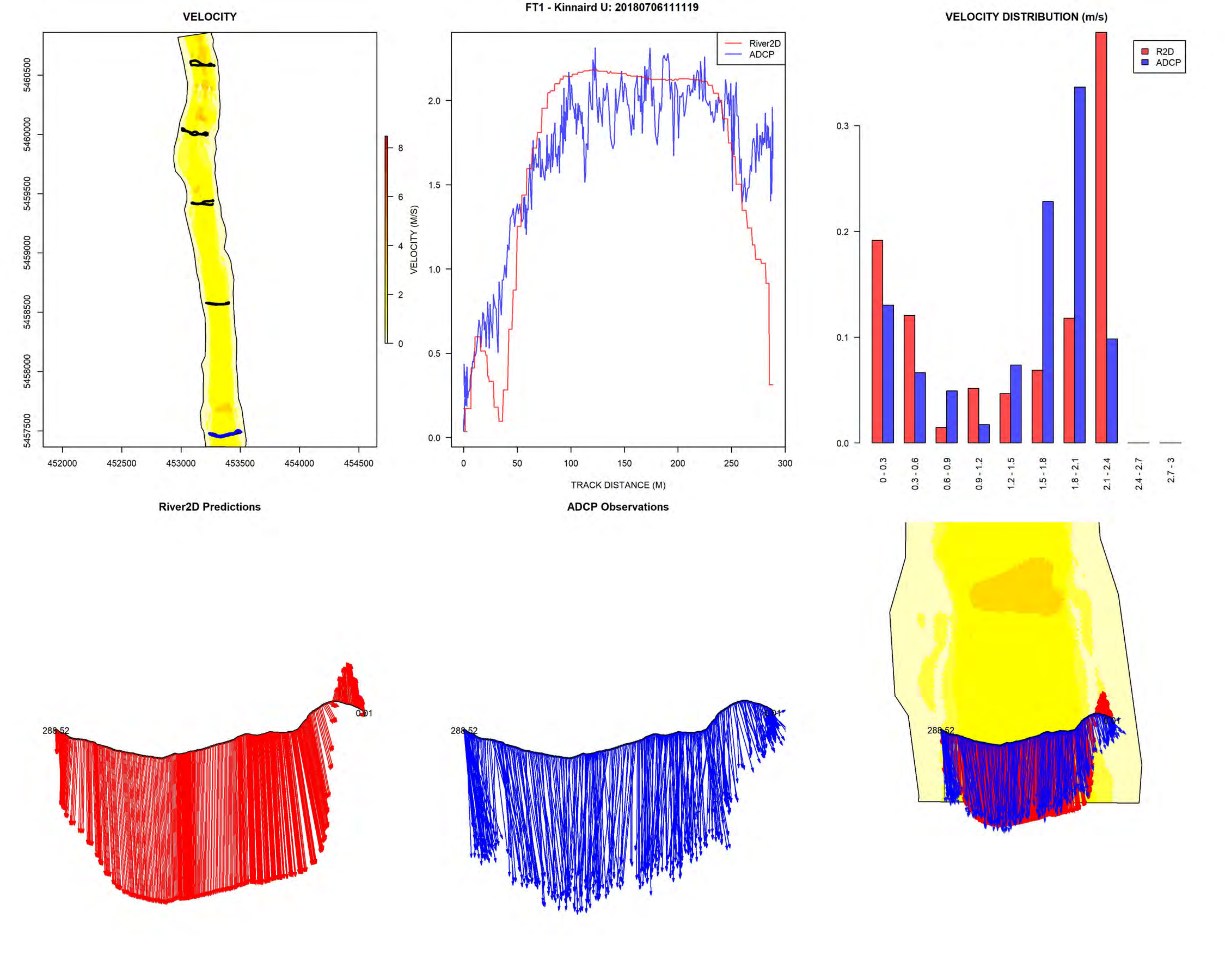
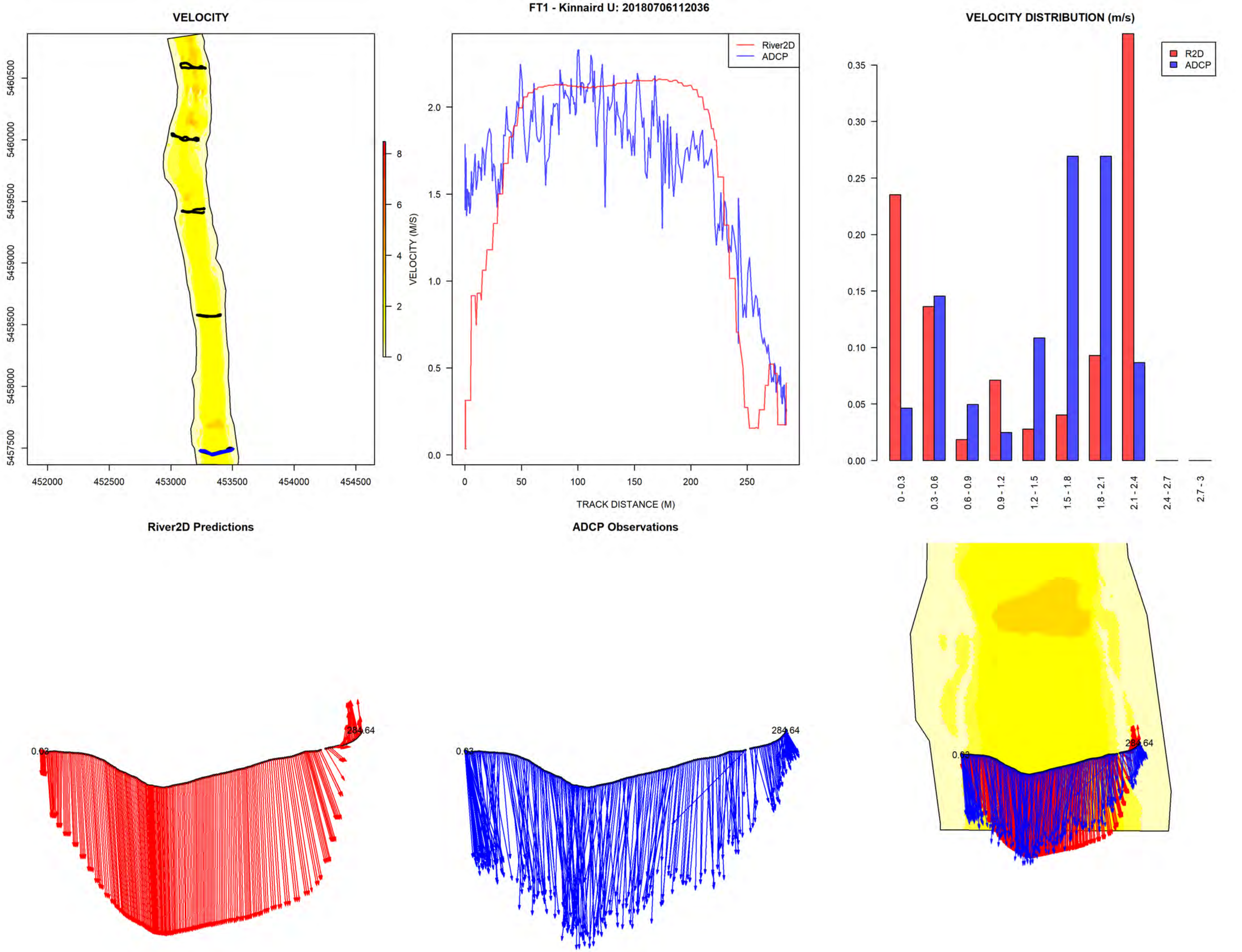
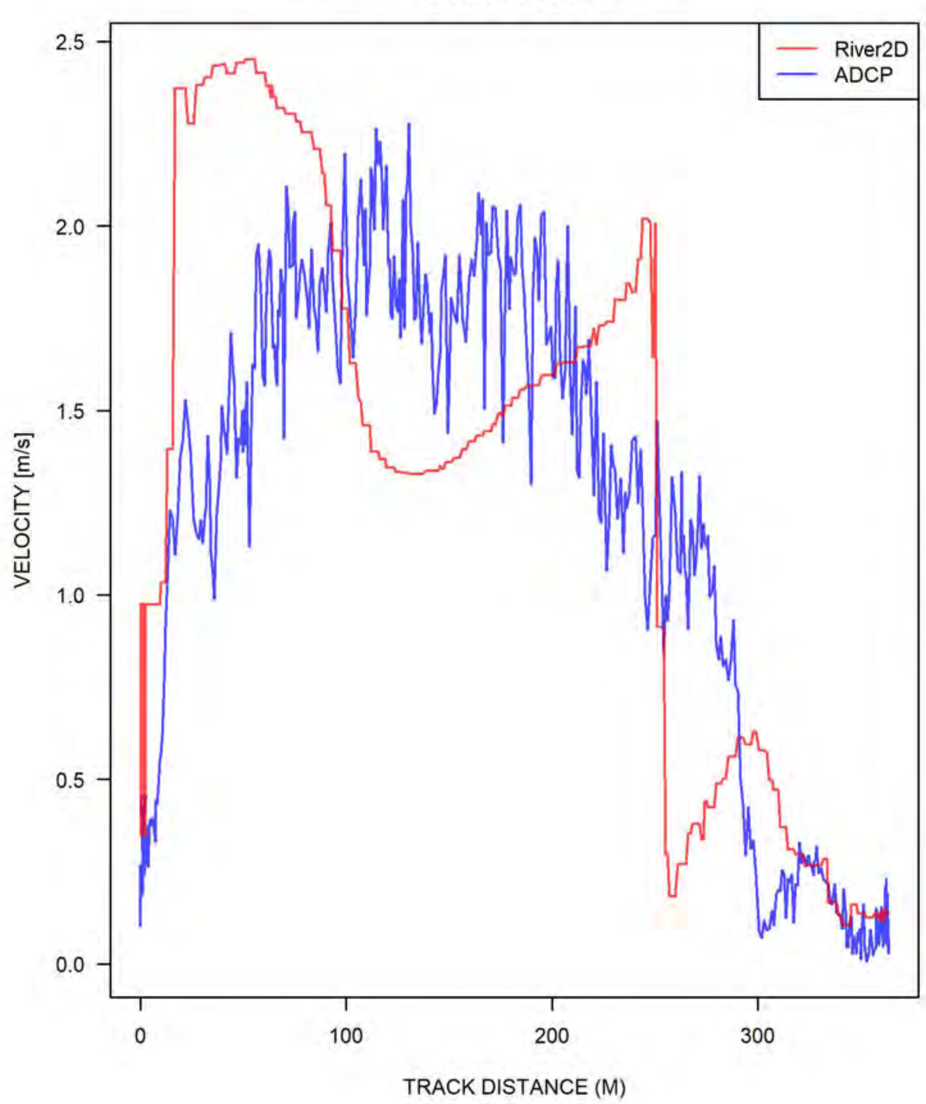
VELOCITY
5460500
5460000
5459500
5459000
5458500
5458000
5457500
452000
452500
453000
453500
454000
454500
8
6
4
2
0
VELOCITY (M/S)
River2D
ADCP
2.0
1.5
1.0
0.5
0
50
100
150
200
TRACK DISTANCE (M)
VELOCITY DISTRIBUTION (m/s)
R2D
ADCP
0.4
0.3
0.2
0.1
0.0
0 - 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
2.4 - 2.7
2.7 - 3
River2D Predictions
ADCP Observations
195.17

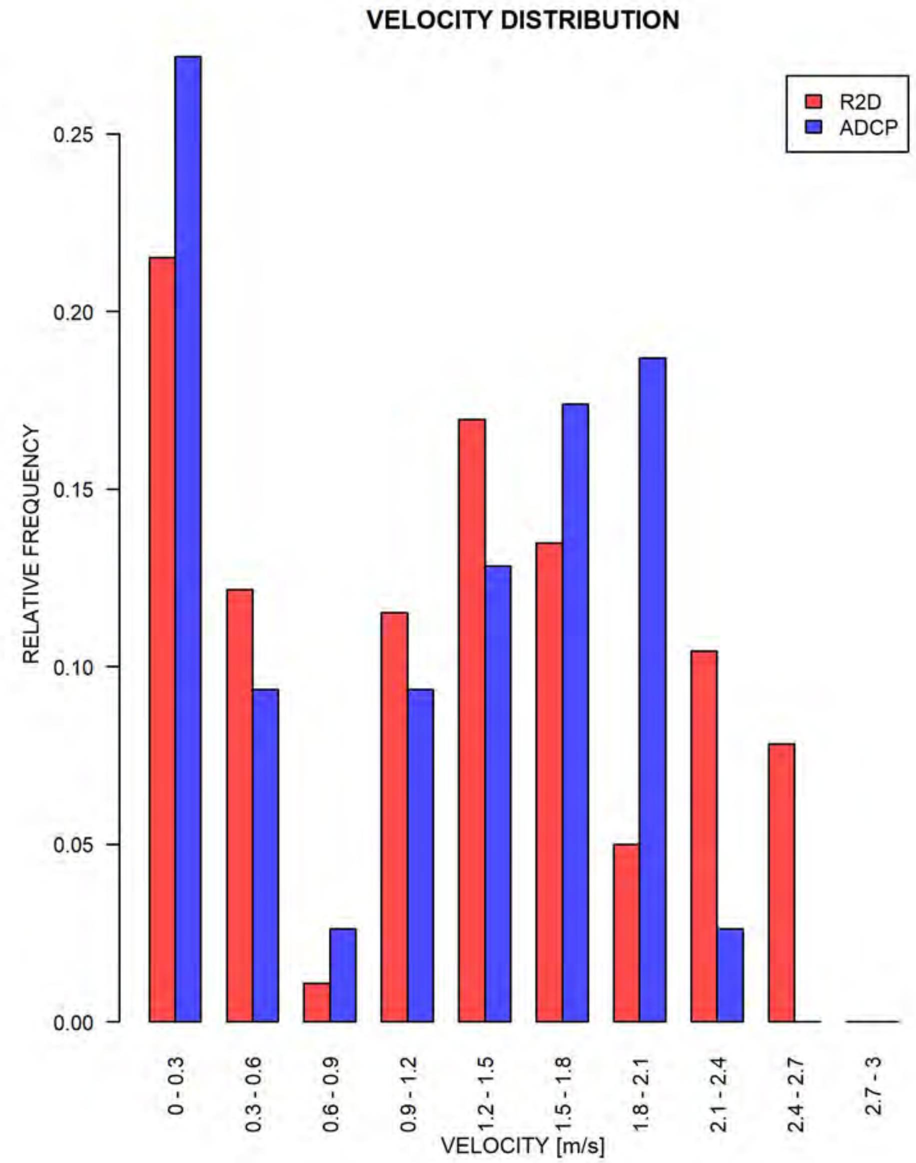

FT1 - Kinnaird U: 20180706105541
VELOCITY
VELOCITY (M/S)
0
2
4
6
8
452000
452500
453000
453500
454000
454500
5457500
5458000
5458500
5459000
5459500
5460000
5460500
River2D
ADCP
TRACK DISTANCE (M)
0
50
100
150
200
0.5
1.0
1.5
2.0
VELOCITY DISTRIBUTION (m/s)
R2D
ADCP
0.0
0.1
0.2
0.3
0.4
0 - 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
2.4 - 2.7
2.7 - 3
River2D Predictions
198.74
0.07
ADCP Observations
198.74
0.07
198.74
0.07

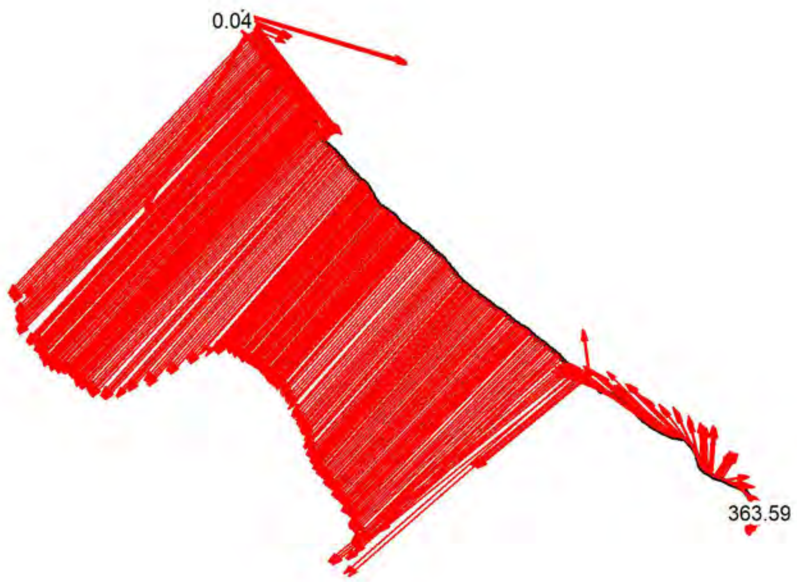

FT1 - Kinnaird U: 20180706111119
VELOCITY
VELOCITY (M/S)
River2D
ADCP
TRACK DISTANCE (M)
VELOCITY DISTRIBUTION (m/s)
R2D
ADCP
0 - 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
2.4 - 2.7
2.7 - 3
River2D Predictions
ADCP Observations
288.52
0.01

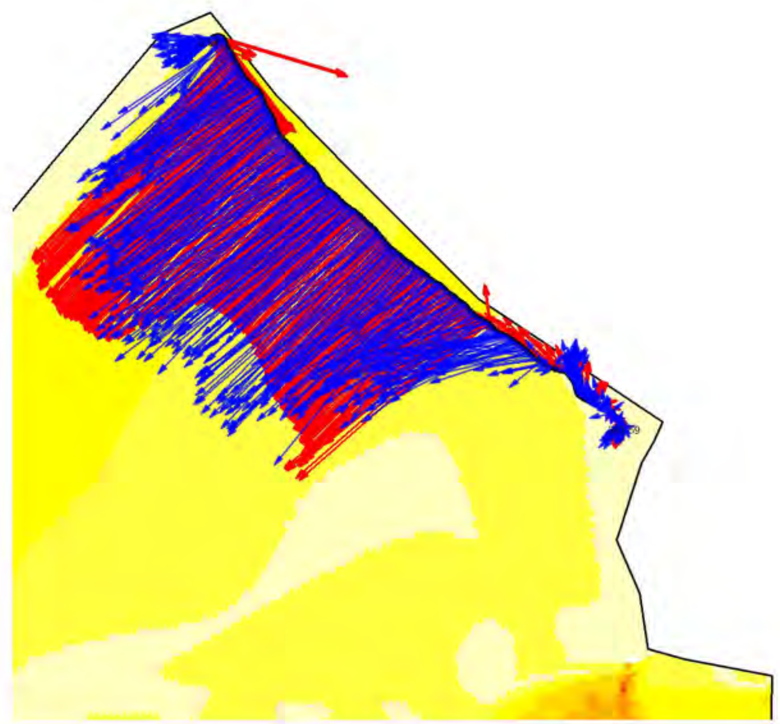

FT1 - Kinnaird U: 20180706112036
VELOCITY
VELOCITY (M/S)
5457500
5458000
5458500
5459000
5459500
5460000
5460500
452000
452500
453000
453500
454000
454500
0
2
4
6
8
River2D
ADCP
0.0
0.5
1.0
1.5
2.0
0
50
100
150
200
250
TRACK DISTANCE (M)
VELOCITY DISTRIBUTION (m/s)
R2D
ADCP
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0 - 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
2.4 - 2.7
2.7 - 3
River2D Predictions
0.03
284.64
ADCP Observations
0.03
284.64
0.03
284.64

FT1 - Waneta: 20180707103043

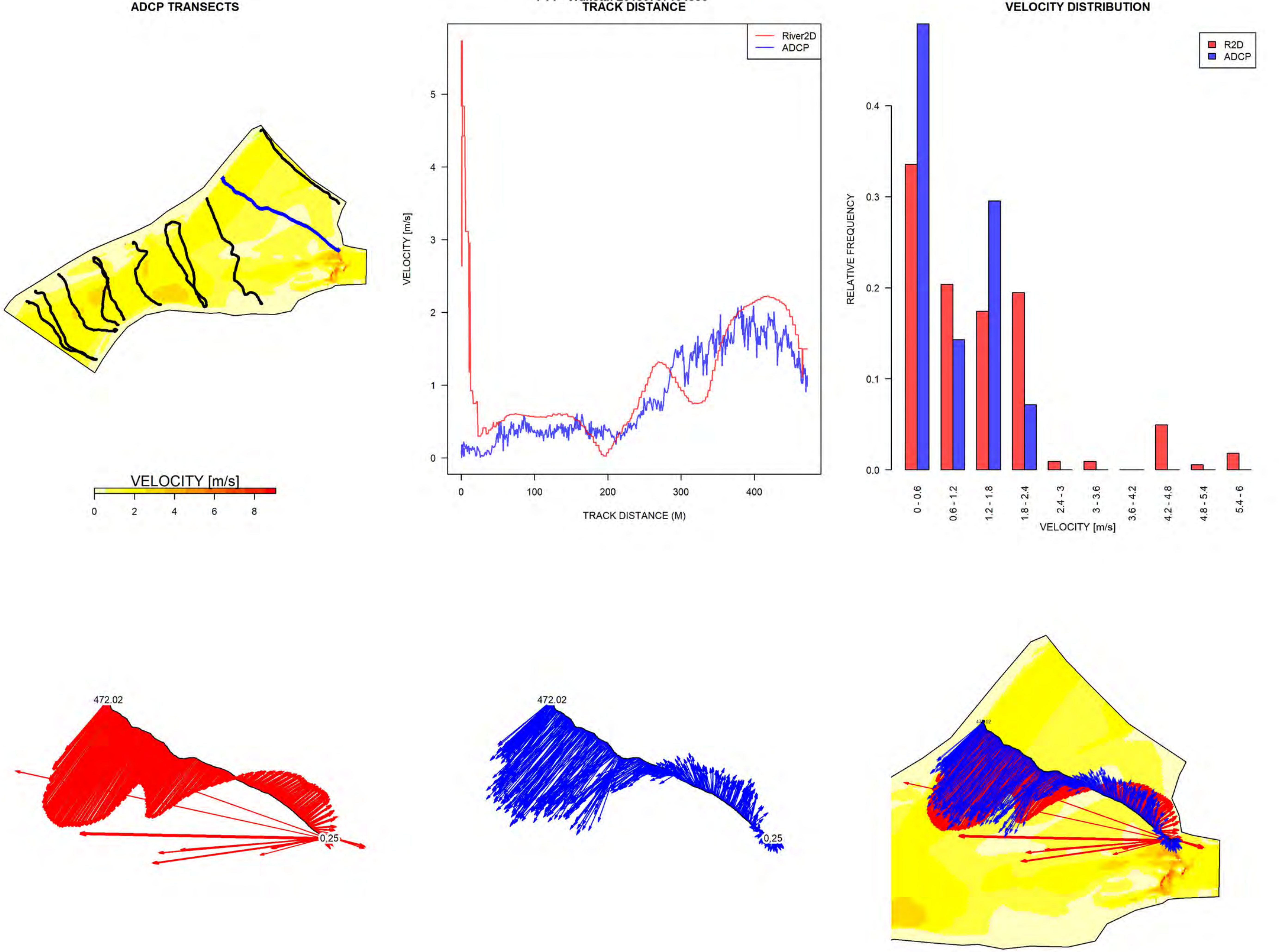




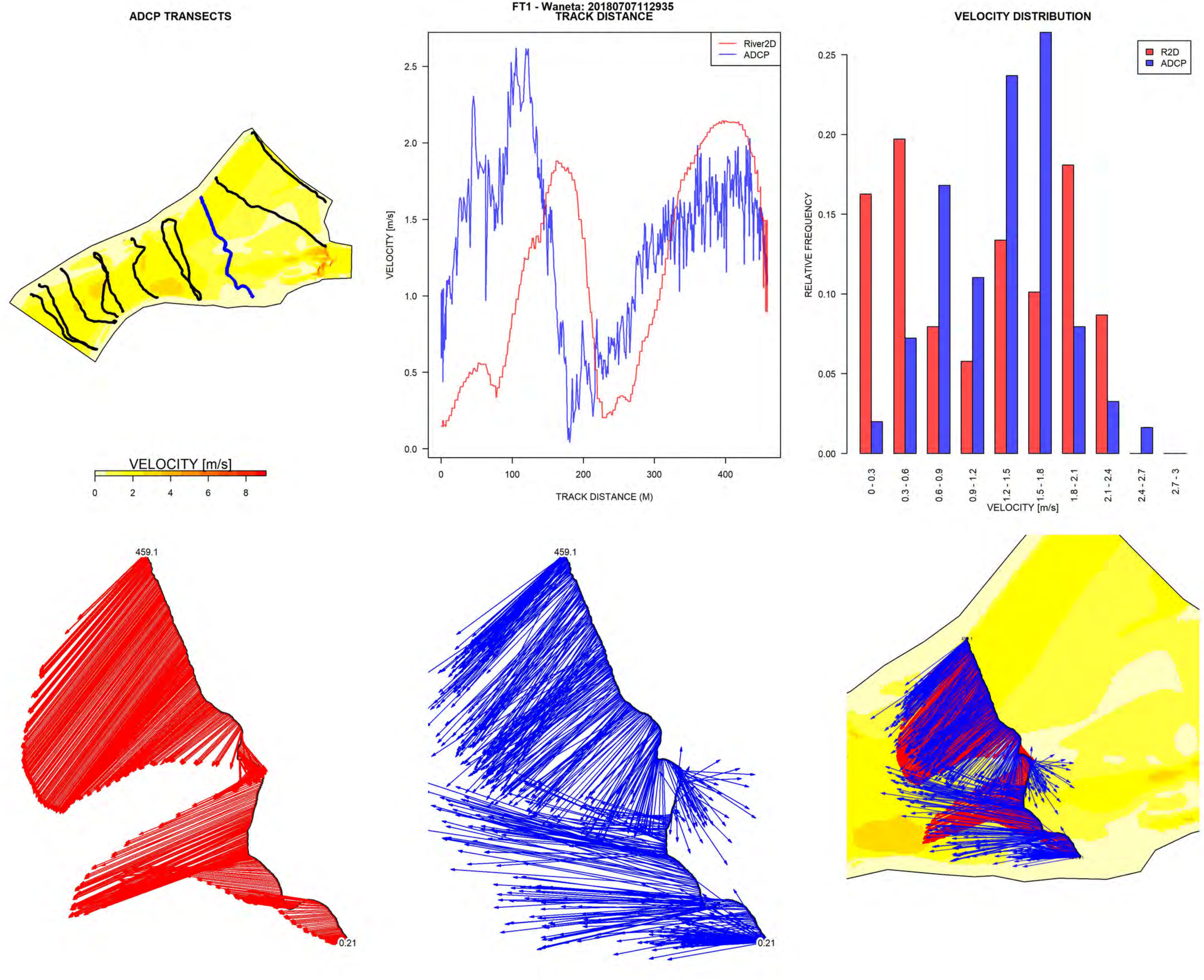


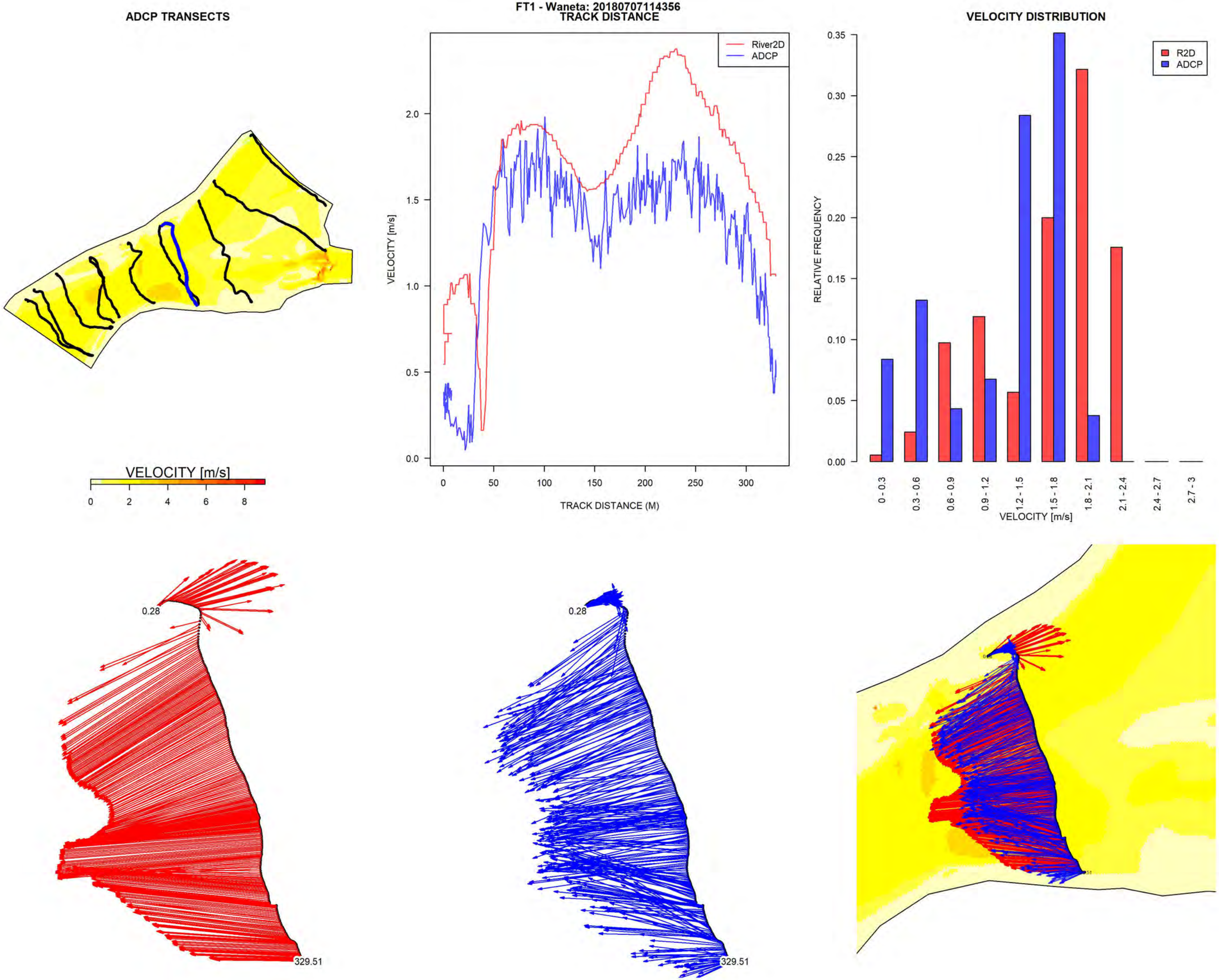


FT1 - Waneta: 20180707104856



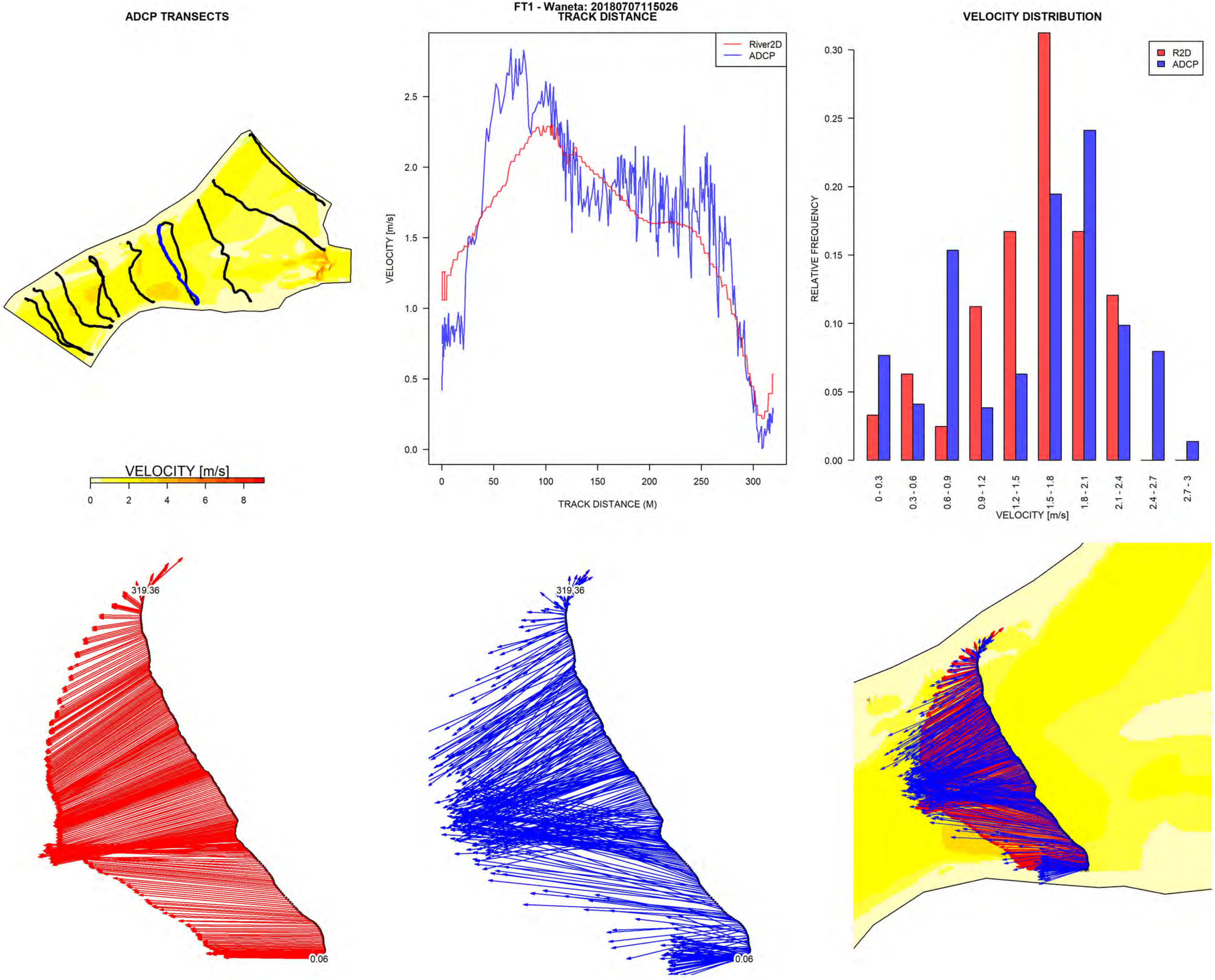
FT1 - Waneta: 20180707112935



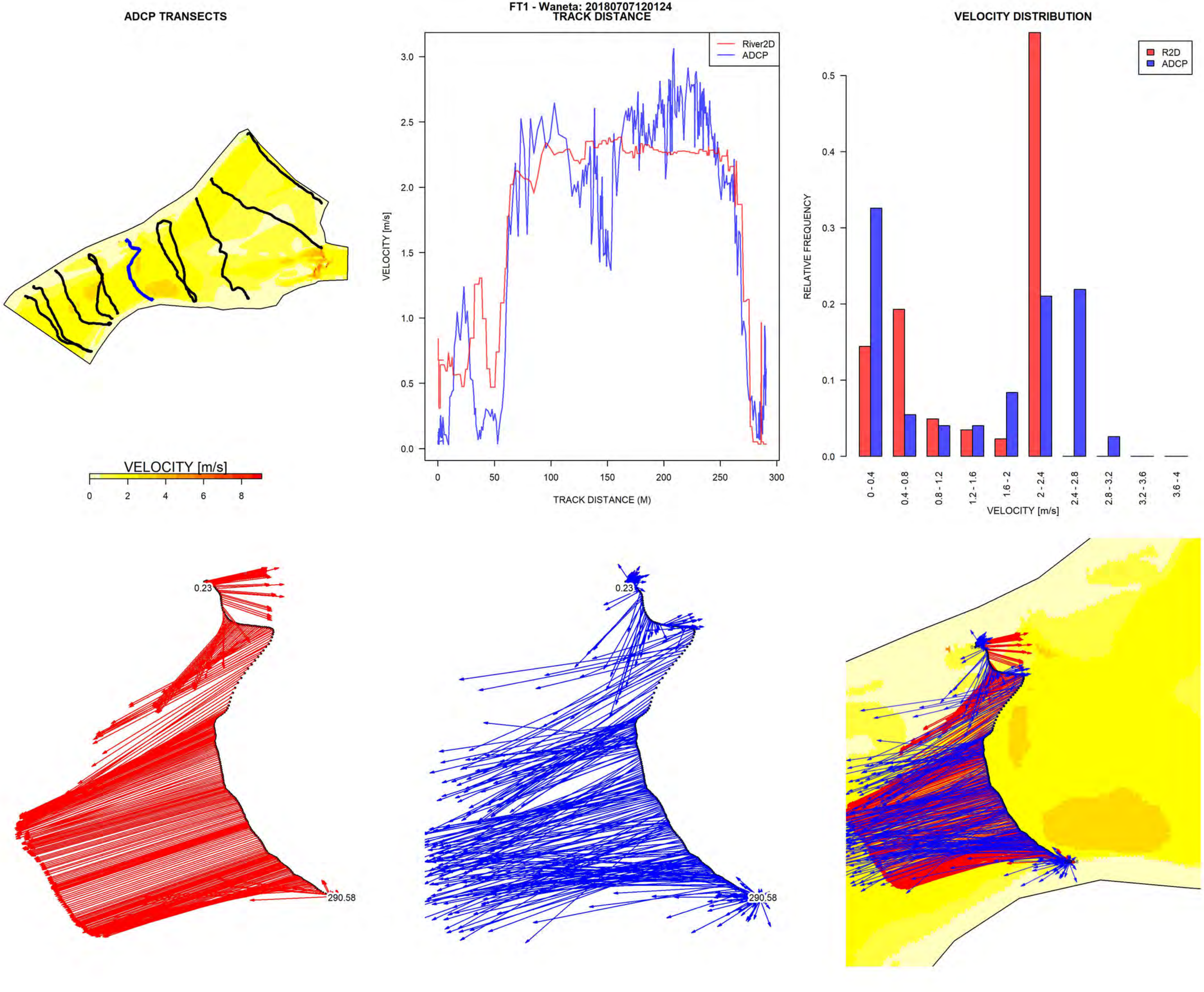


FT1 - Waneta: 20180707114356
ADCP TRANSECTS
VELOCITY [m/s]
0
2
4
6
8
TRACK DISTANCE
River2D
ADCP
VELOCITY [m/s]
TRACK DISTANCE (M)
VELOCITY DISTRIBUTION
R2D
ADCP
RELATIVE FREQUENCY
0 - 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
2.4 - 2.7
2.7 - 3
VELOCITY [m/s]
0.28
329.51
0.28
329.51

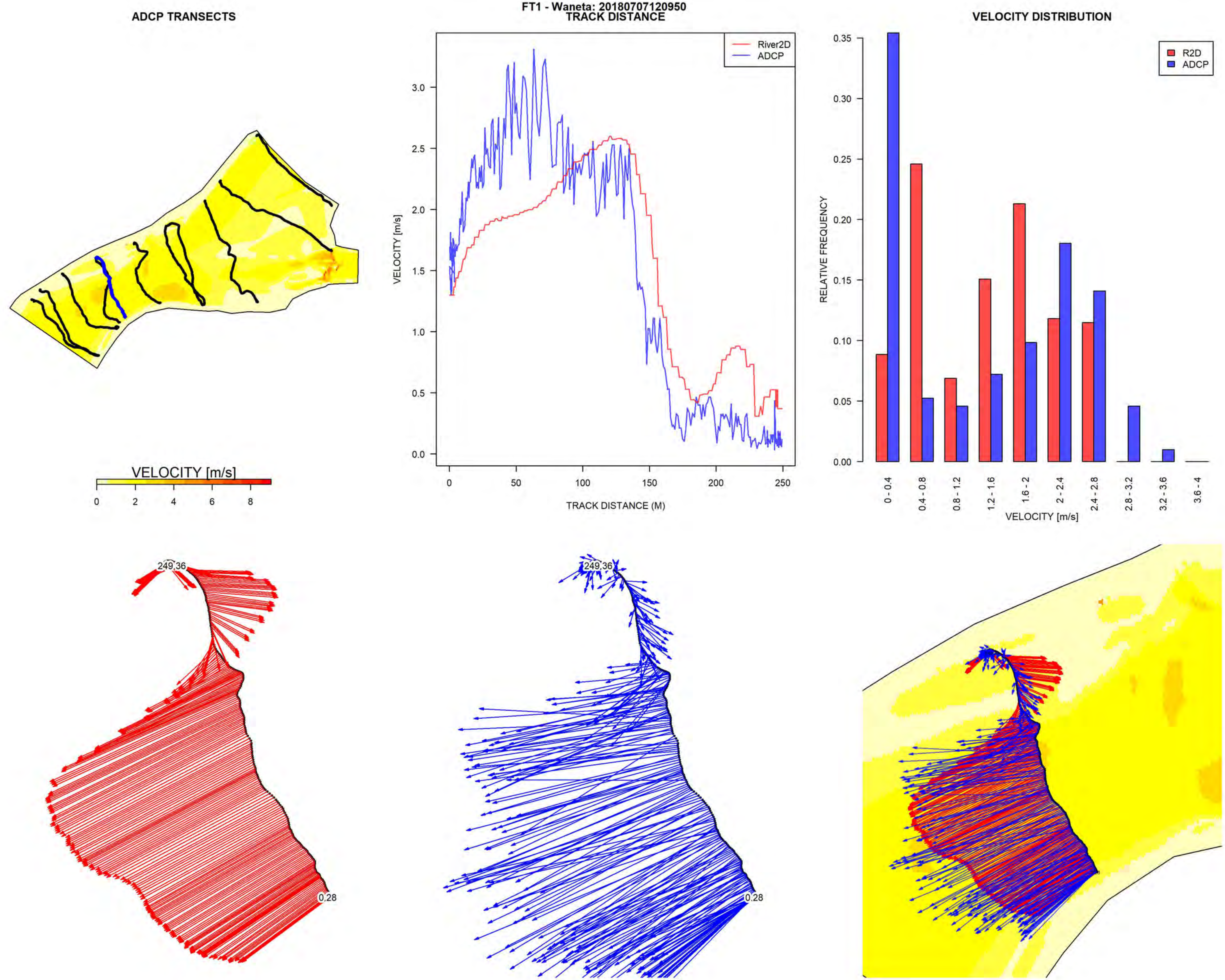
FT1 - Waneta: 20180707115026

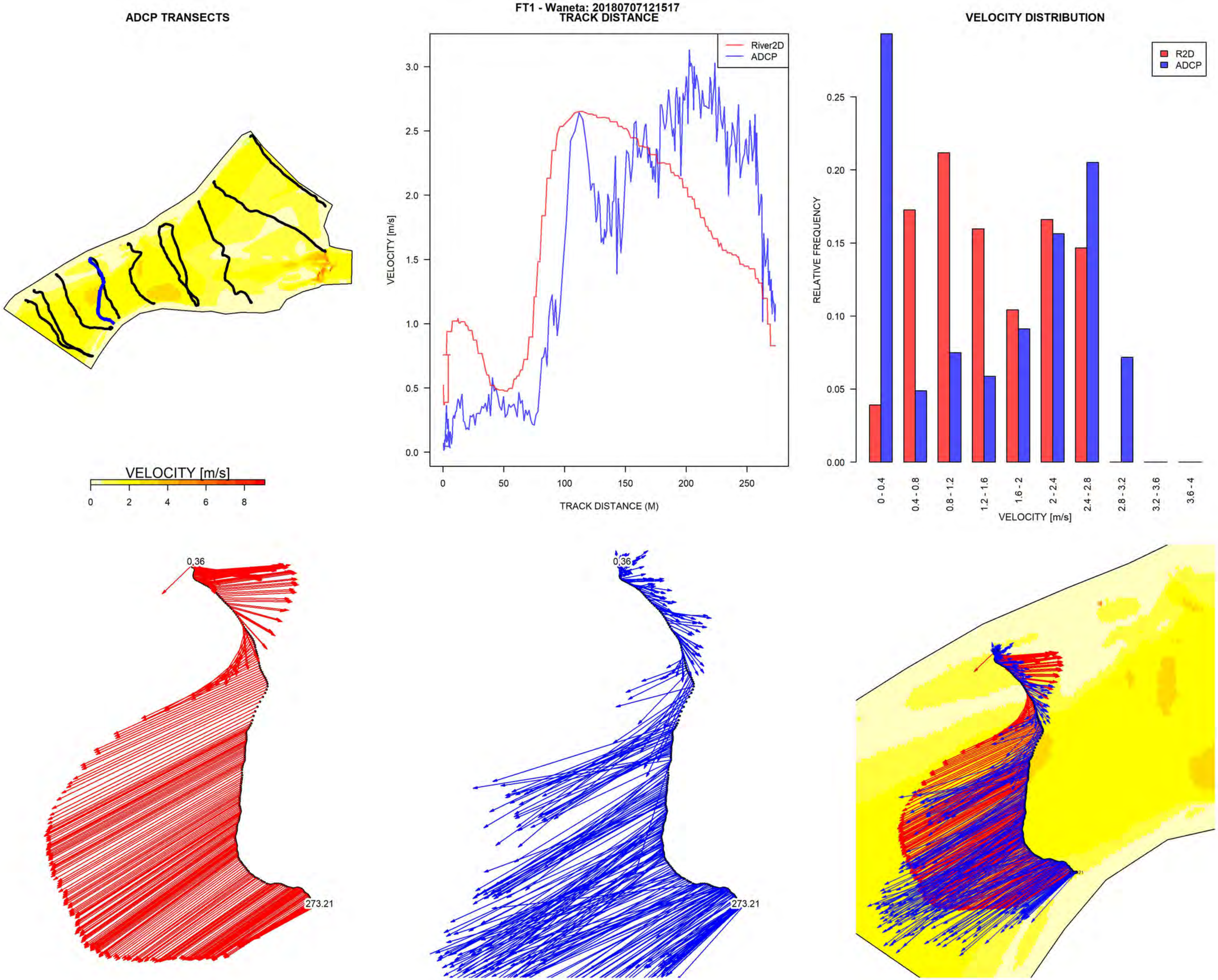


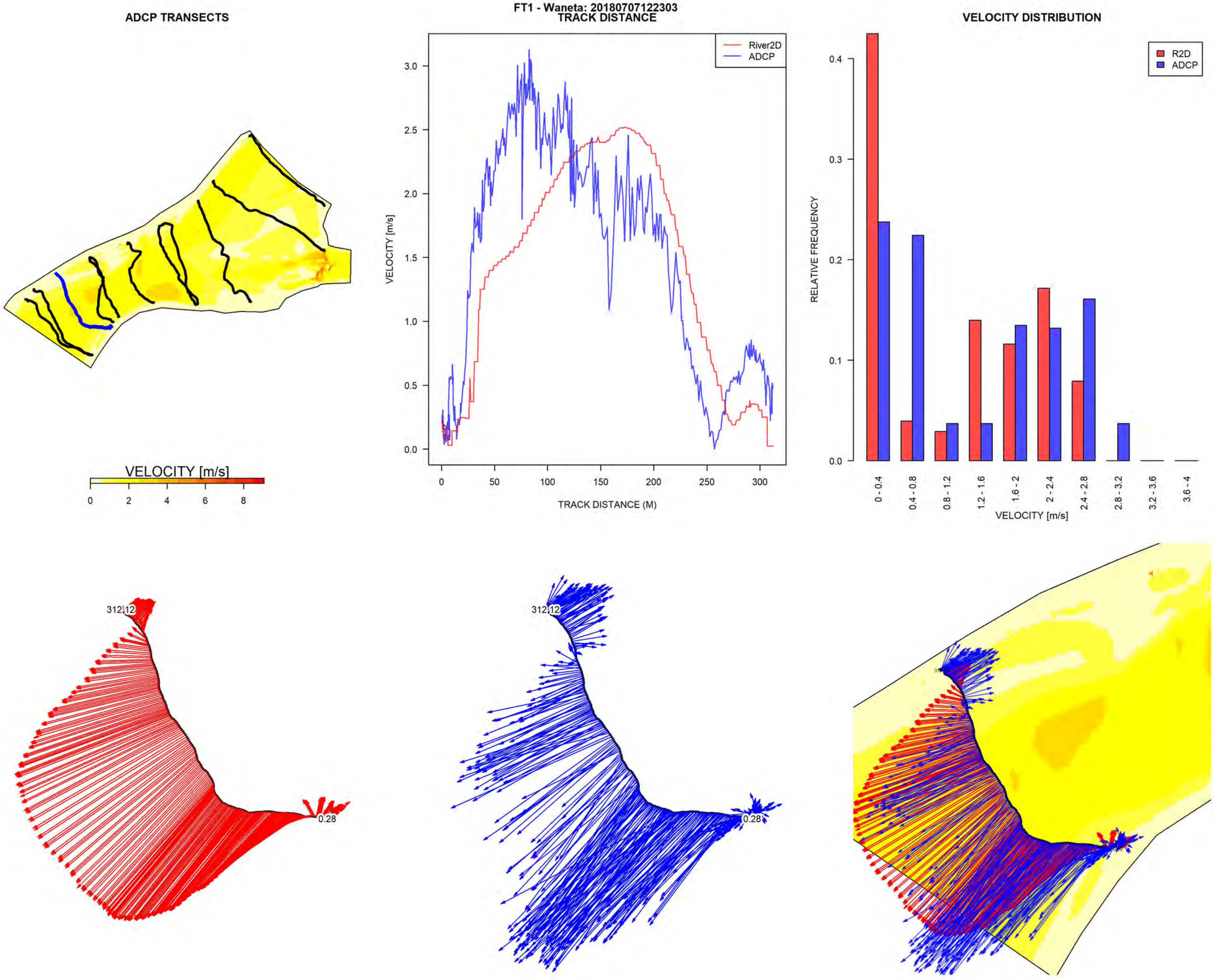
FT1 - Waneta: 20180707120124

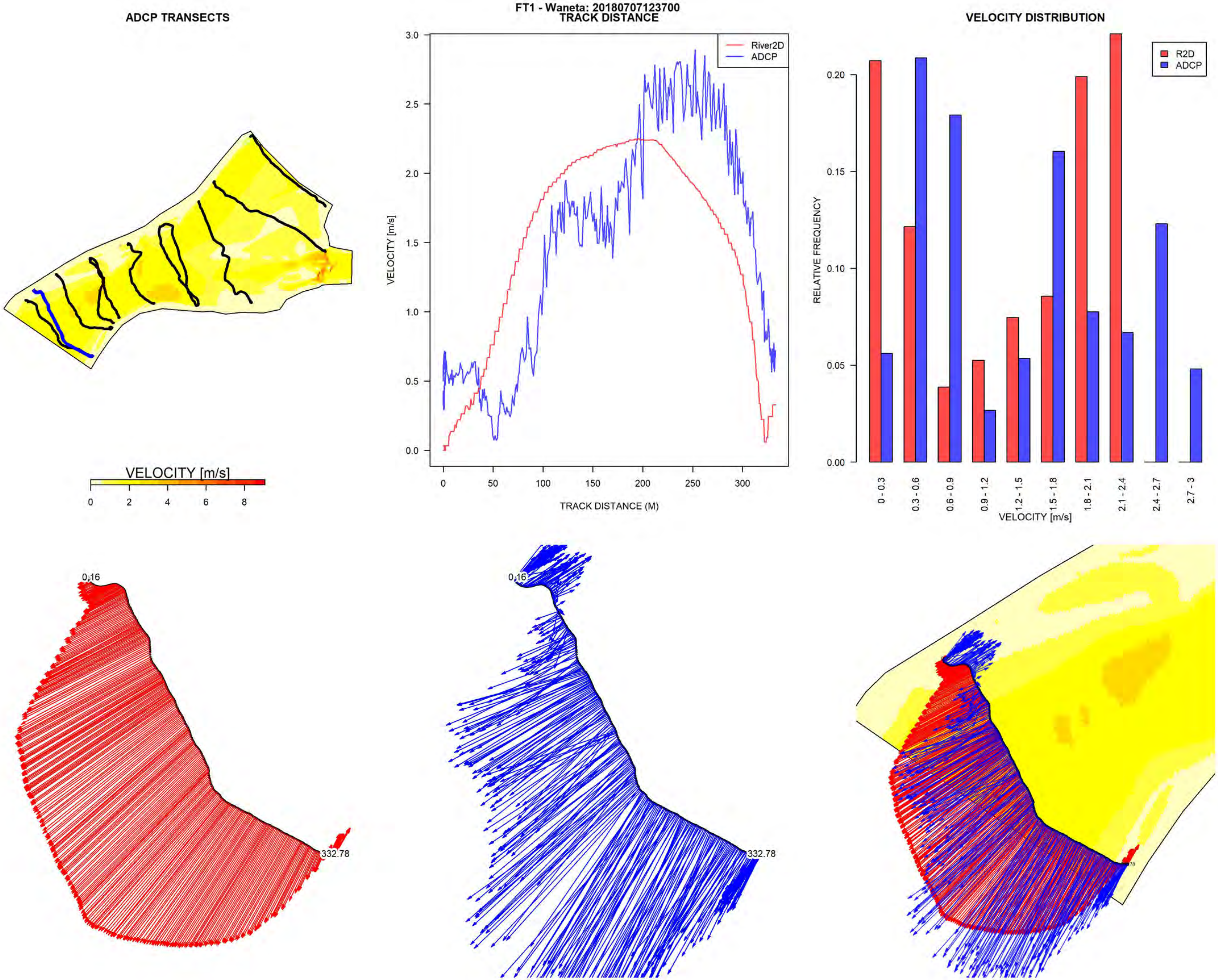


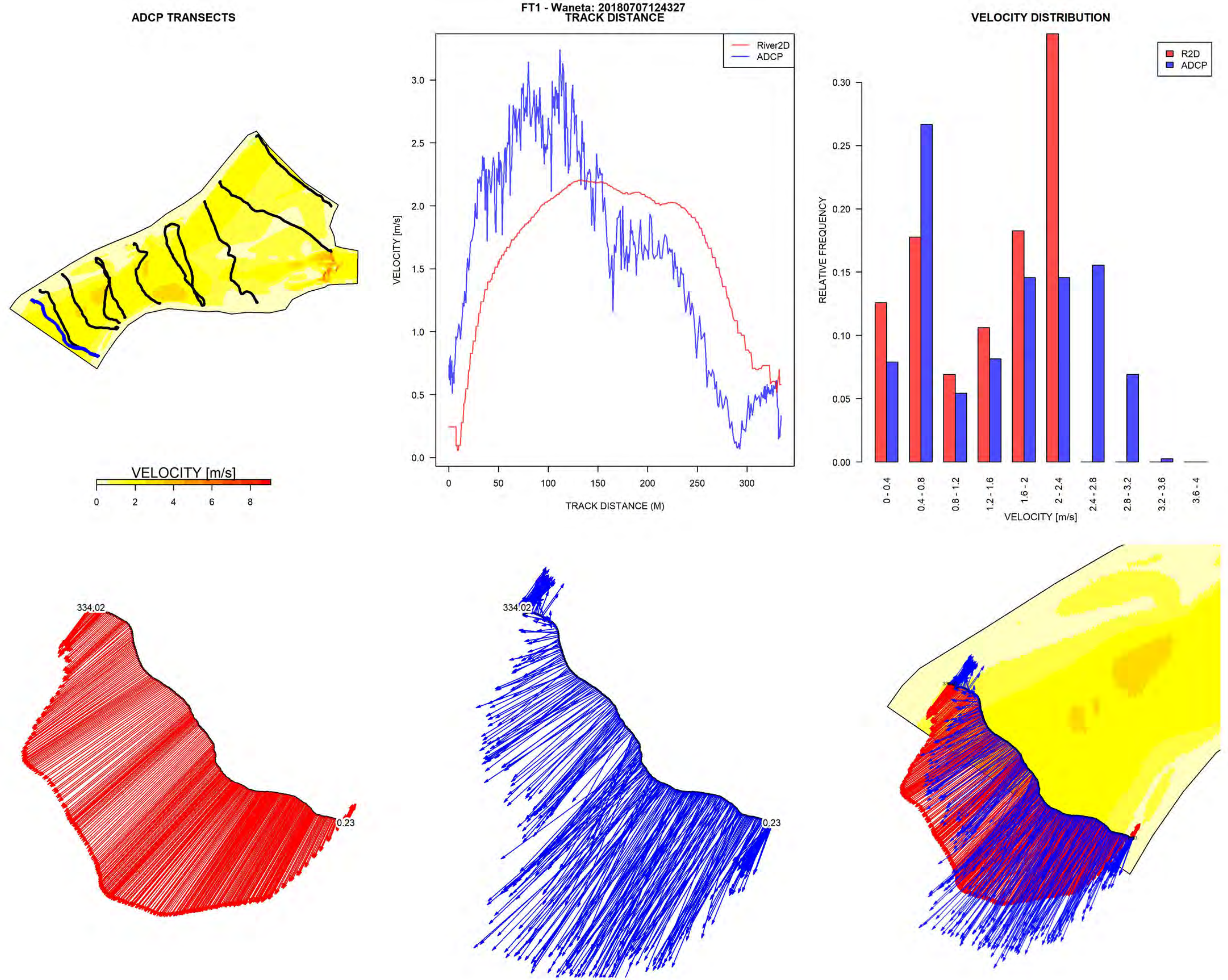
FT1 - Waneta: 20180707120950



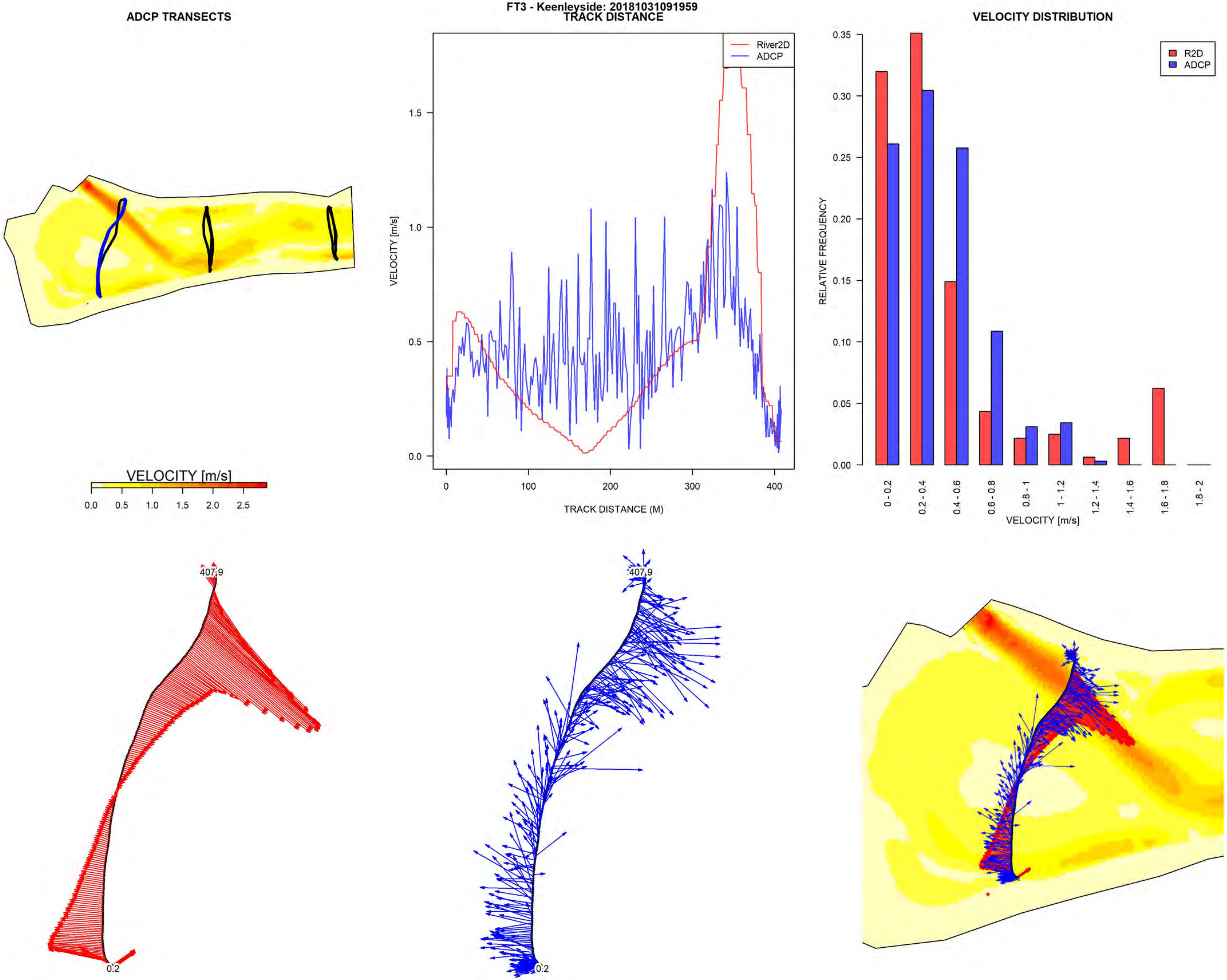

FT1 - Waneta: 20180707121517
ADCP TRANSECTS
TRACK DISTANCE
VELOCITY DISTRIBUTION
VELOCITY [m/s]
0
2
4
6
8
River2D
ADCP
VELOCITY [m/s]
TRACK DISTANCE (M)
R2D
ADCP
RELATIVE FREQUENCY
VELOCITY [m/s]
0 - 0.4
0.4 - 0.8
0.8 - 1.2
1.2 - 1.6
1.6 - 2
2 - 2.4
2.4 - 2.8
2.8 - 3.2
3.2 - 3.6
3.6 - 4
0.36
273.21
0.36
273.21


FT1 - Waneta: 20180707122303
ADCP TRANSECTS
VELOCITY [m/s]
0
2
4
6
8
TRACK DISTANCE
River2D
ADCP
VELOCITY [m/s]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
50
100
150
200
250
300
TRACK DISTANCE (M)
VELOCITY DISTRIBUTION
R2D
ADCP
RELATIVE FREQUENCY
0.4
0.3
0.2
0.1
0.0
0 - 0.4
0.4 - 0.8
0.8 - 1.2
1.2 - 1.6
1.6 - 2
2 - 2.4
2.4 - 2.8
2.8 - 3.2
3.2 - 3.6
3.6 - 4
VELOCITY [m/s]
312.12
0.28
312.12
0.28

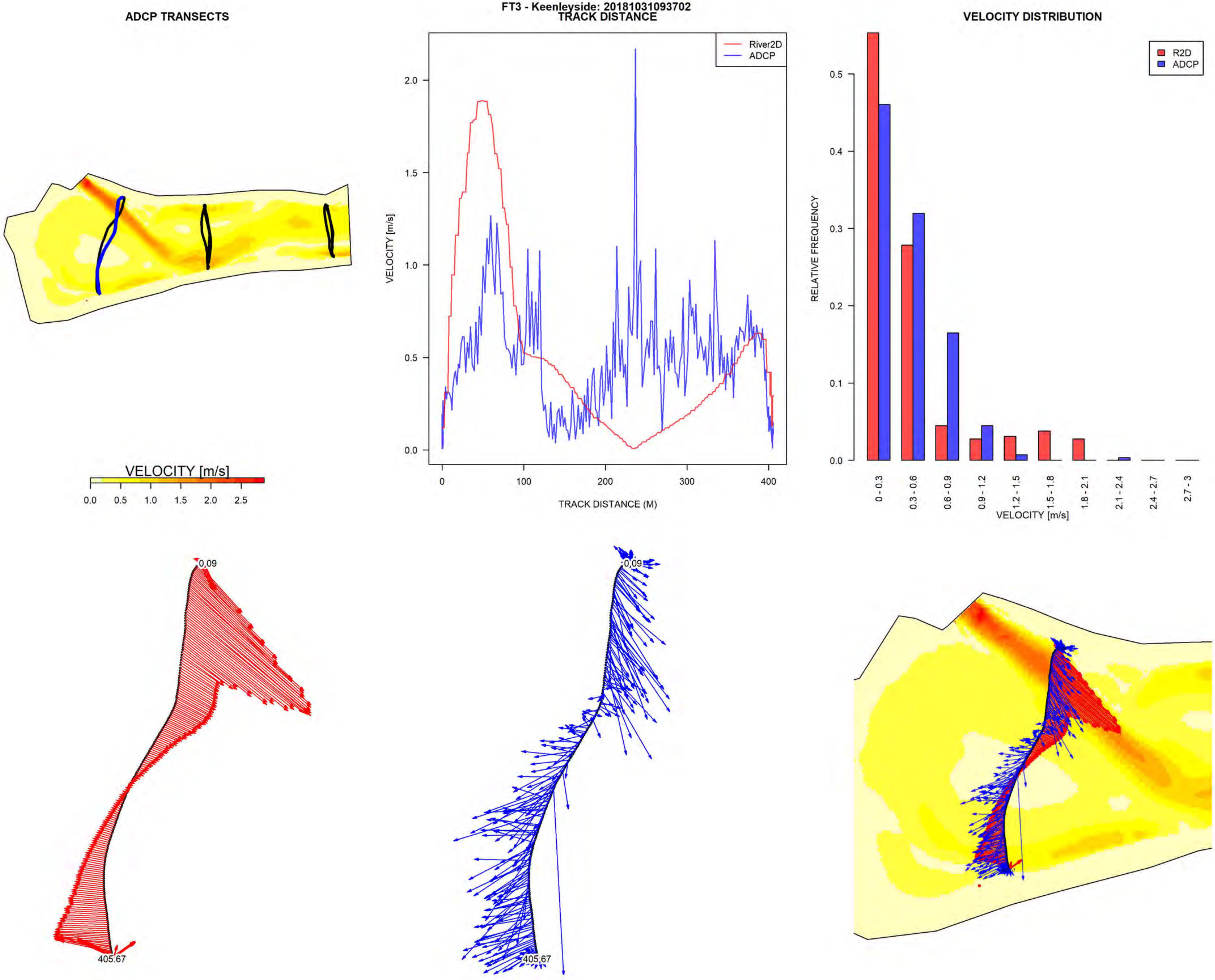

FT1 - Waneta: 20180707123700
ADCP TRANSECTS
VELOCITY [m/s]
0
2
4
6
8
TRACK DISTANCE
River2D
ADCP
VELOCITY [m/s]
TRACK DISTANCE (M)
0
50
100
150
200
250
300
0.0
0.5
1.0
1.5
2.0
2.5
3.0
VELOCITY DISTRIBUTION
R2D
ADCP
RELATIVE FREQUENCY
0.00
0.05
0.10
0.15
0.20
0 - 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
2.4 - 2.7
2.7 - 3
VELOCITY [m/s]
0.16
332.78
0.16
332.78


FT1 - Waneta: 20180707124327
ADCP TRANSECTS
VELOCITY [m/s]
0
2
4
6
8
TRACK DISTANCE
River2D
ADCP
VELOCITY [m/s]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
50
100
150
200
250
300
TRACK DISTANCE (M)
VELOCITY DISTRIBUTION
R2D
ADCP
RELATIVE FREQUENCY
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0 - 0.4
0.4 - 0.8
0.8 - 1.2
1.2 - 1.6
1.6 - 2
2 - 2.4
2.4 - 2.8
2.8 - 3.2
3.2 - 3.6
3.6 - 4
VELOCITY [m/s]
334.02
0.23
334.02
0.23

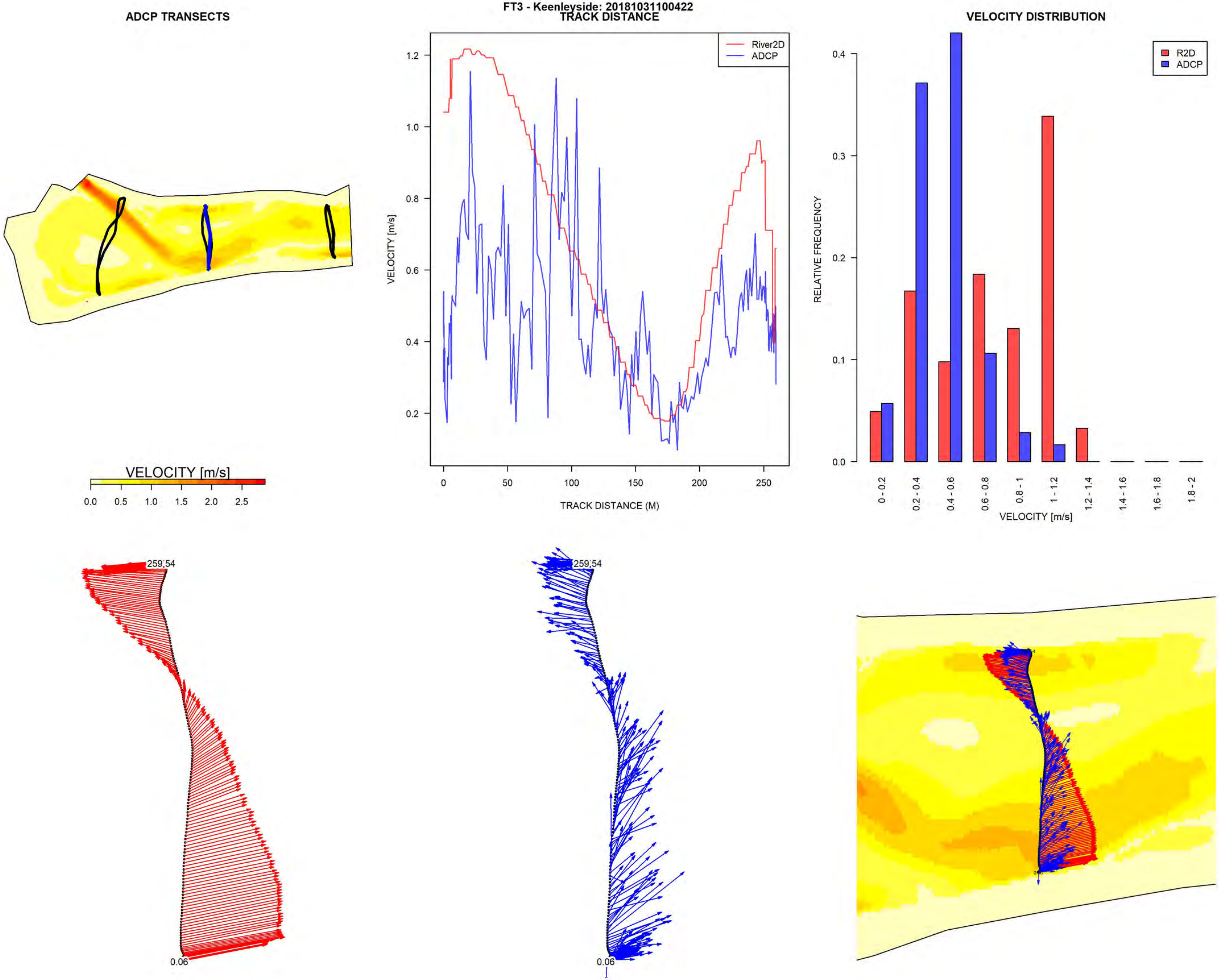
FT3 - Keenleyside: 20181031091959

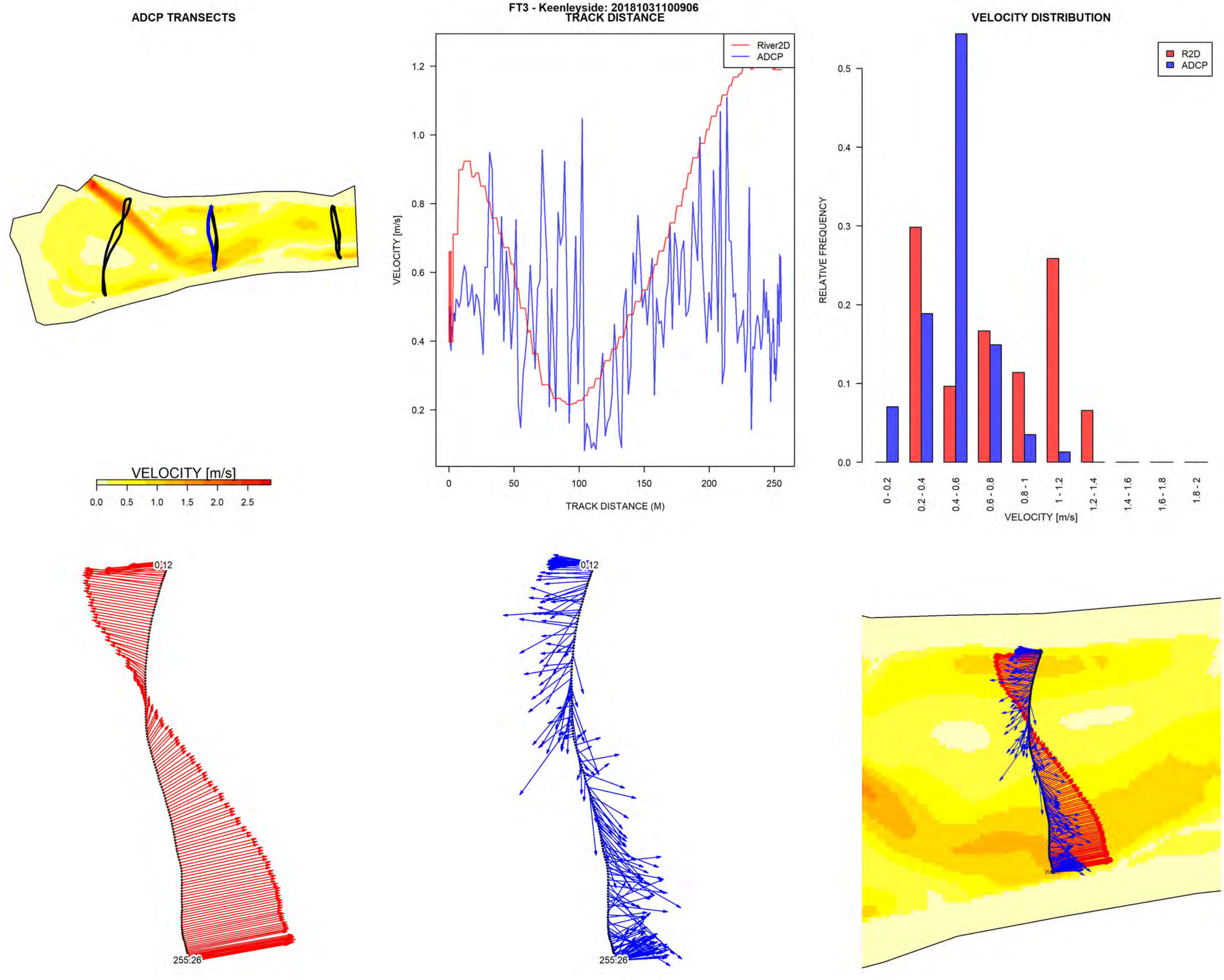


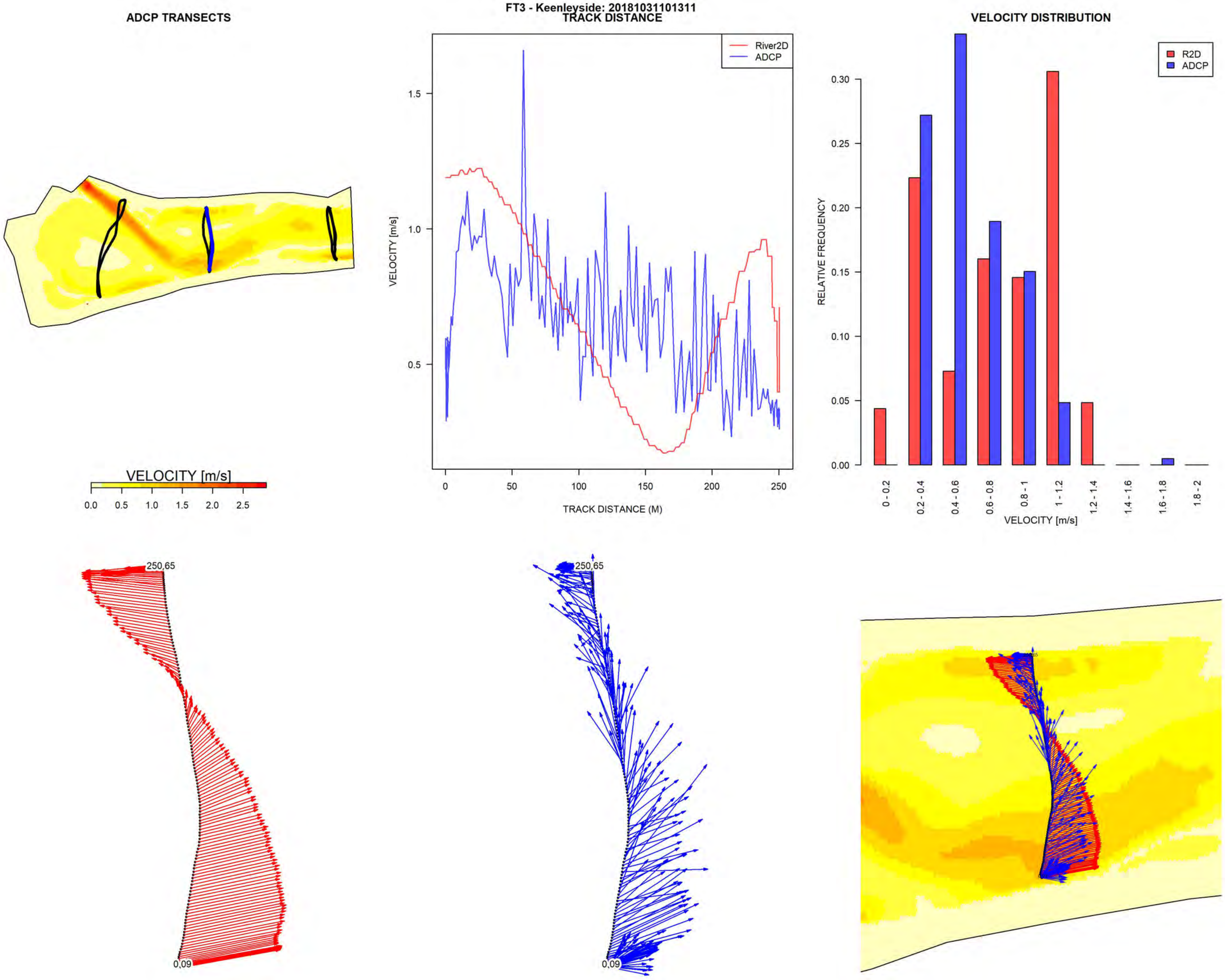
FT3 - Keenleyside: 20181031093702



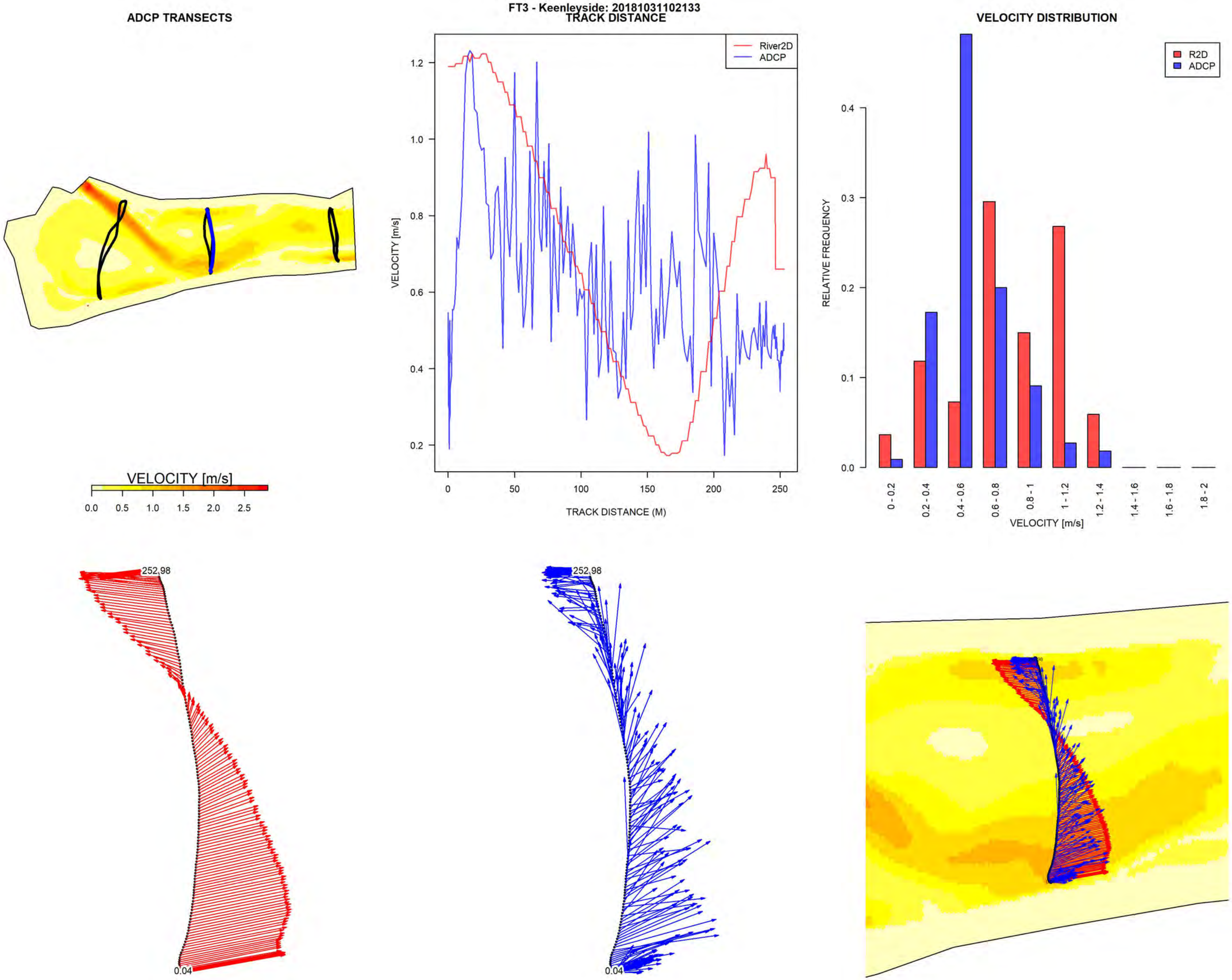
FT3 - Keenleyside: 20181031100422



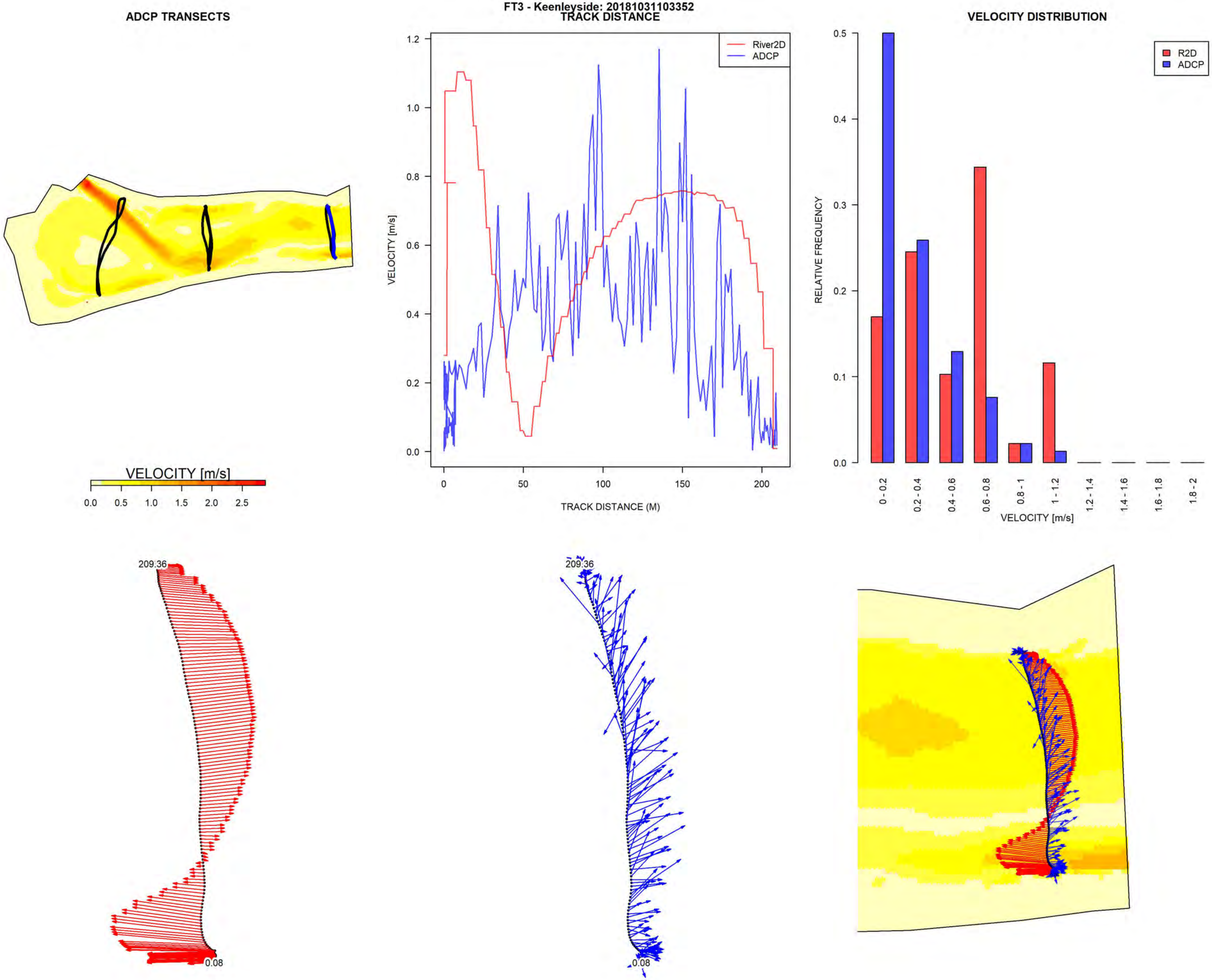

FT3 - Keenleyside: 20181031100906
ADCP TRANSECTS
VELOCITY [m/s]
0.0 0.5 1.0 1.5 2.0 2.5
TRACK DISTANCE
River2D
ADCP
VELOCITY [m/s]
TRACK DISTANCE (M)
VELOCITY DISTRIBUTION
R2D
ADCP
RELATIVE FREQUENCY
VELOCITY [m/s]
0 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 1
1 - 1.2
1.2 - 1.4
1.4 - 1.6
1.6 - 1.8
1.8 - 2
0.12
255.26



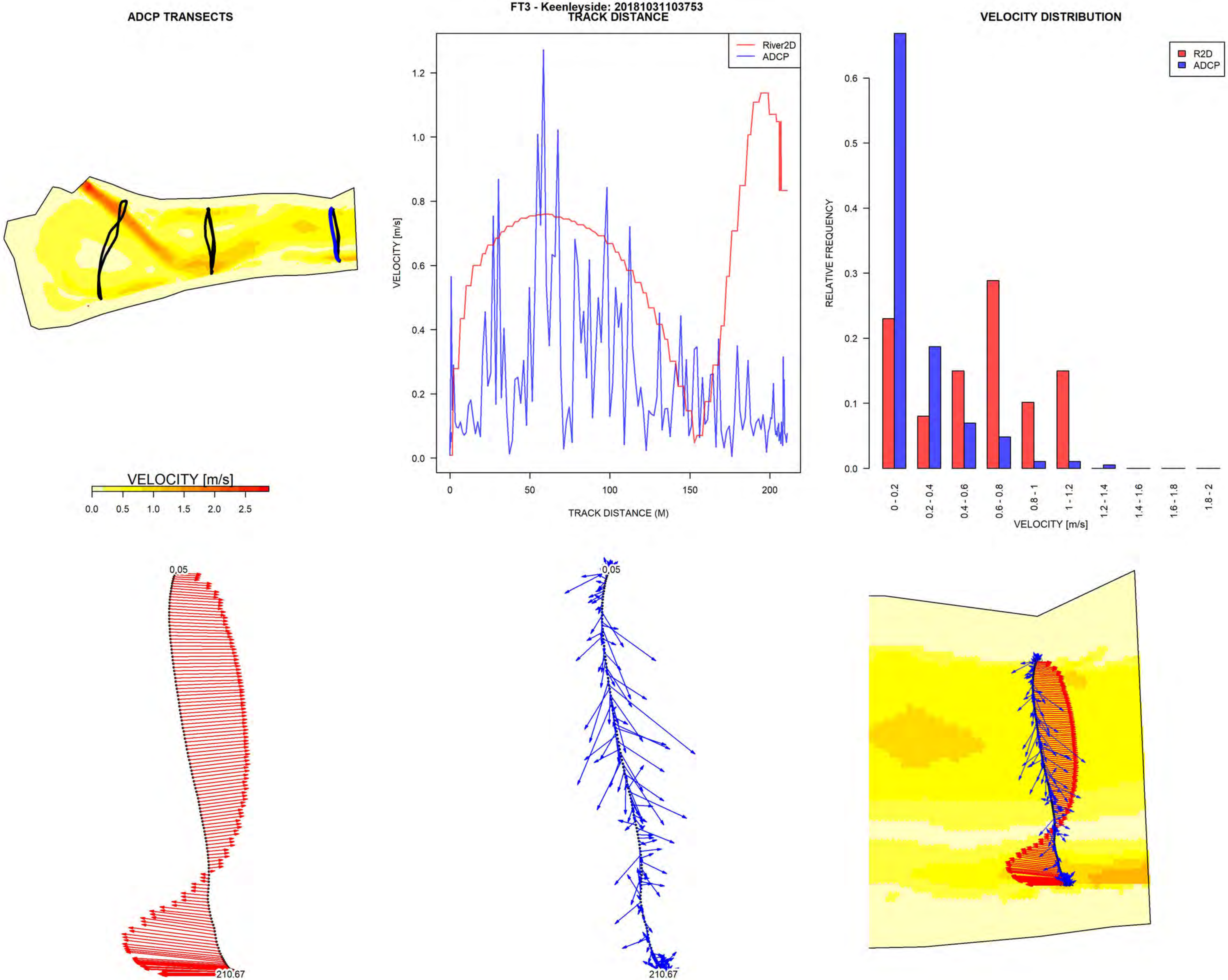
FT3 - Keenleyside: 20181031101311
ADCP TRANSECTS
VELOCITY [m/s]
0.0 0.5 1.0 1.5 2.0 2.5
TRACK DISTANCE
River2D
ADCP
VELOCITY [m/s]
TRACK DISTANCE (M)
0 50 100 150 200 250
0.5 1.0 1.5
VELOCITY DISTRIBUTION
R2D
ADCP
RELATIVE FREQUENCY
0.00 0.05 0.10 0.15 0.20 0.25 0.30
0 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 1
1 - 1.2
1.2 - 1.4
1.4 - 1.6
1.6 - 1.8
1.8 - 2
VELOCITY [m/s]
250,65
0,09
250,65
0,09


FT3 - Keenleyside: 20181031102133
ADCP TRANSECTS
TRACK DISTANCE
VELOCITY DISTRIBUTION
VELOCITY [m/s]
0.0 0.5 1.0 1.5 2.0 2.5
River2D
ADCP
VELOCITY [m/s]
TRACK DISTANCE (M)
R2D
ADCP
RELATIVE FREQUENCY
0 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 1
1 - 1.2
1.2 - 1.4
1.4 - 1.6
1.6 - 1.8
1.8 - 2
VELOCITY [m/s]
252.98
0.04
252.98
0.04

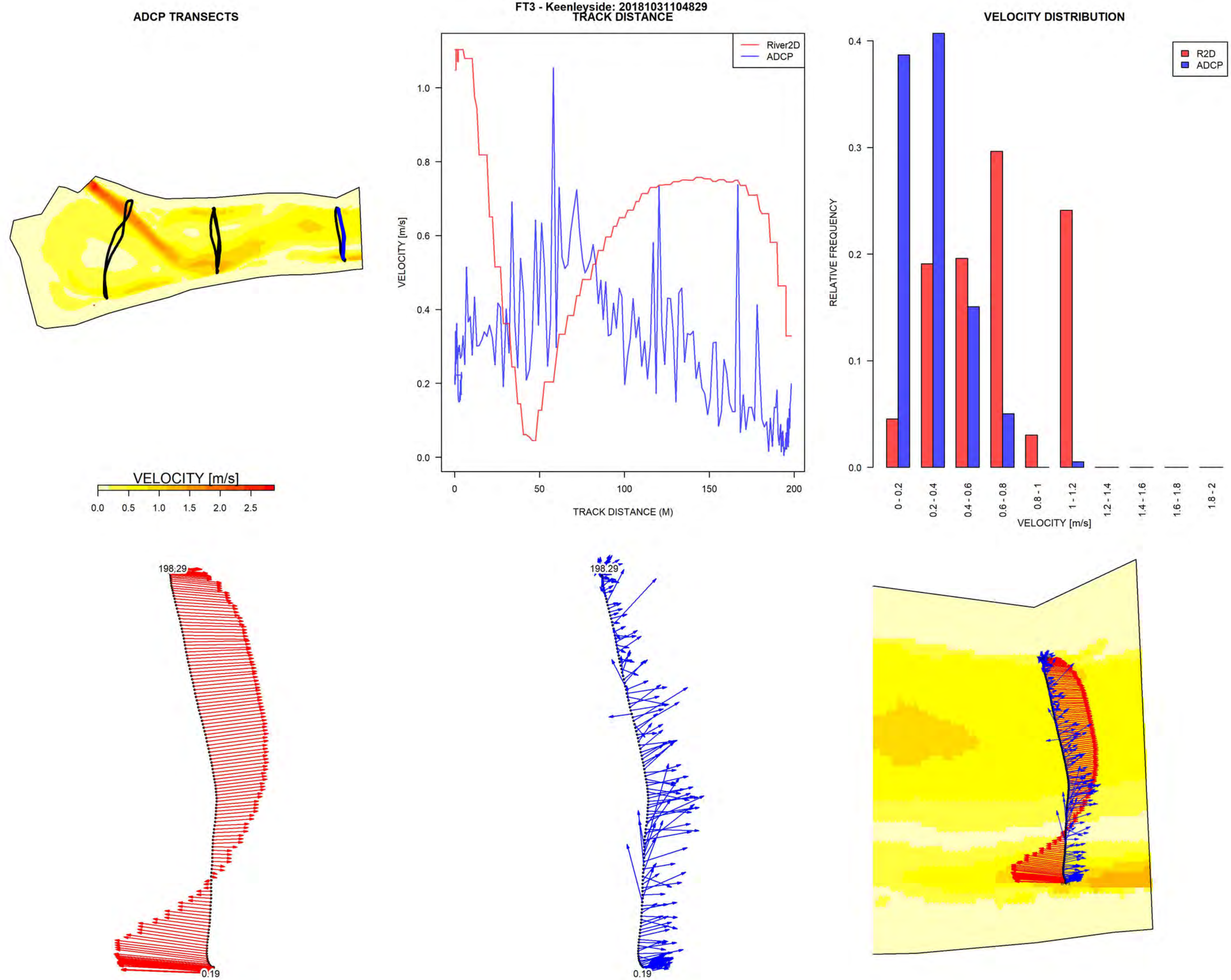
FT3 - Keenleyside: 20181031103352



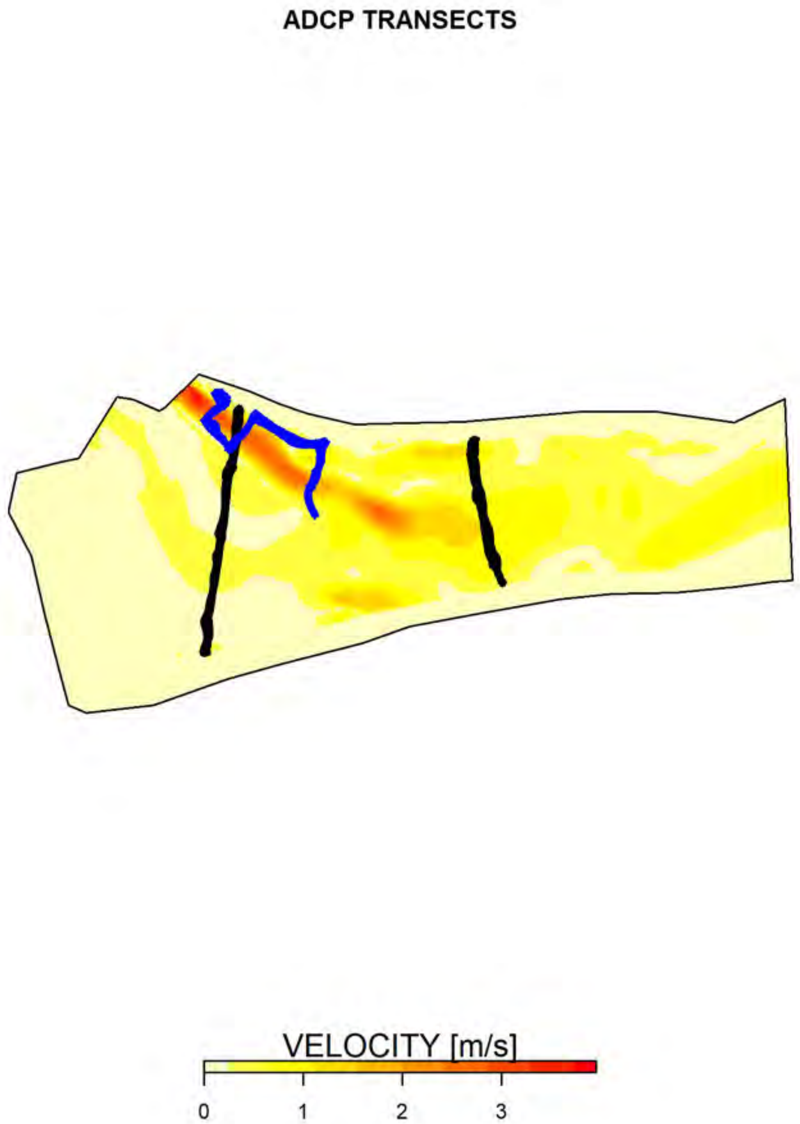
FT3 - Keenleyside: 20181031103753

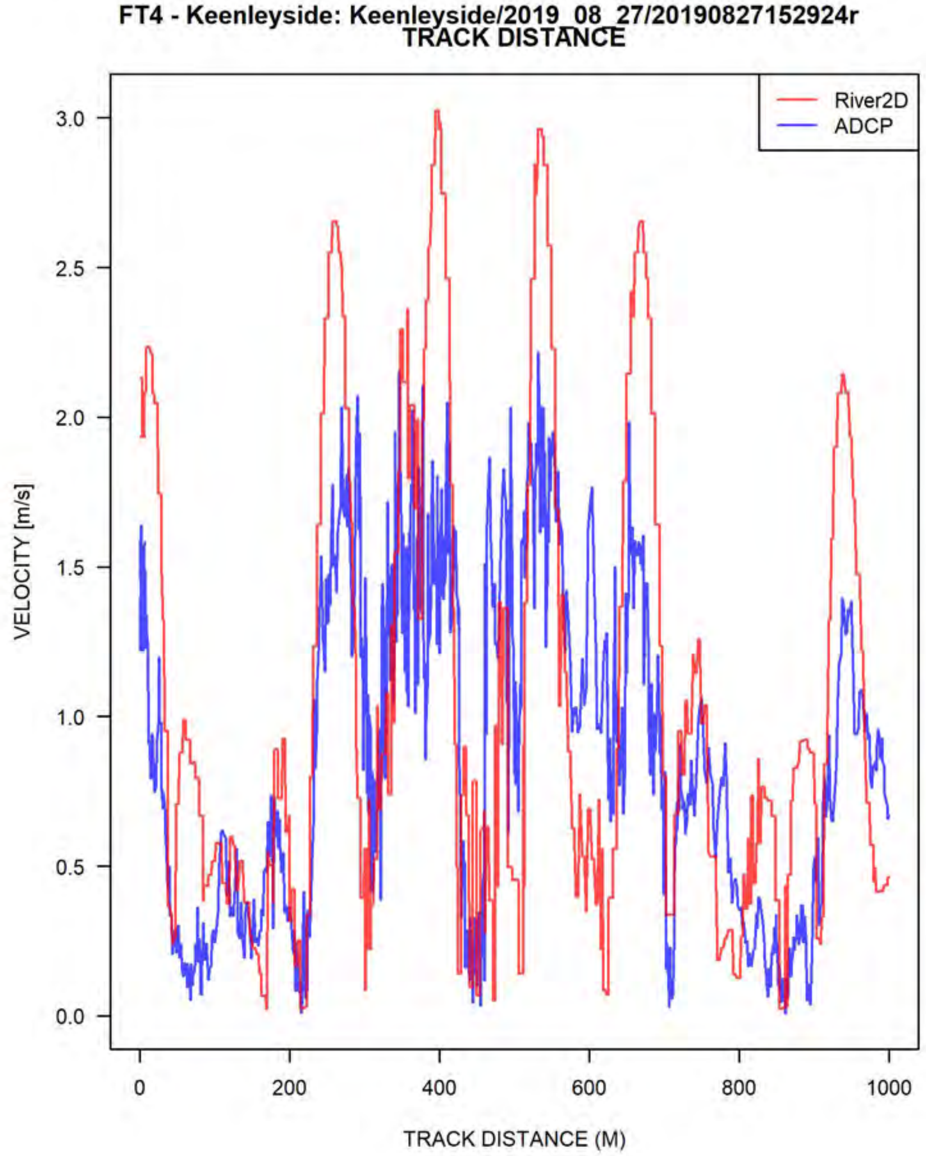


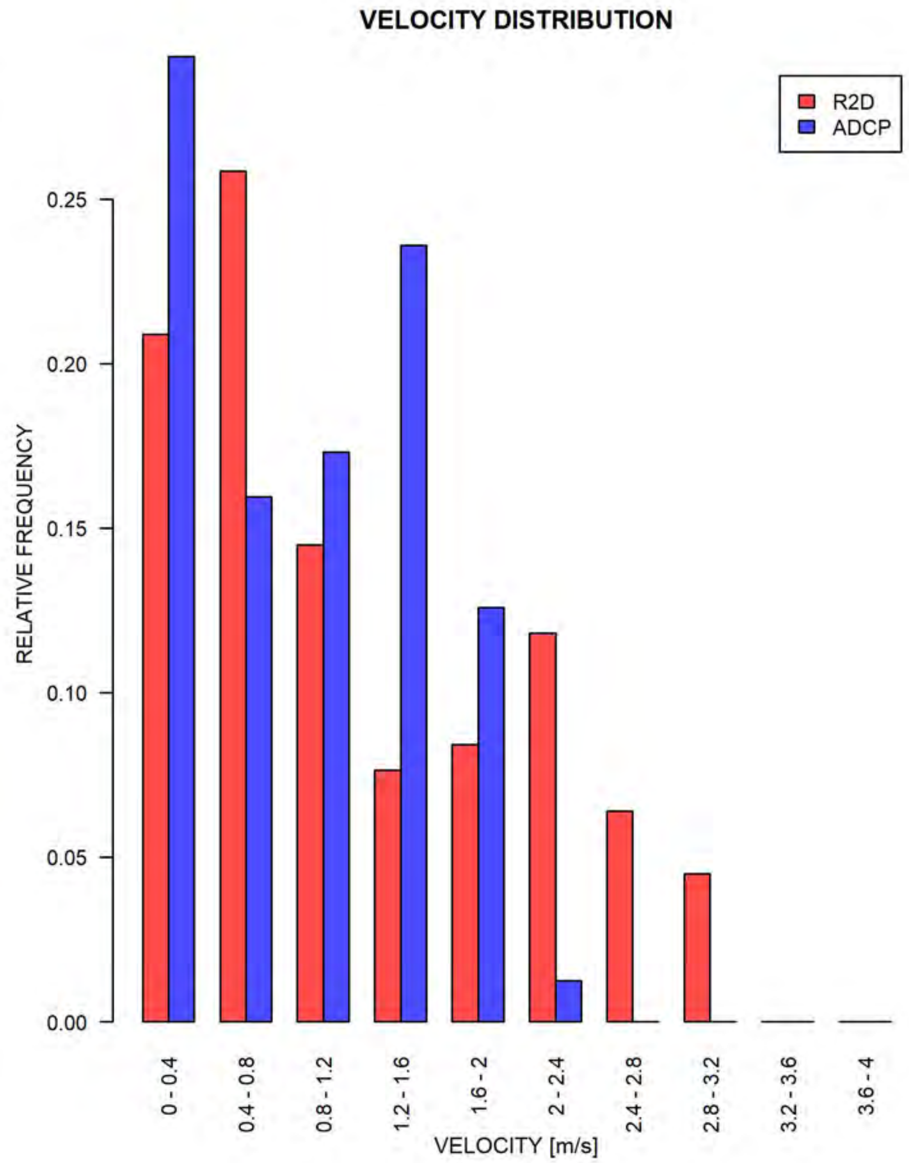
FT3 - Keenleyside: 20181031104829

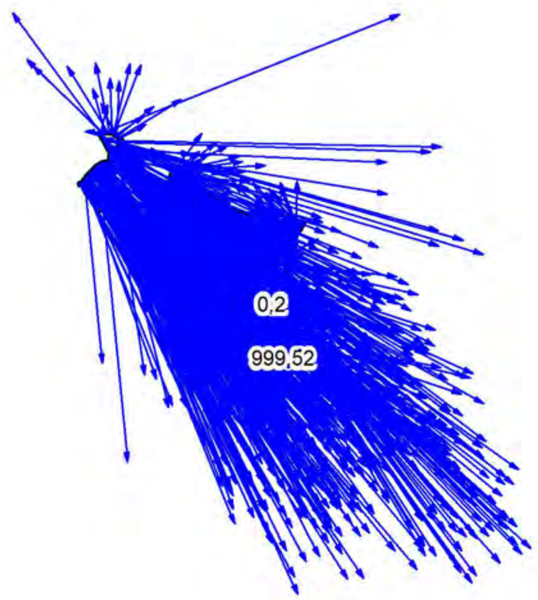


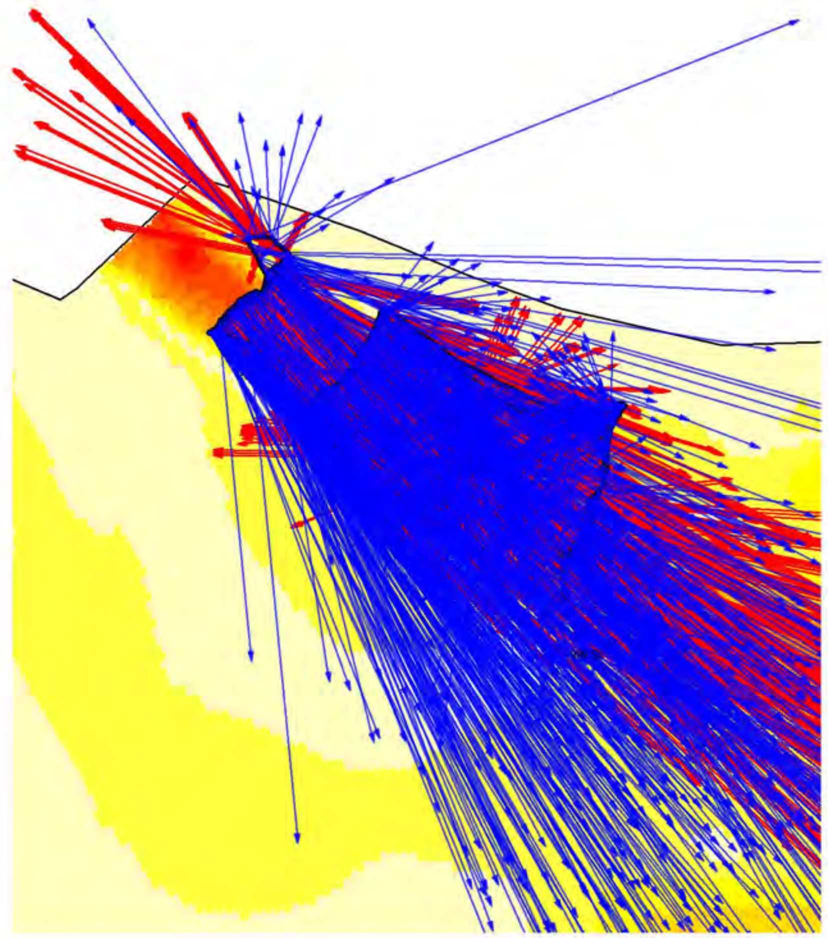
FT4 - Keenleyside: Keenleyside/2019_08_27/20190827152924r



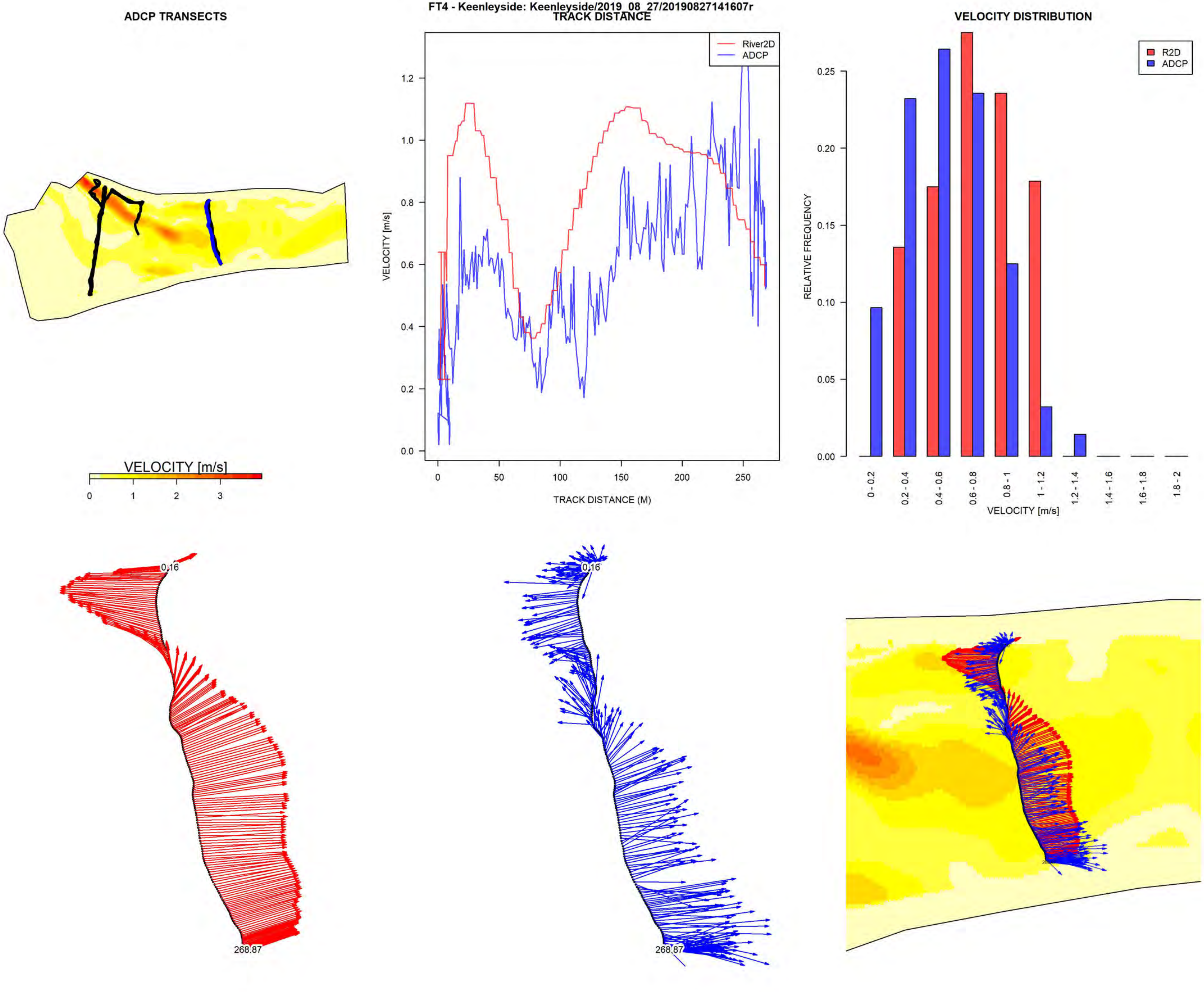




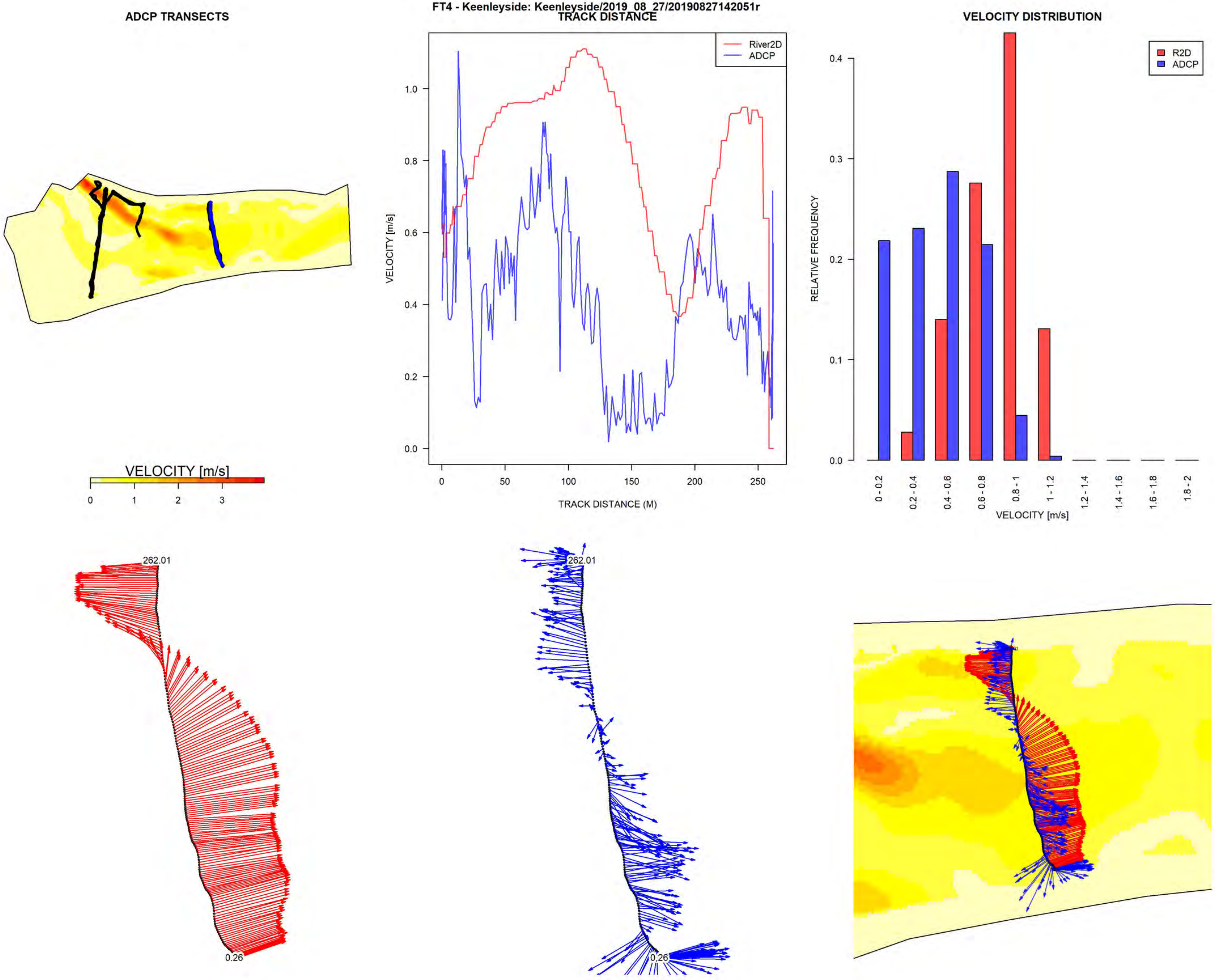




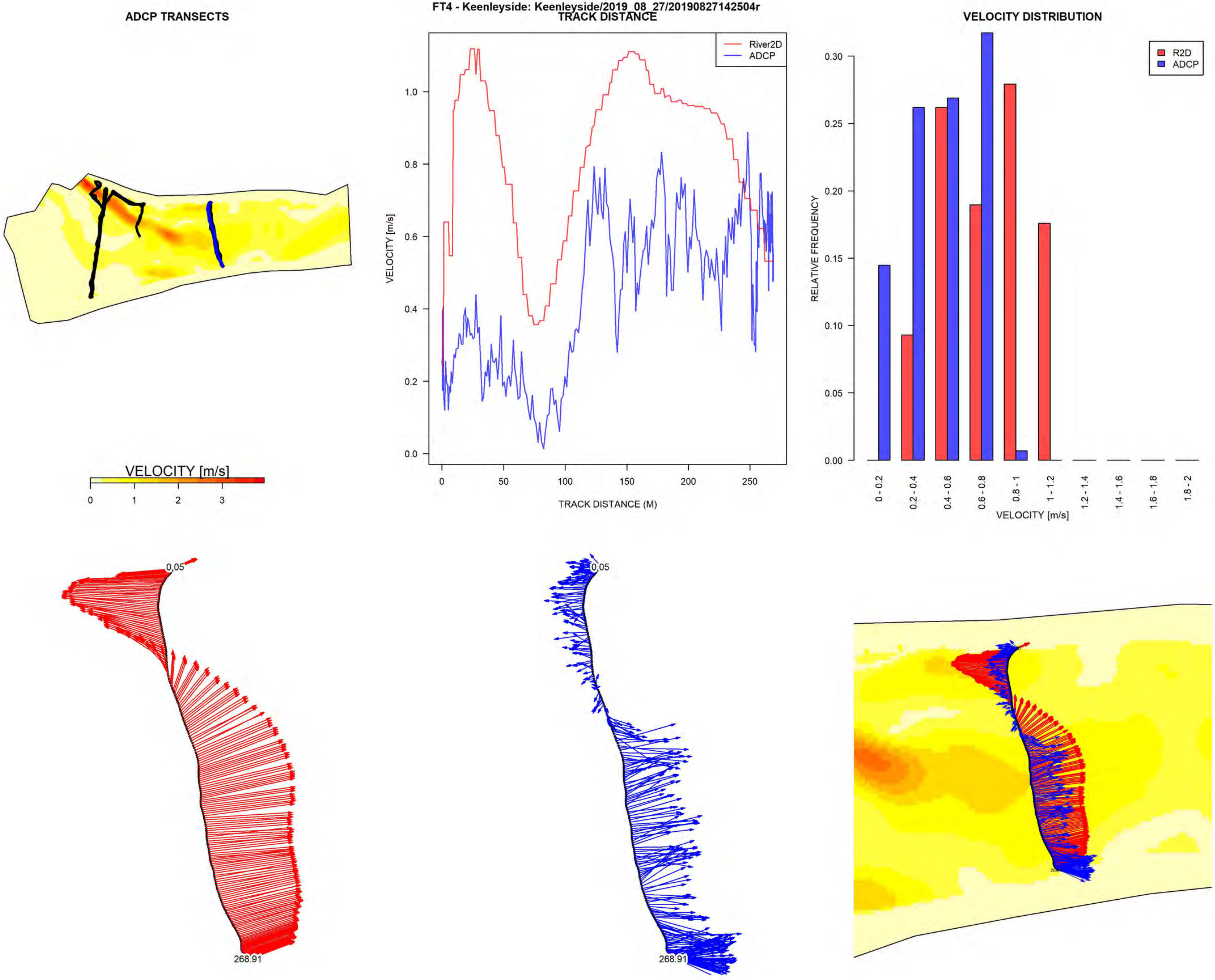
FT4 - Keenleyside: Keenleyside/2019_08_27/20190827141607r



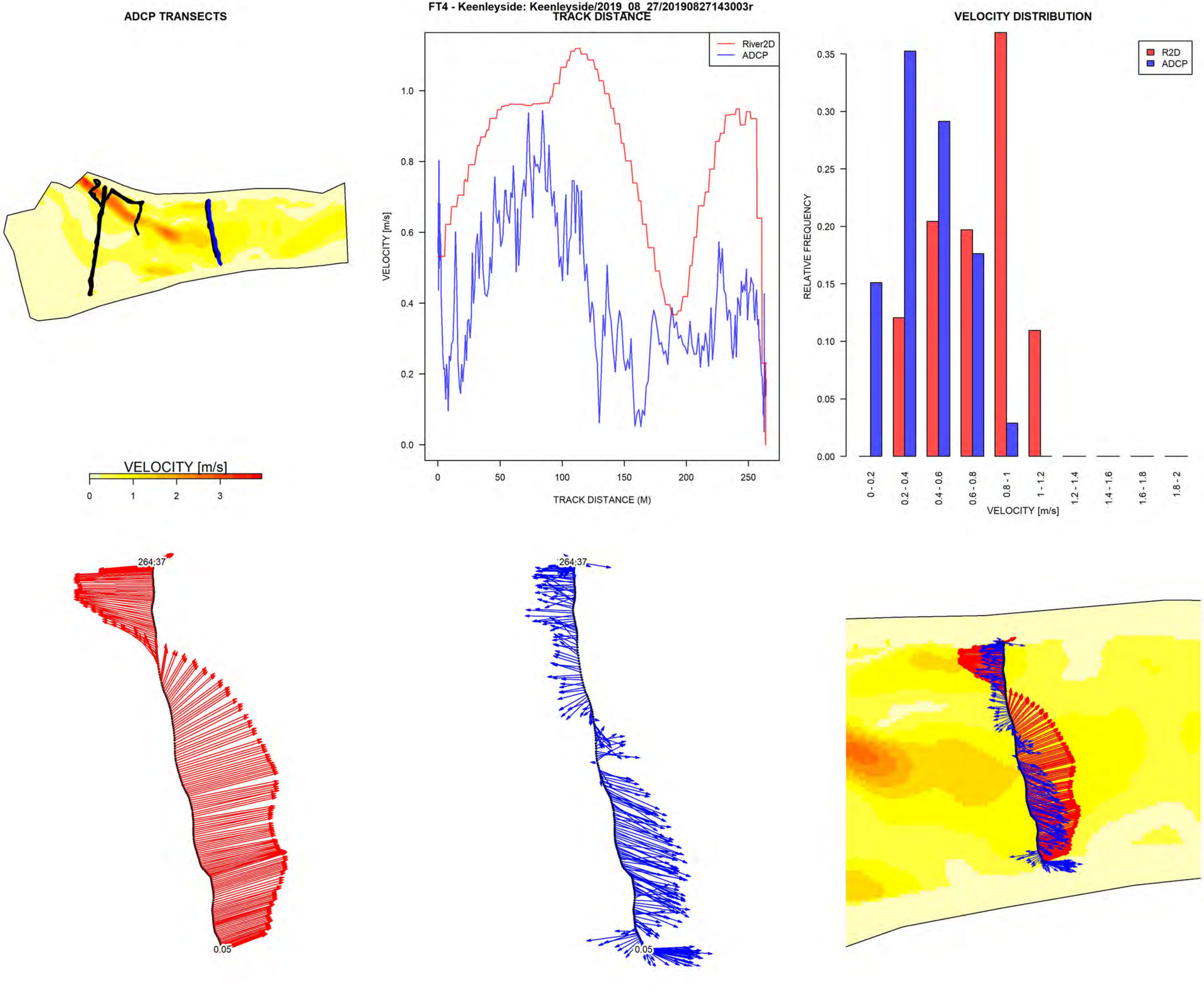
FT4 - Keenleyside: Keenleyside/2019_08_27/20190827142051r



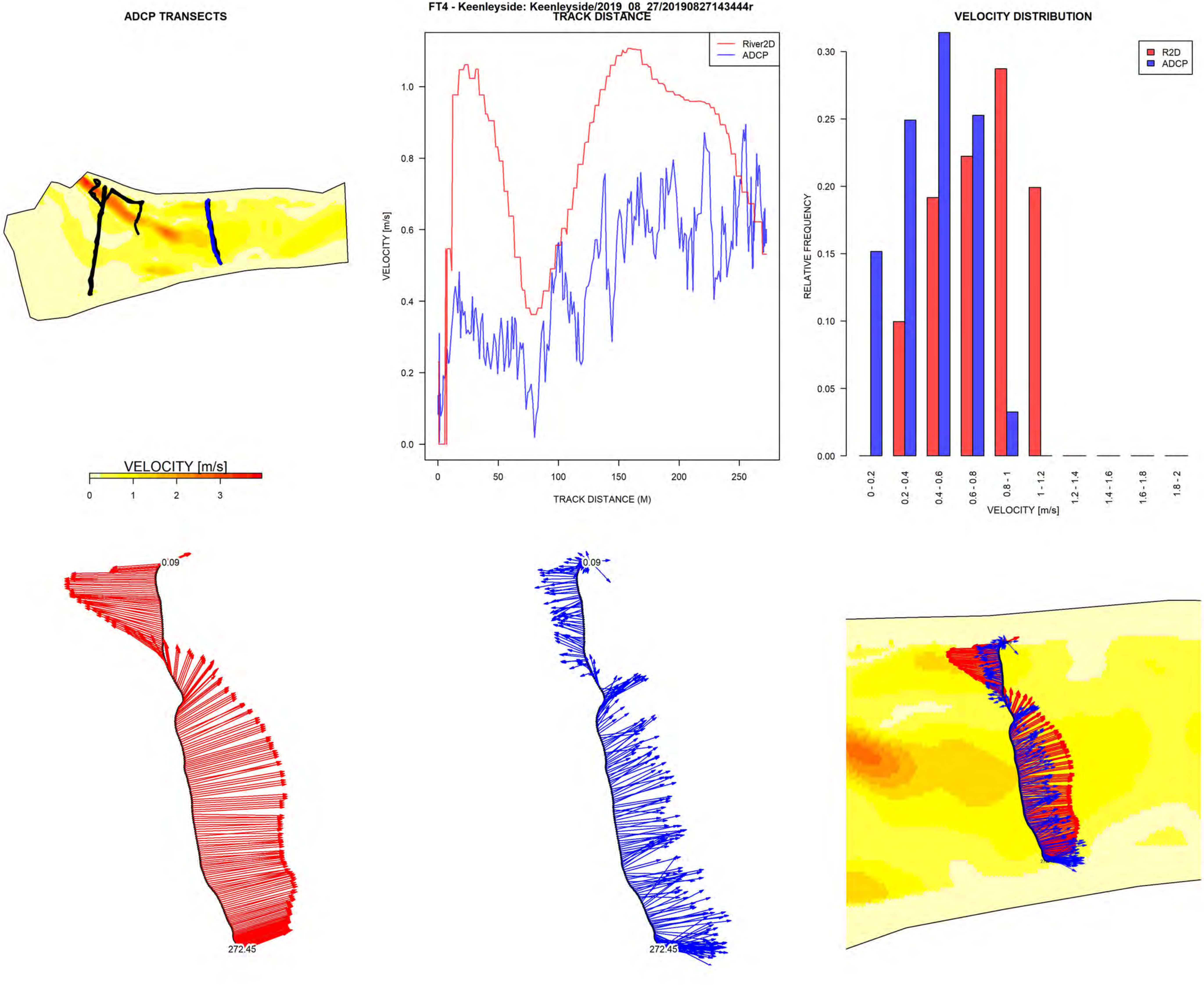
FT4 - Keenleyside: Keenleyside/2019_08_27/20190827142504r



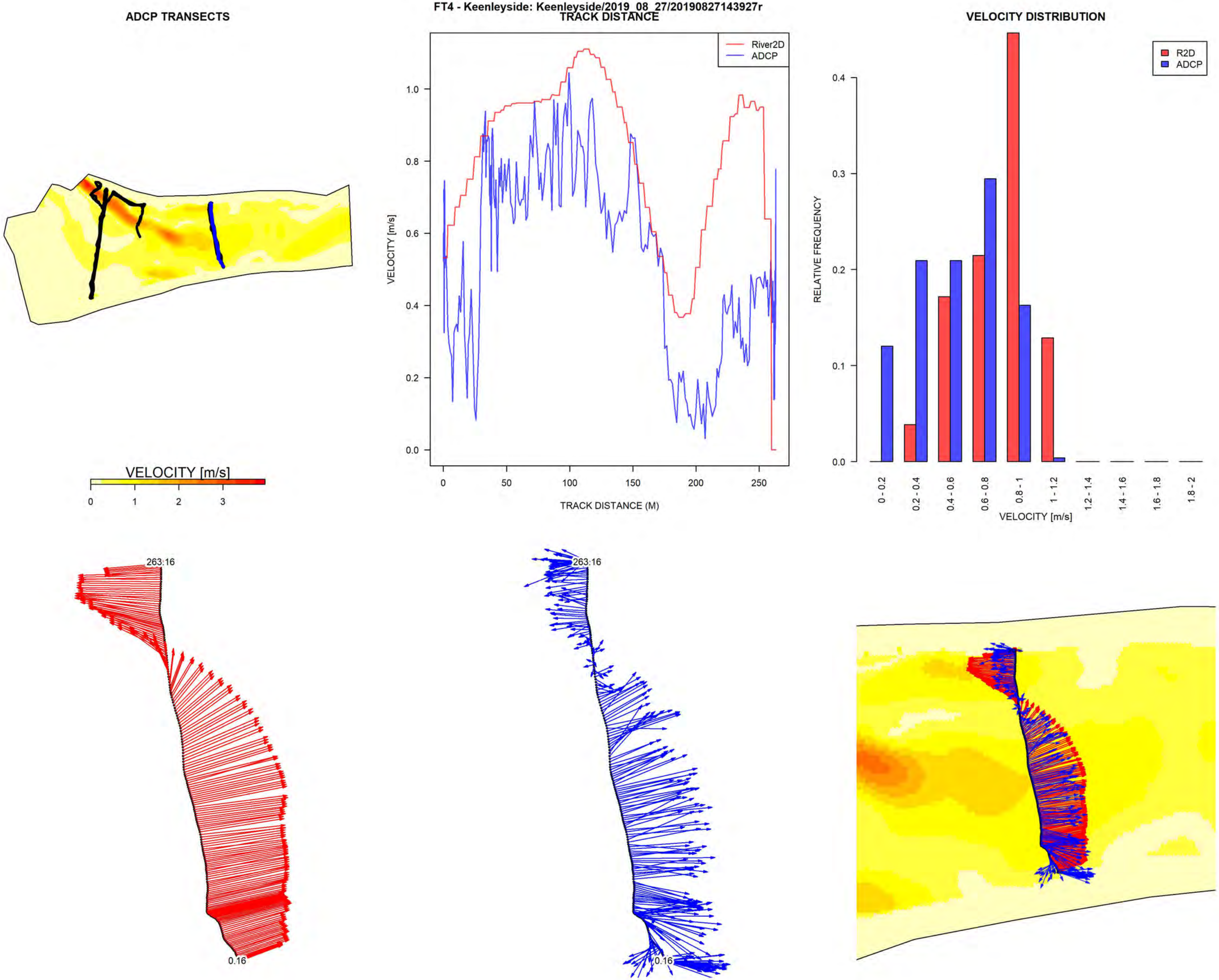
FT4 - Keenleyside: Keenleyside/2019_08_27/20190827143003r



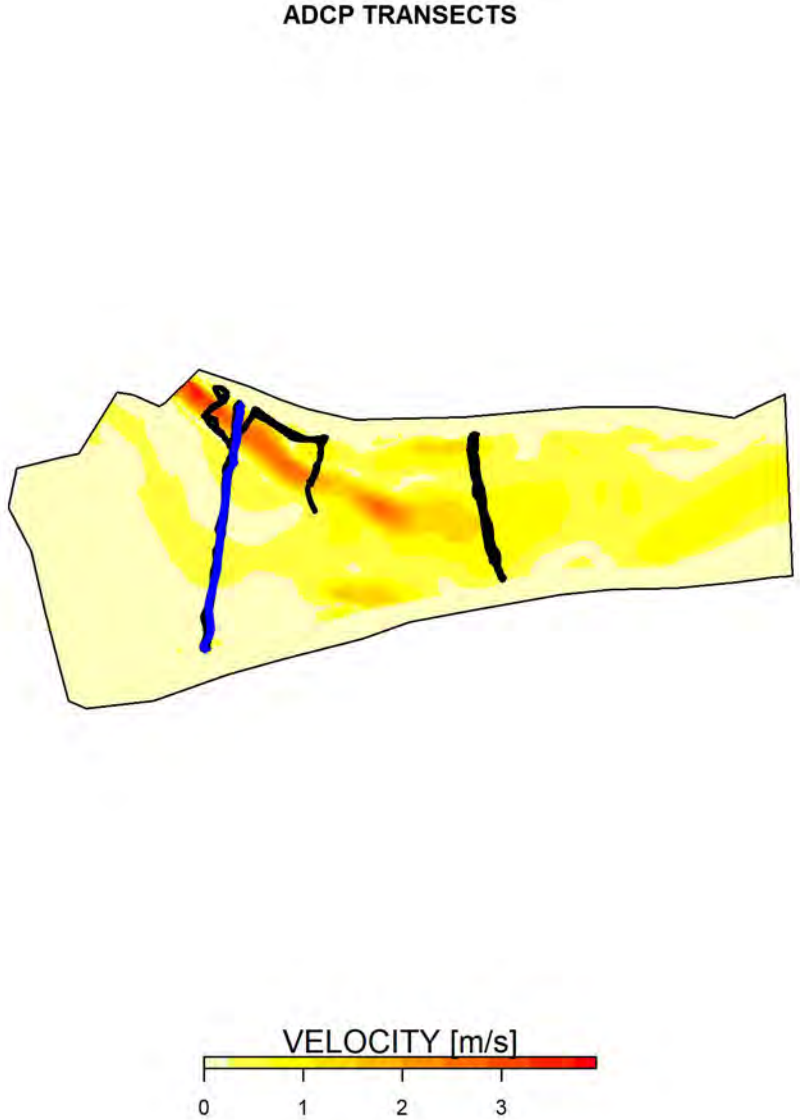
FT4 - Keenleyside: Keenleyside/2019_08_27/20190827143444r

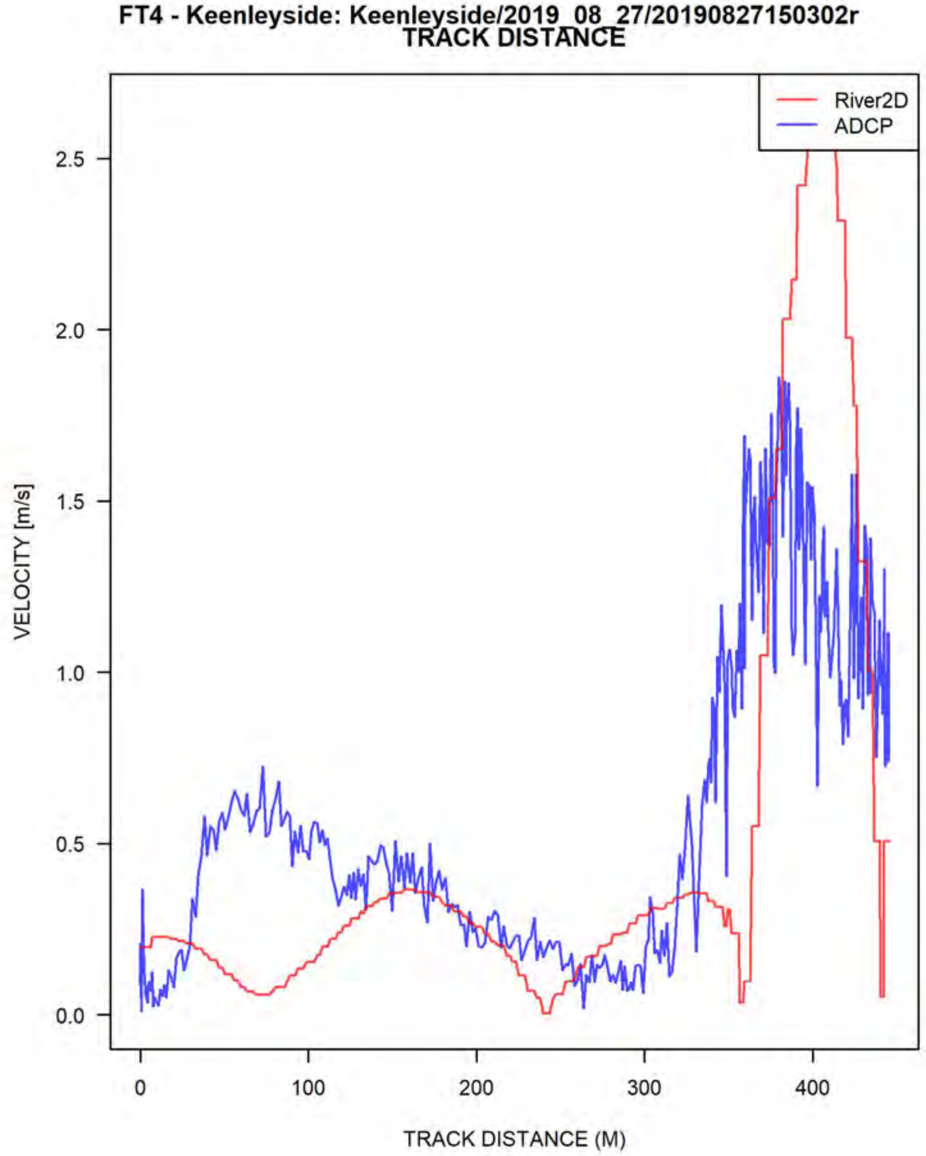


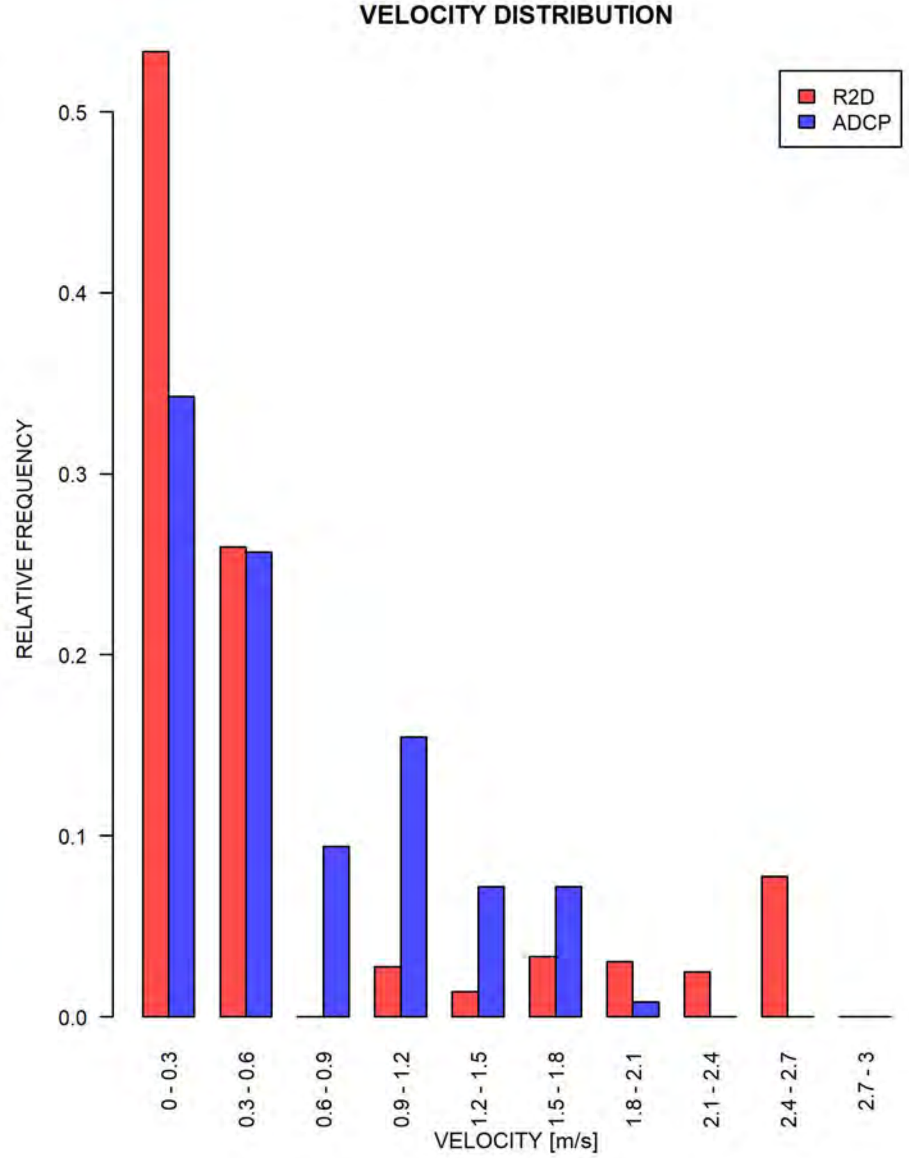
FT4 - Keenleyside: Keenleyside/2019_08_27/20190827143927r

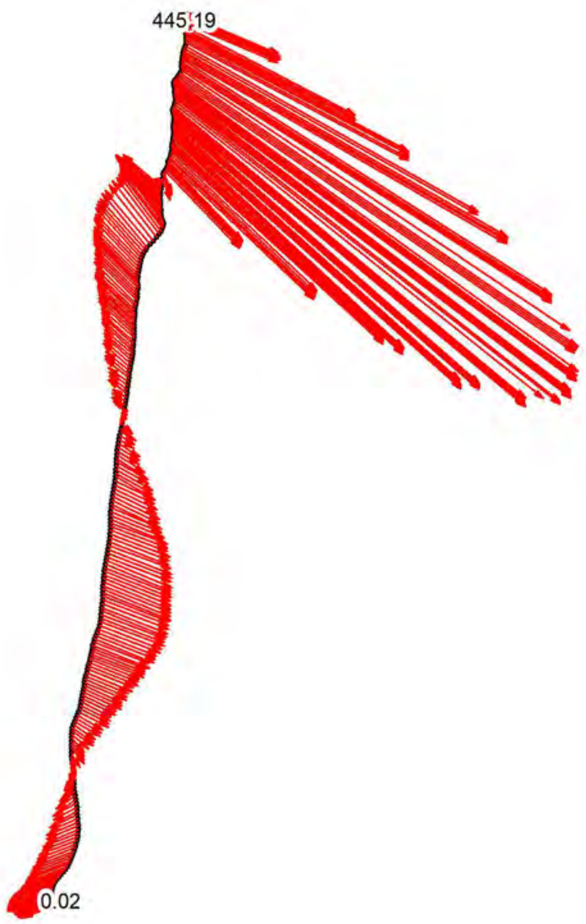


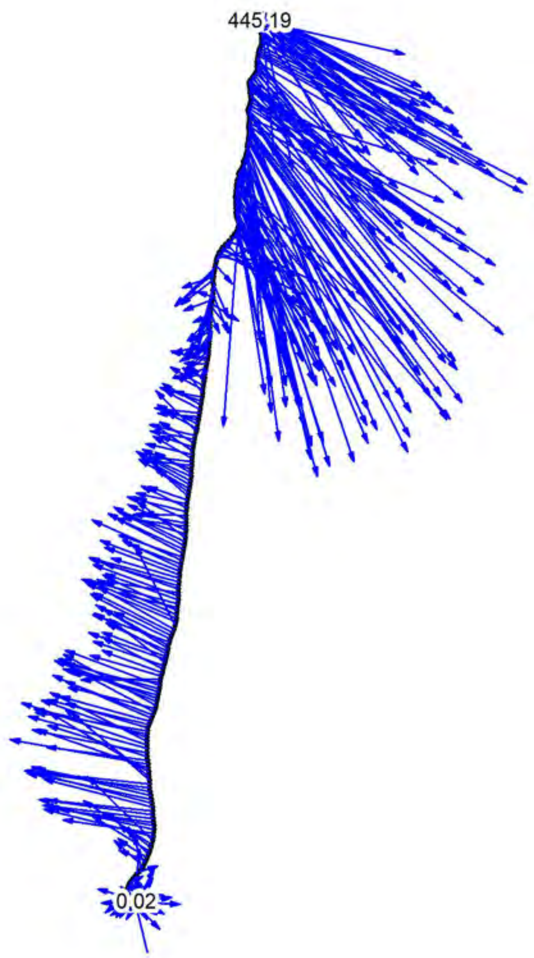
FT4 - Keenleyside: Keenleyside/2019_08_27/20190827150302r

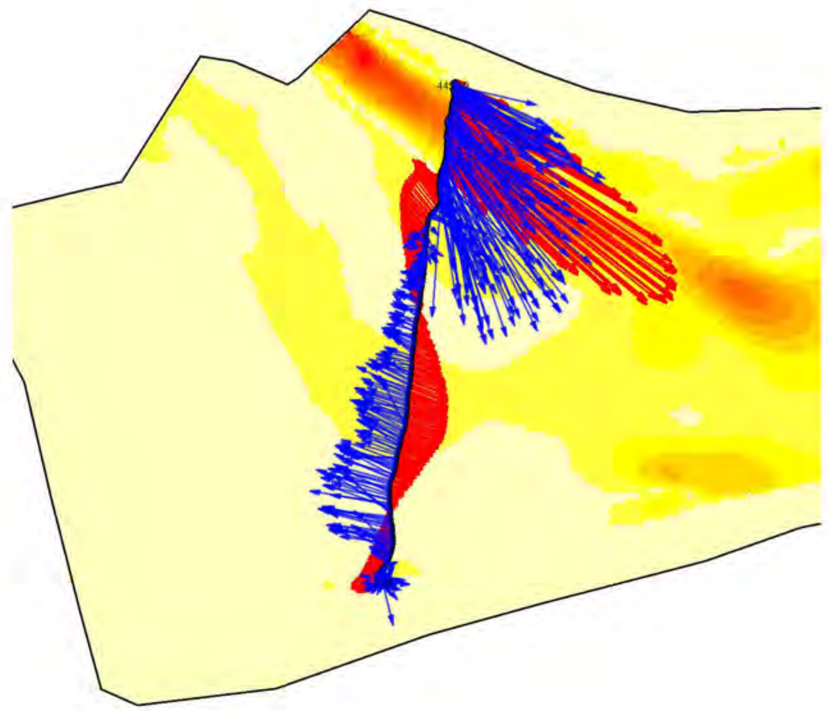


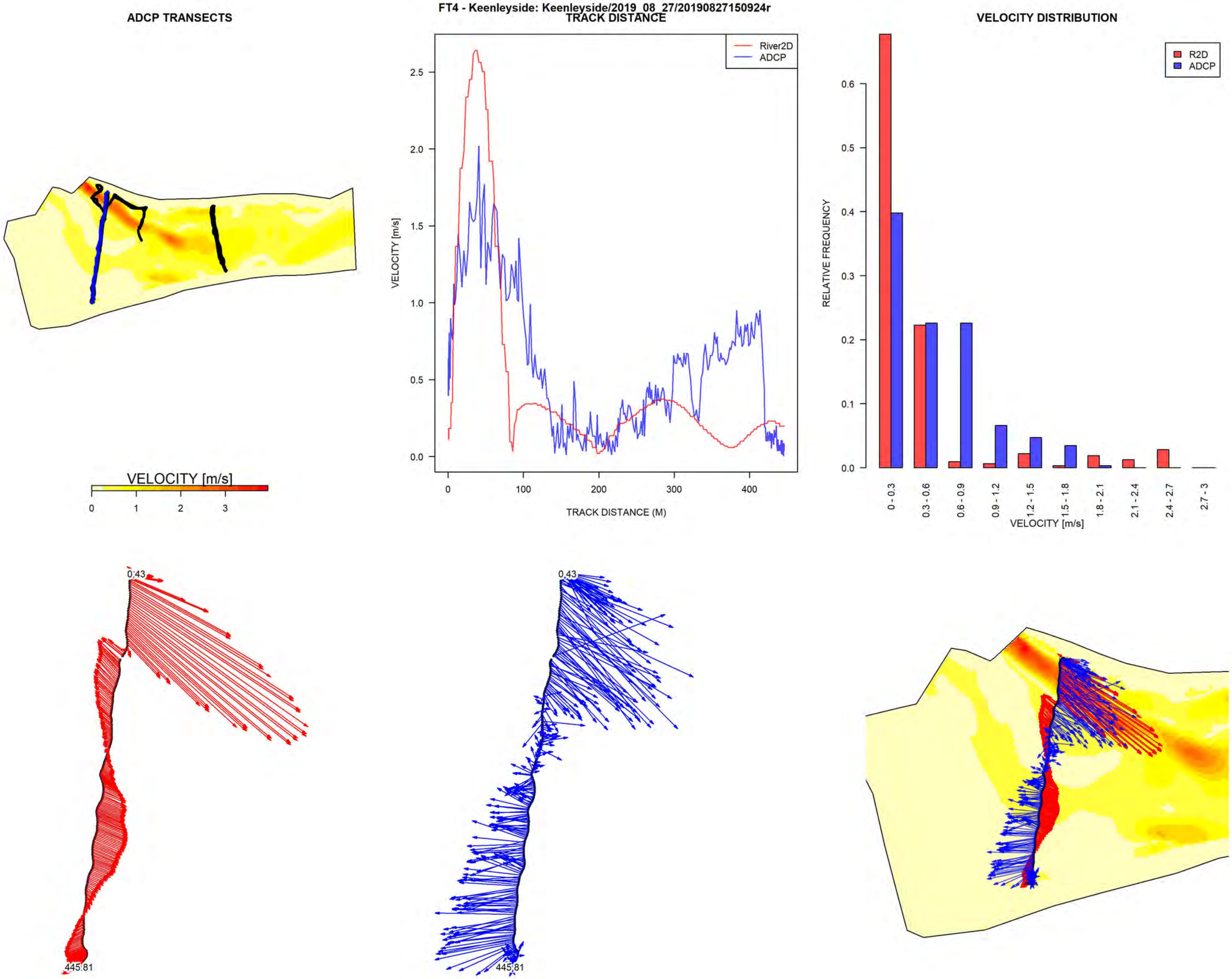


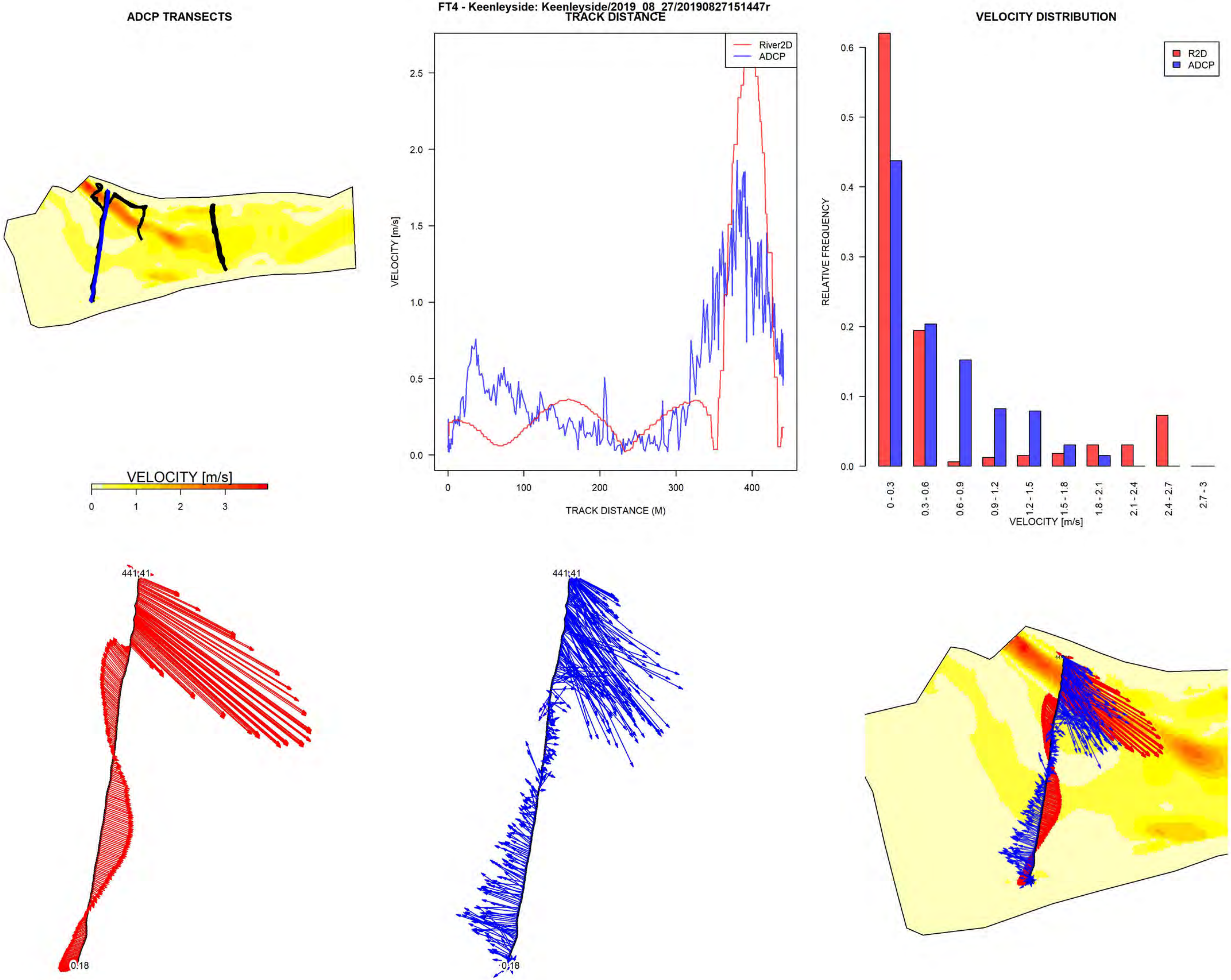






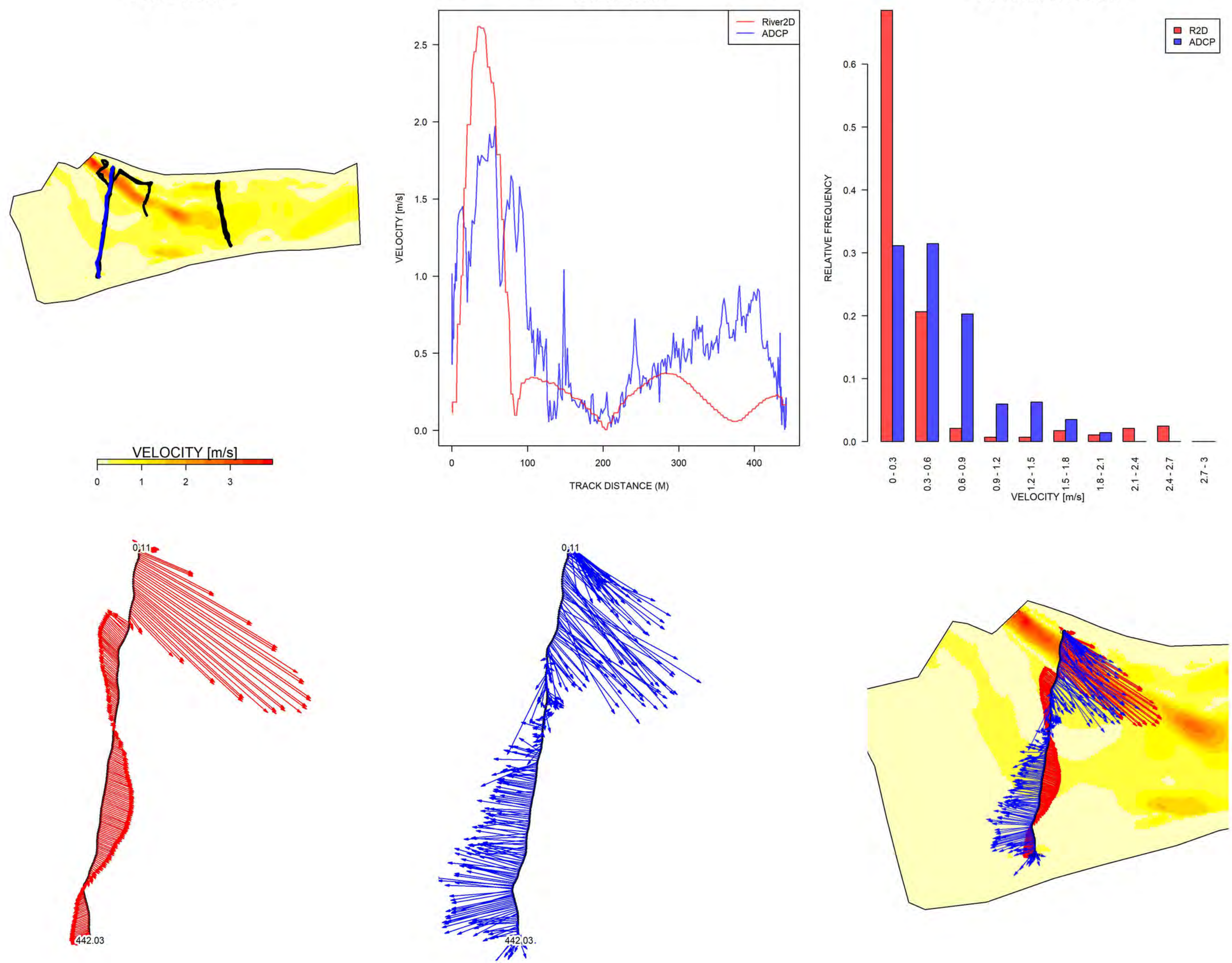


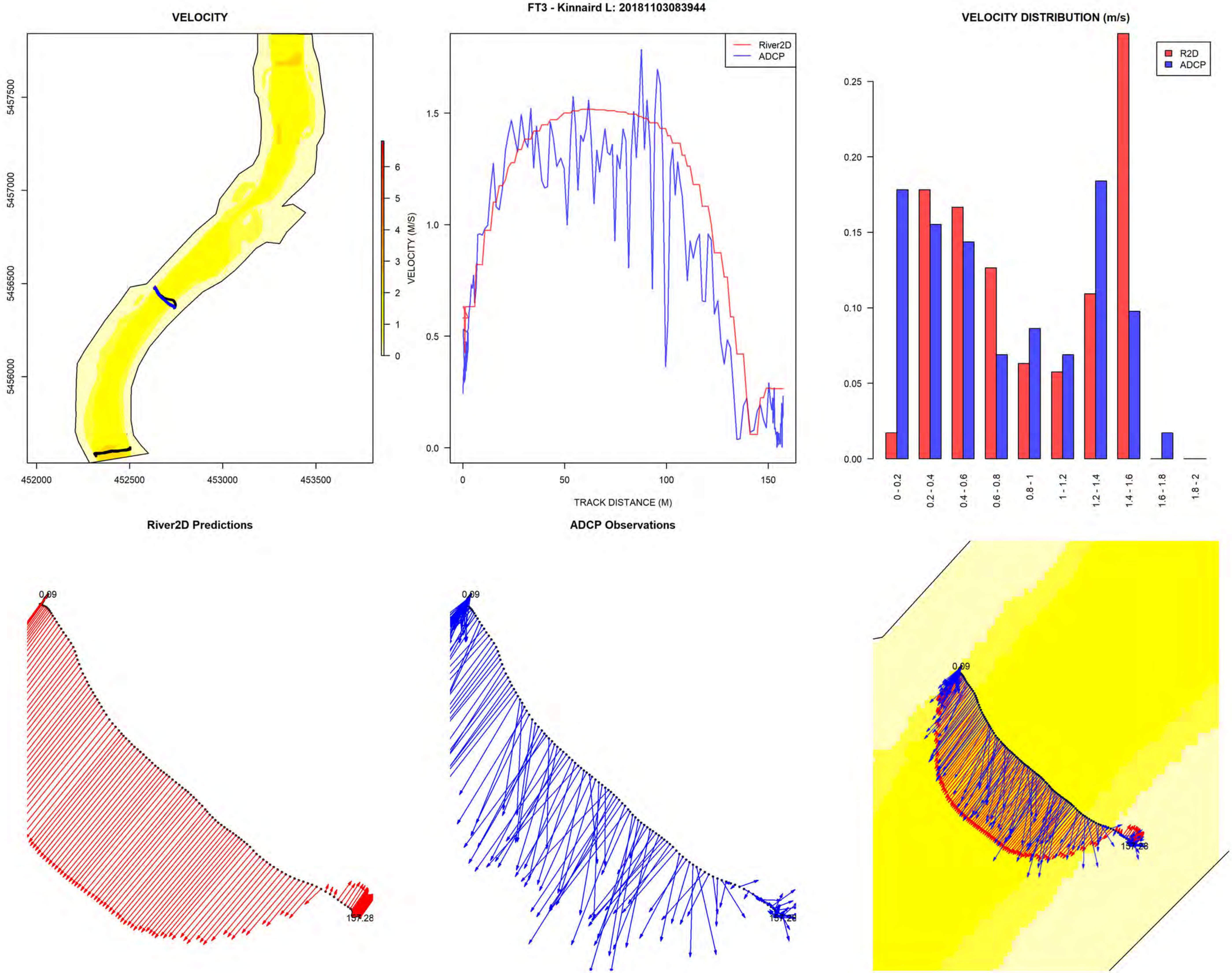

FT4 - Keenleyside: Keenleyside/2019_08_27/20190827150924r
ADCP TRANSECTS
TRACK DISTANCE
VELOCITY DISTRIBUTION
VELOCITY [m/s]
0
1
2
3
River2D
ADCP
VELOCITY [m/s]
TRACK DISTANCE (M)
0.0
0.5
1.0
1.5
2.0
2.5
0
100
200
300
400
R2D
ADCP
RELATIVE FREQUENCY
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0 - 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
2.4 - 2.7
2.7 - 3
VELOCITY [m/s]
0.43
445.81
0.43
445.81

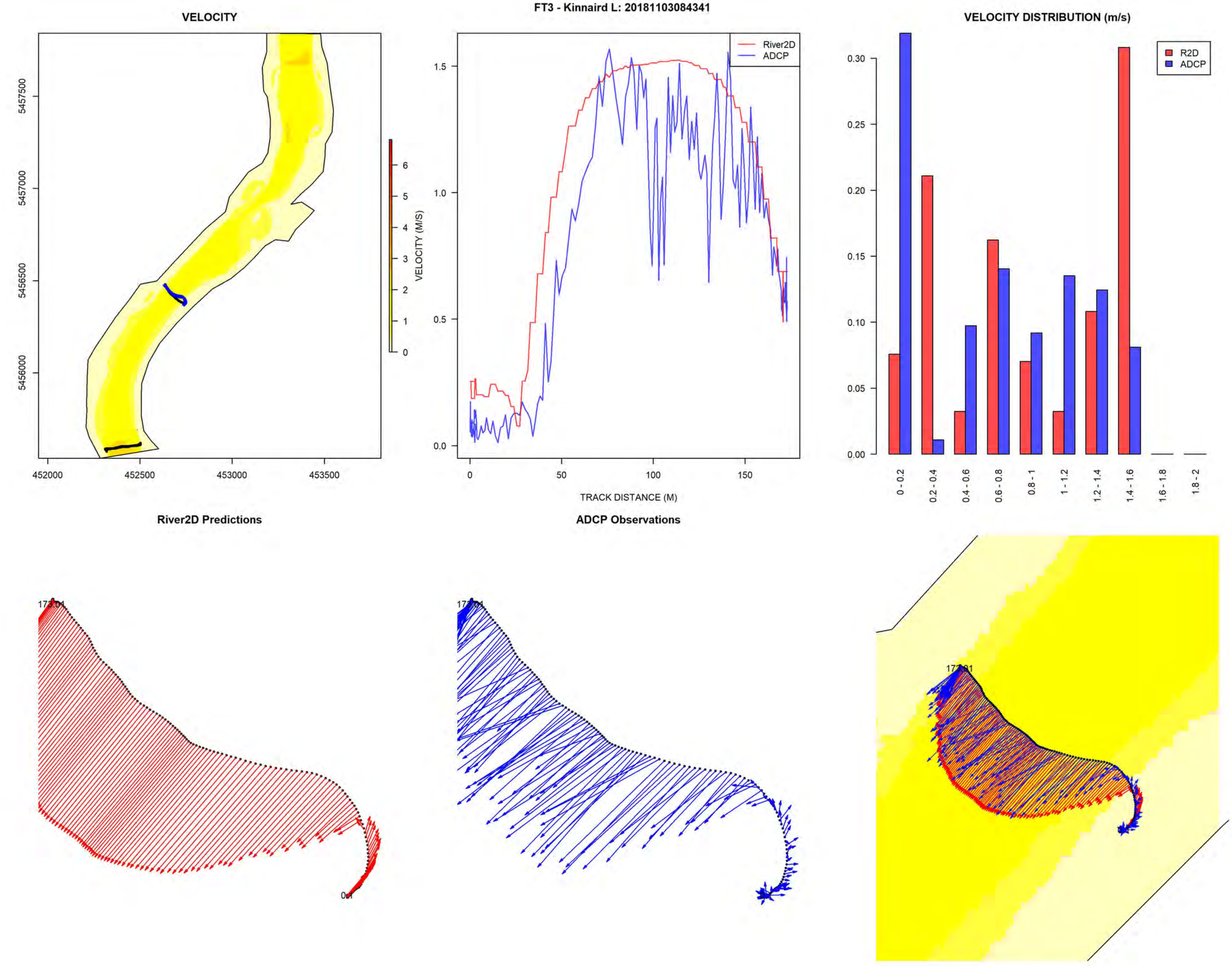


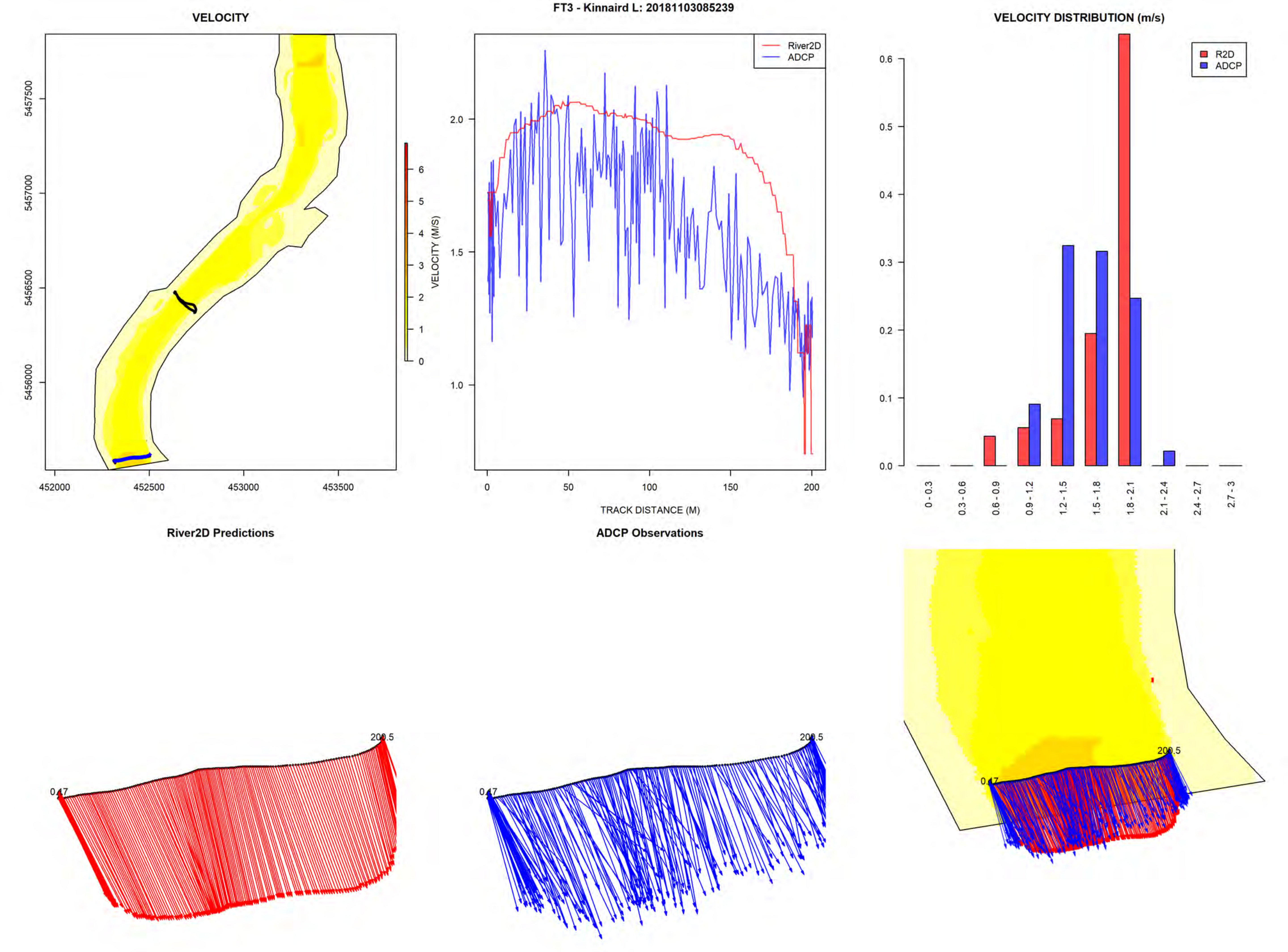
FT4 - Keenleyside: Keenleyside/2019_08_27/20190827151447r
ADCP TRANSECTS
VELOCITY [m/s]
0
1
2
3
TRACK DISTANCE
River2D
ADCP
VELOCITY [m/s]
TRACK DISTANCE (M)
VELOCITY DISTRIBUTION
R2D
ADCP
RELATIVE FREQUENCY
VELOCITY [m/s]
0 - 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
2.4 - 2.7
2.7 - 3
441.41
0.18
441.41
0.18

FT4 - Keenleyside: Keenleyside/2019_08_27/20190827152027r



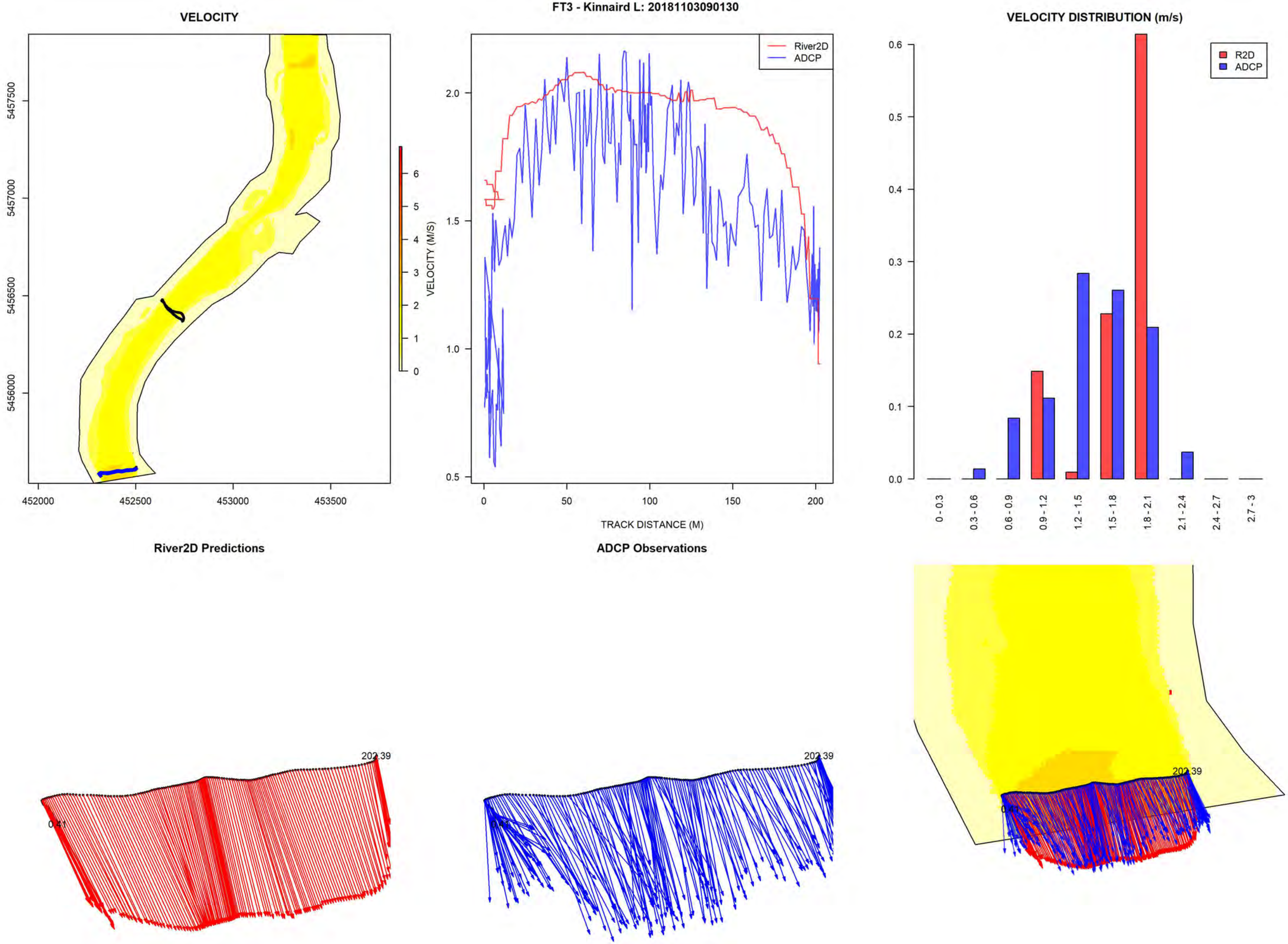

FT3 - Kinnaird L: 20181103083944
VELOCITY
5457500
5457000
5456500
5456000
452000
452500
453000
453500
0
1
2
3
4
5
6
VELOCITY (M/S)
River2D
ADCP
0.0
0.5
1.0
1.5
0
50
100
150
TRACK DISTANCE (M)
VELOCITY DISTRIBUTION (m/s)
R2D
ADCP
0.00
0.05
0.10
0.15
0.20
0.25
0 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 1
1 - 1.2
1.2 - 1.4
1.4 - 1.6
1.6 - 1.8
1.8 - 2
River2D Predictions
0.09
157.28
ADCP Observations
0.09
0.09
157.28


FT3 - Kinnaird L: 20181103084341
VELOCITY
5457500
5457000
5456500
5456000
452000
452500
453000
453500
VELOCITY (M/S)
0
1
2
3
4
5
6
River2D
ADCP
1.5
1.0
0.5
0.0
0
50
100
150
TRACK DISTANCE (M)
VELOCITY DISTRIBUTION (m/s)
R2D
ADCP
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 1
1 - 1.2
1.2 - 1.4
1.4 - 1.6
1.6 - 1.8
1.8 - 2
River2D Predictions
ADCP Observations

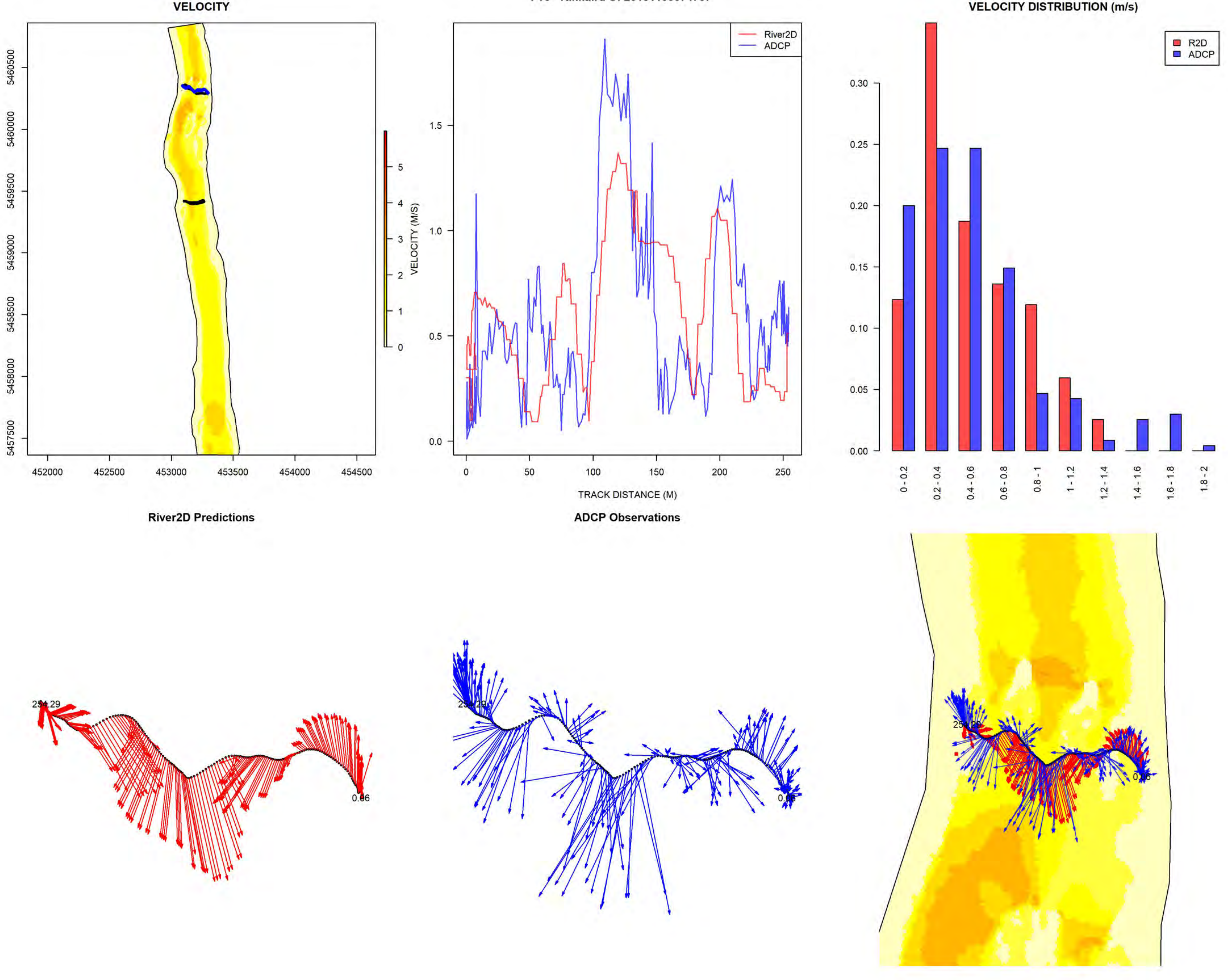


FT3 - Kinnaird L: 20181103085239
VELOCITY
VELOCITY DISTRIBUTION (m/s)
River2D
ADCP
R2D
VELOCITY (M/S)
TRACK DISTANCE (M)
River2D Predictions
ADCP Observations
0.47
200.5

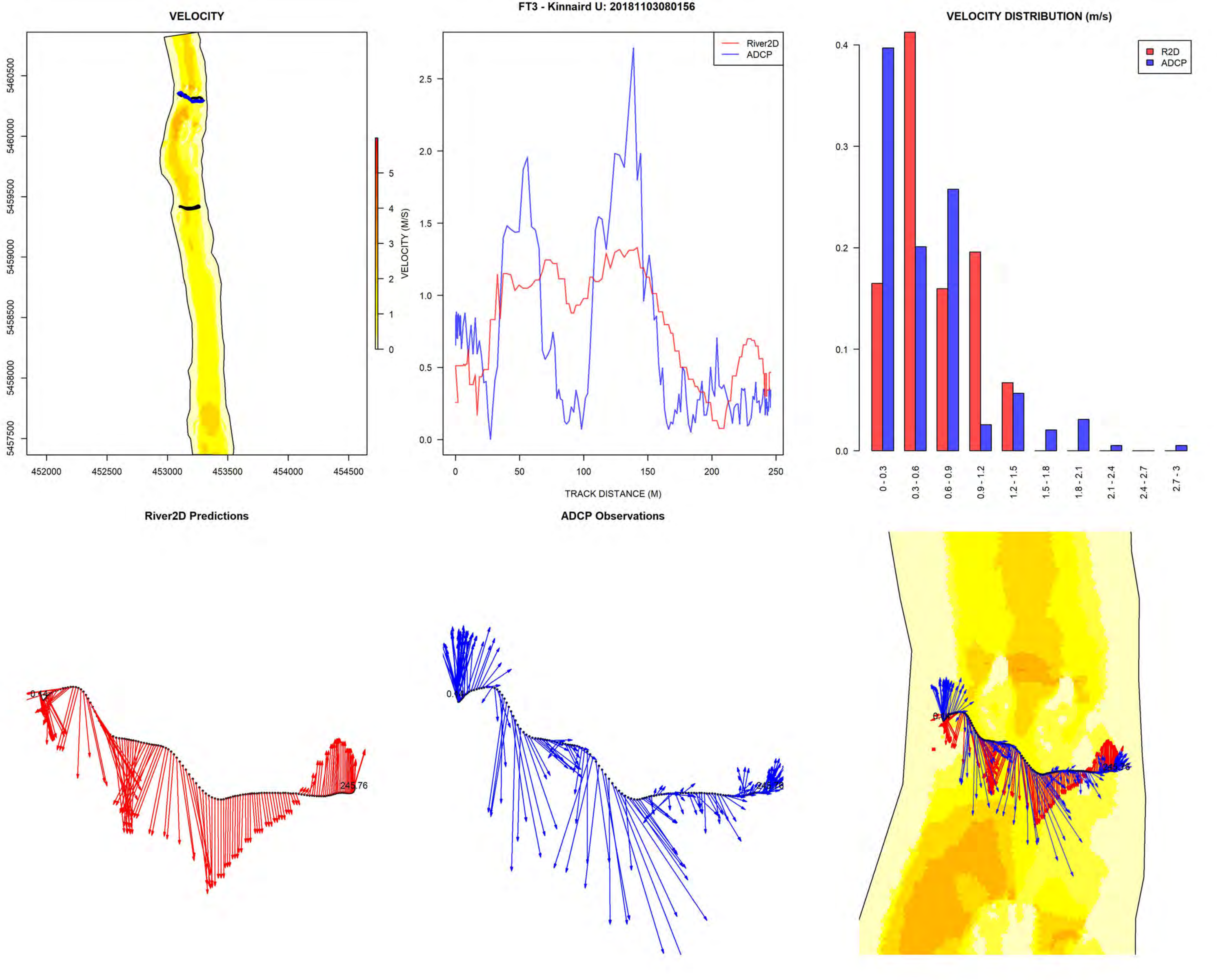
FT3 - Kinnaird L: 20181103090130

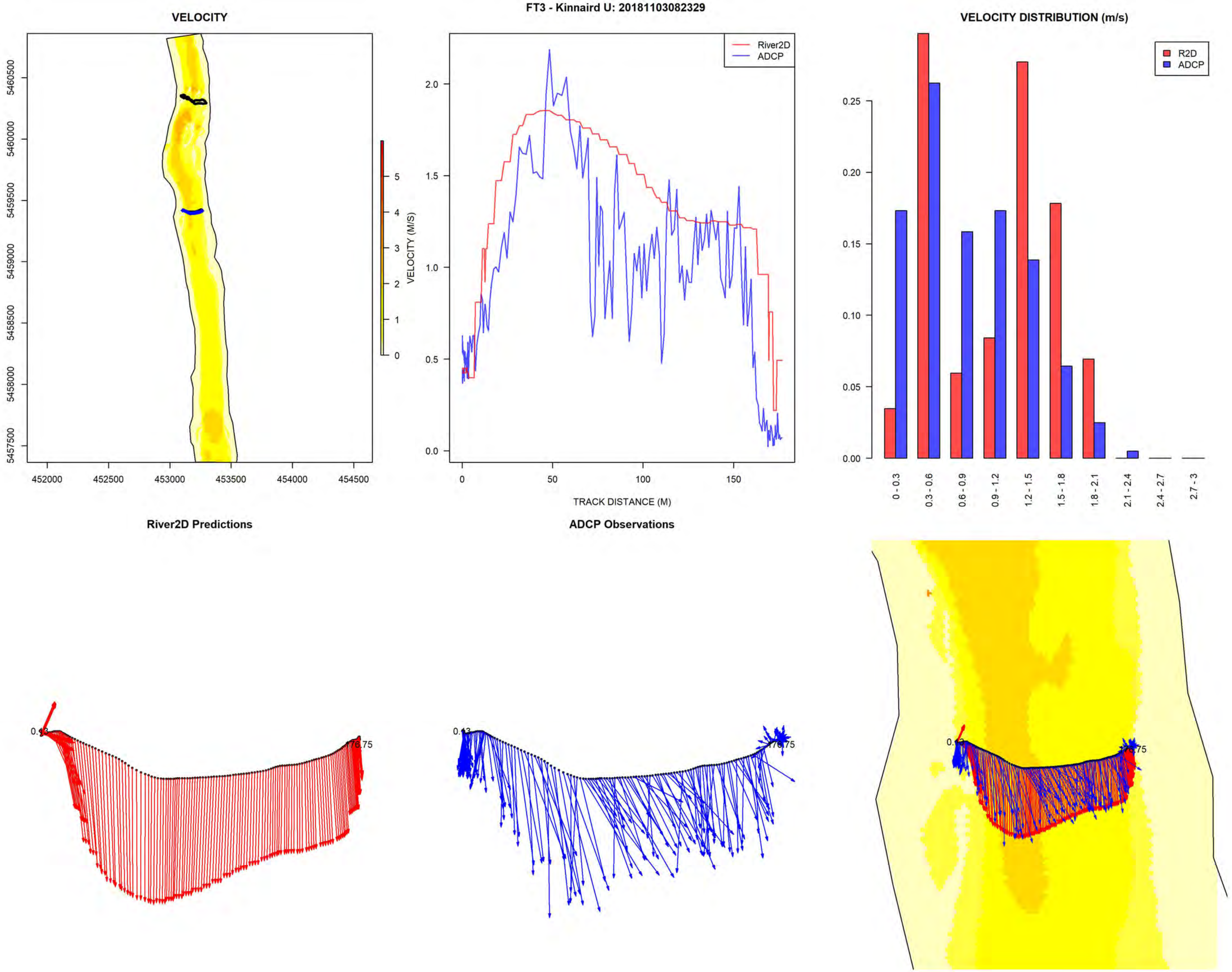


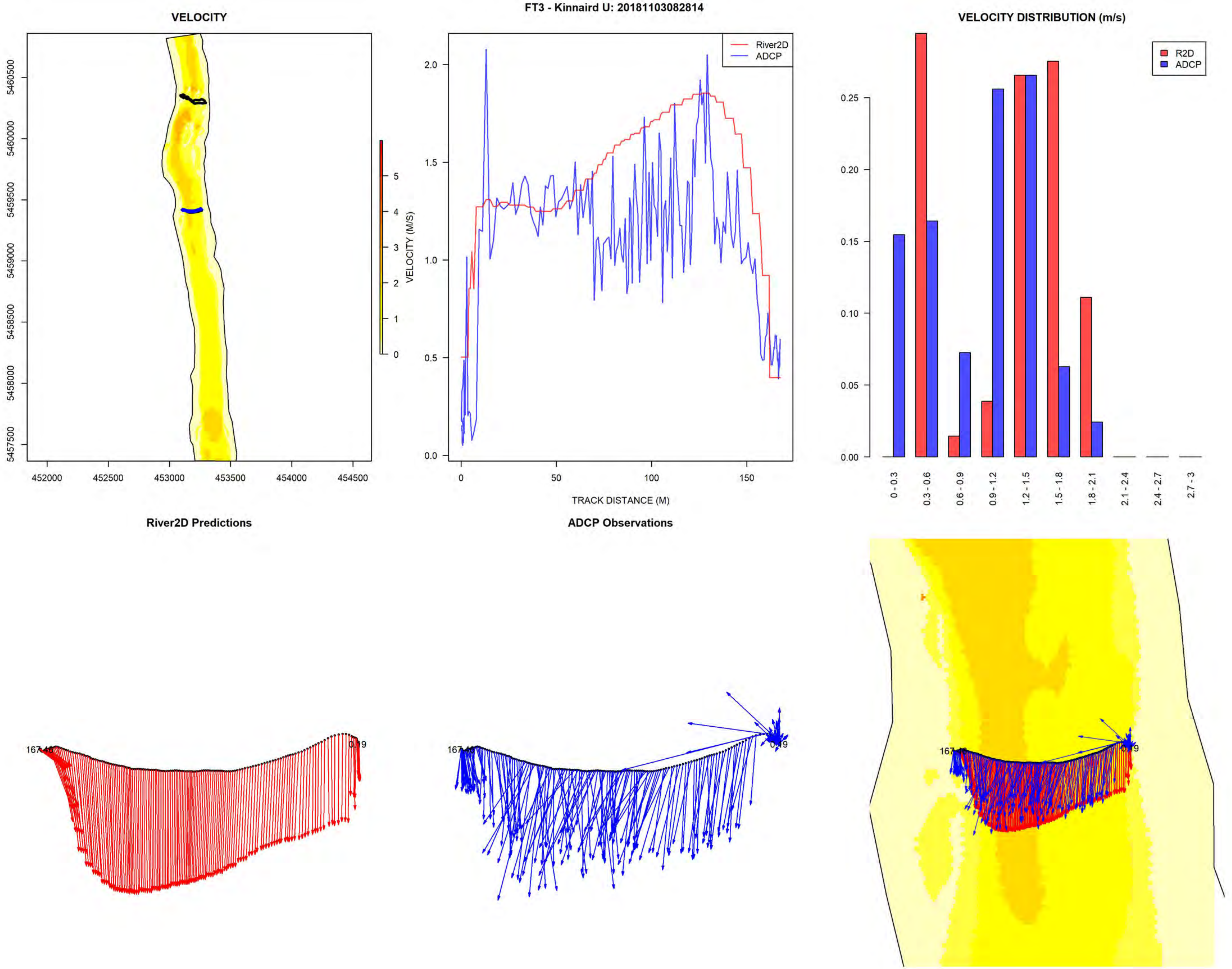
FT3 - Kinnaird U: 20181103074737



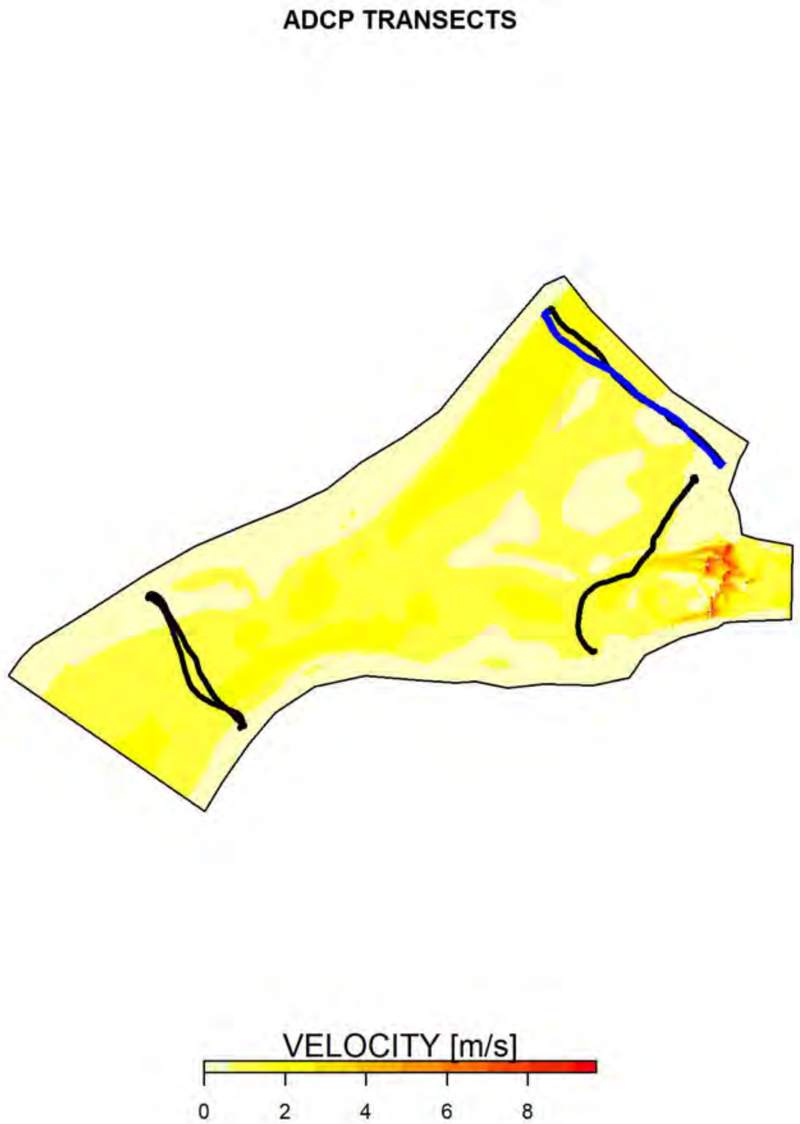
FT3 - Kinnaird U: 20181103080156

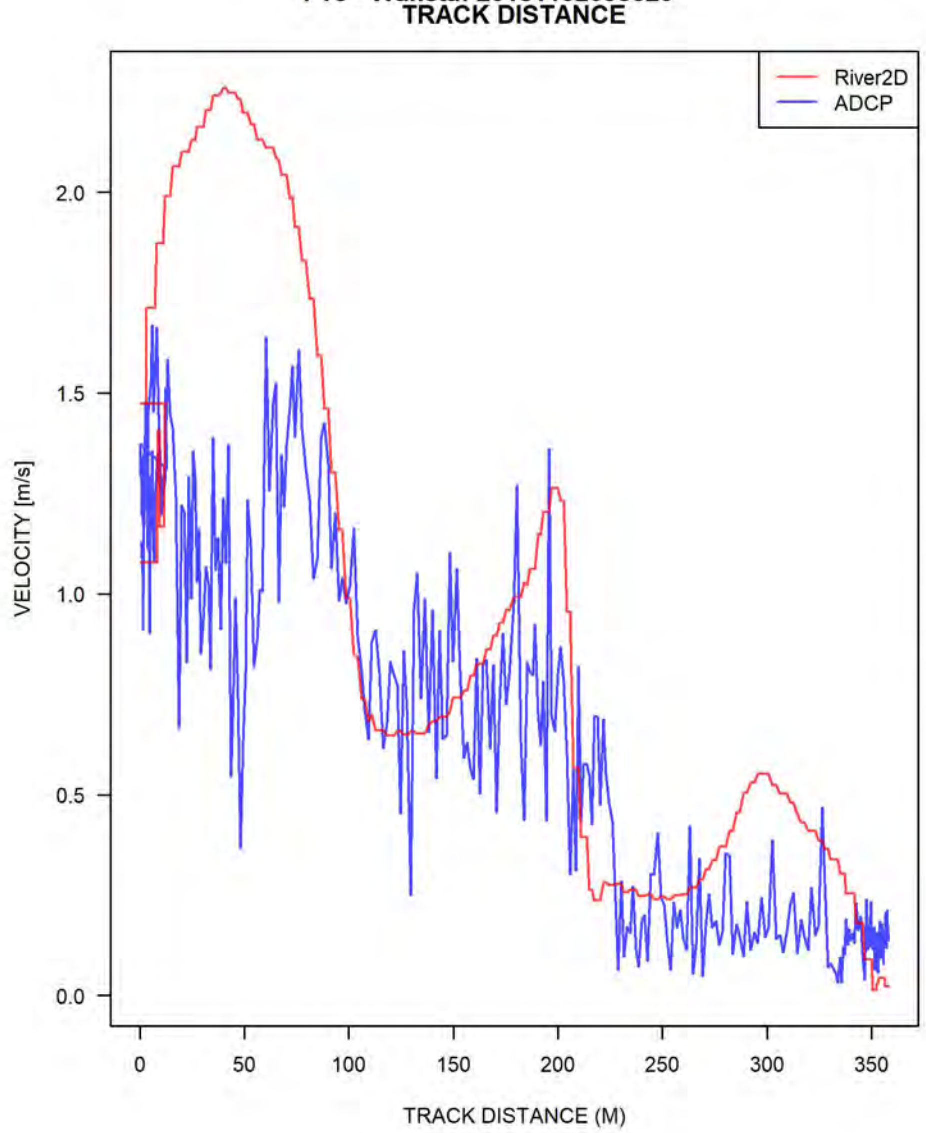


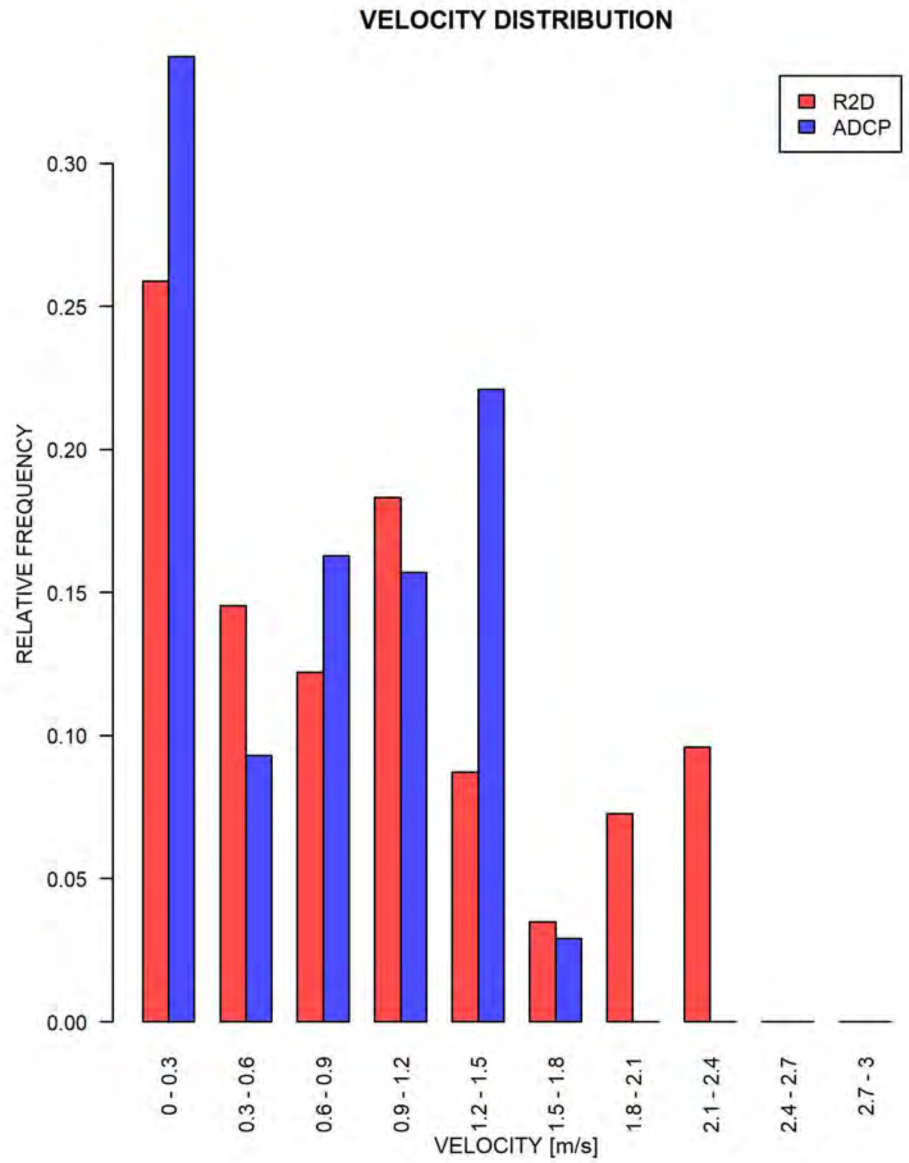

FT3 - Kinnaird U: 20181103082329
VELOCITY
5457500
5458000
5458500
5459000
5459500
5460000
5460500
452000
452500
453000
453500
454000
454500
VELOCITY (M/S)
0
1
2
3
4
5
River2D
ADCP
0.0
0.5
1.0
1.5
2.0
0
50
100
150
TRACK DISTANCE (M)
VELOCITY DISTRIBUTION (m/s)
R2D
ADCP
0.00
0.05
0.10
0.15
0.20
0.25
0 - 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
2.4 - 2.7
2.7 - 3
River2D Predictions
ADCP Observations
176.75
176.75

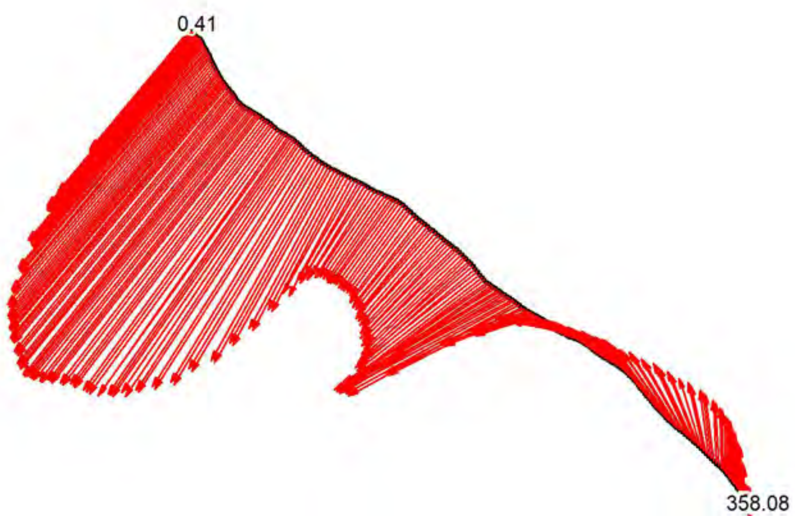

FT3 - Kinnaird U: 20181103082814
VELOCITY
5460500
5460000
5459500
5459000
5458500
5458000
5457500
452000
452500
453000
453500
454000
454500
VELOCITY (M/S)
0
1
2
3
4
5
River2D
ADCP
2.0
1.5
1.0
0.5
0.0
0
50
100
150
TRACK DISTANCE (M)
VELOCITY DISTRIBUTION (m/s)
R2D
ADCP
0.25
0.20
0.15
0.10
0.05
0.00
0 - 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
2.4 - 2.7
2.7 - 3
River2D Predictions
167.48
0.19
ADCP Observations

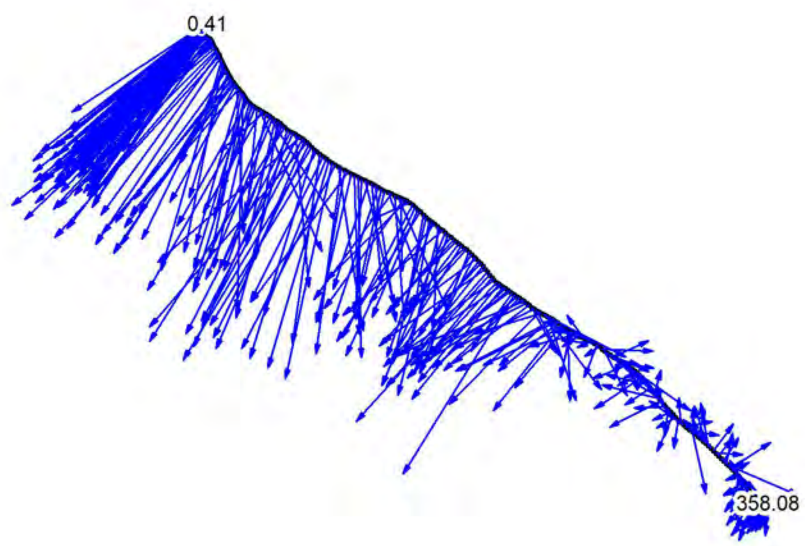
FT3 - Waneta: 20181102095020

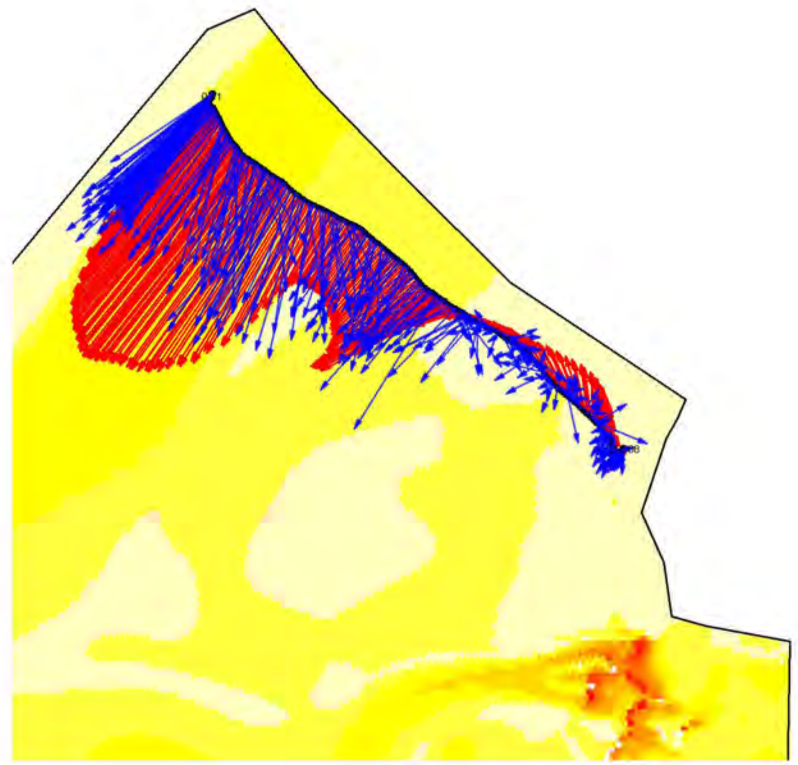












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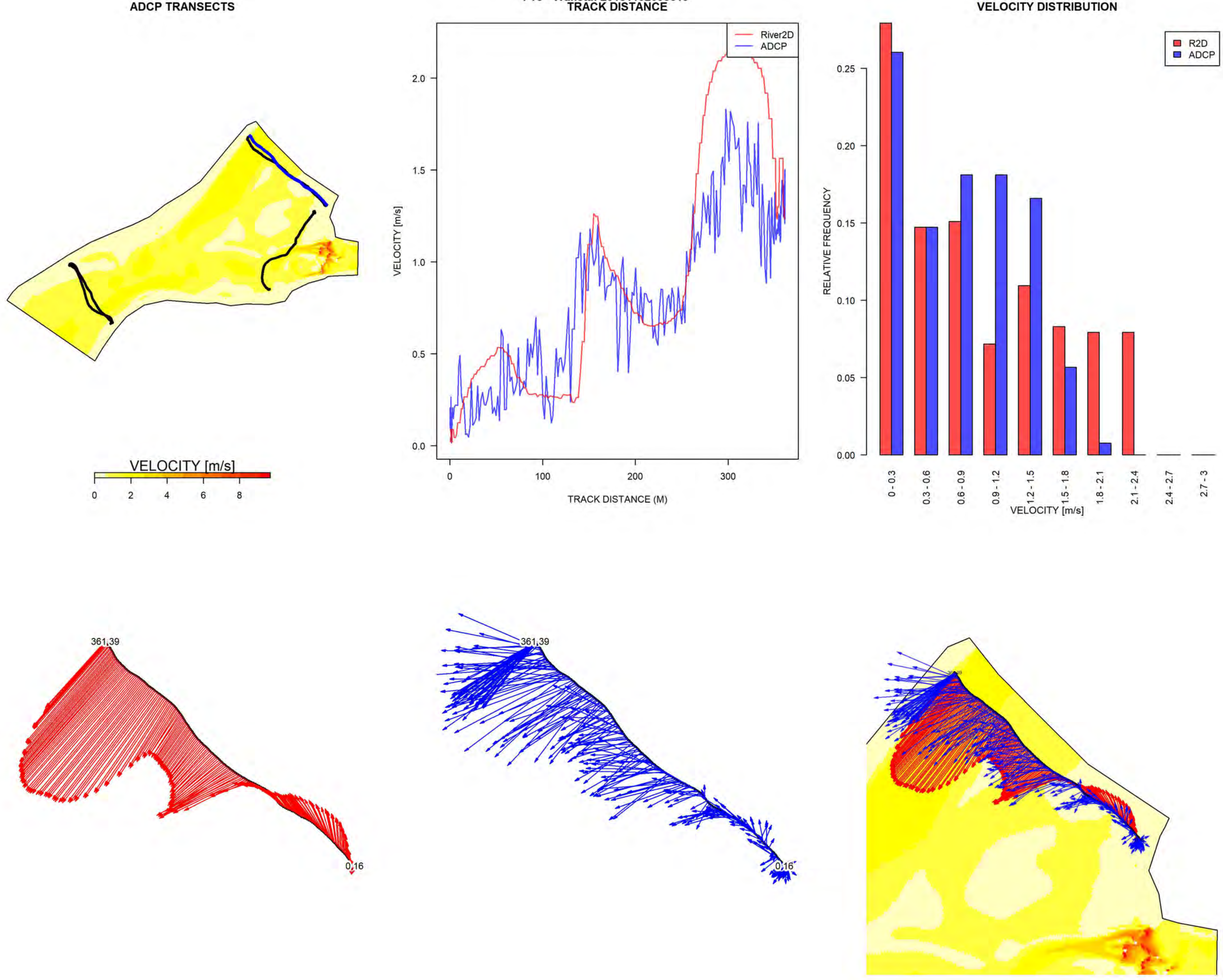
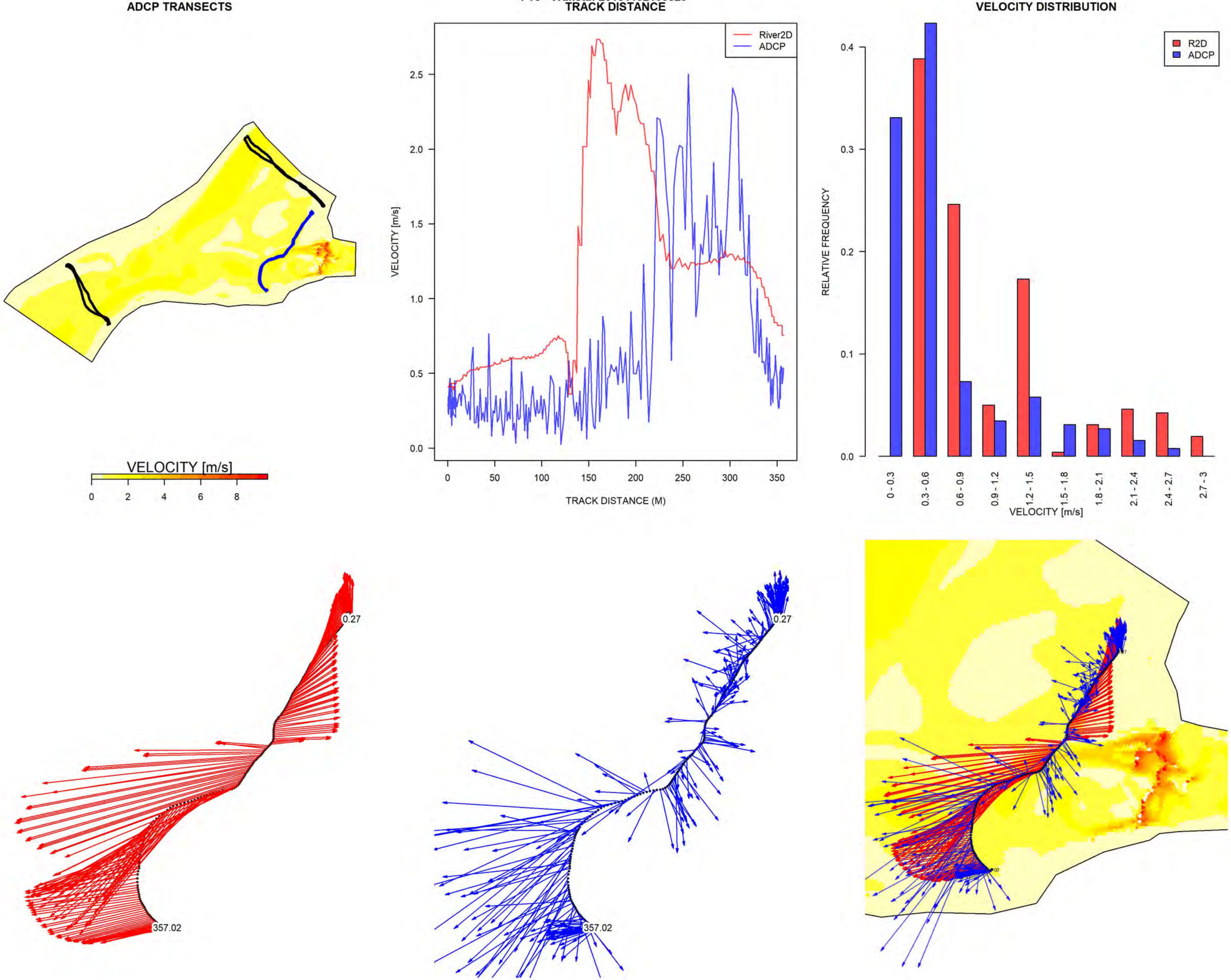
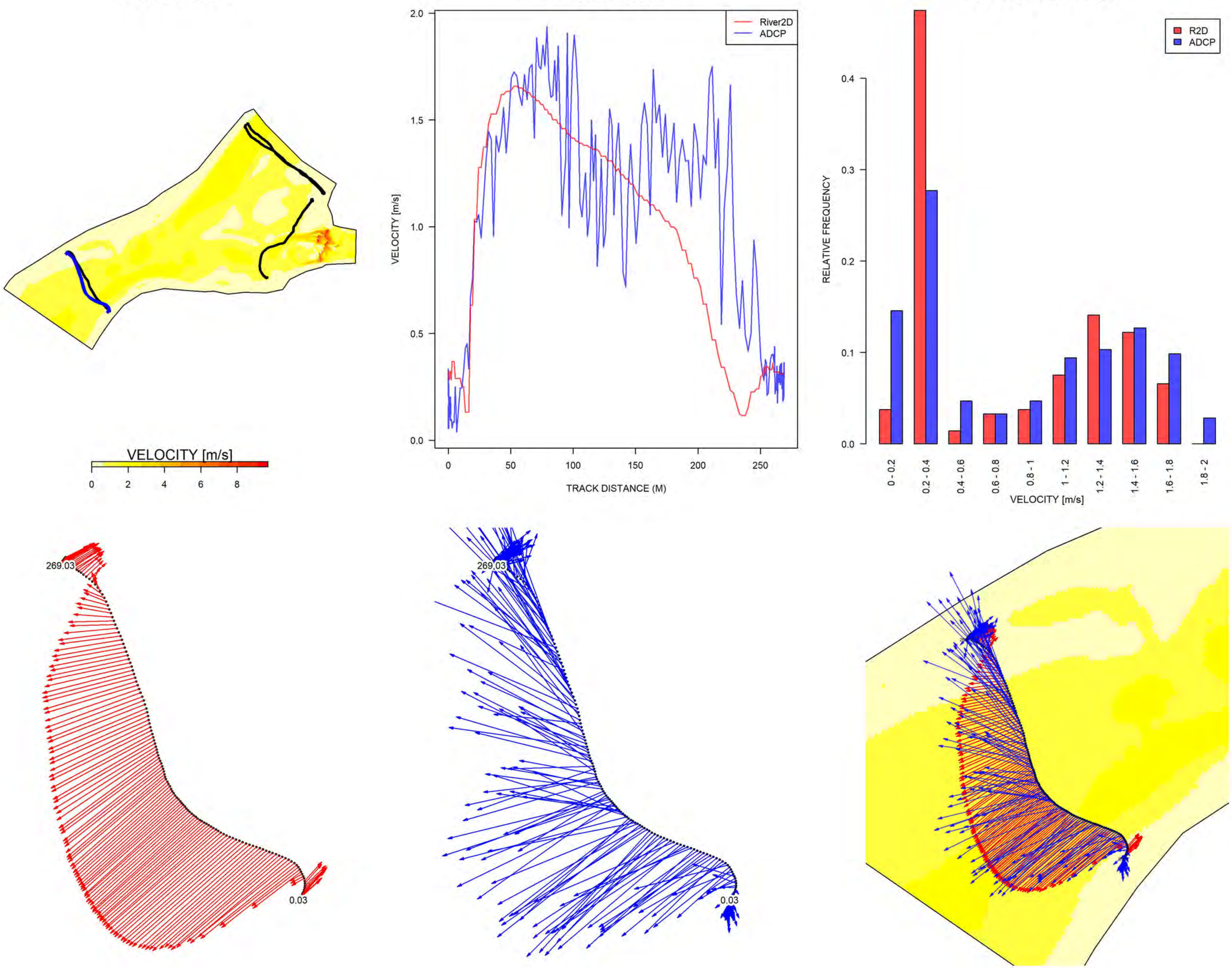


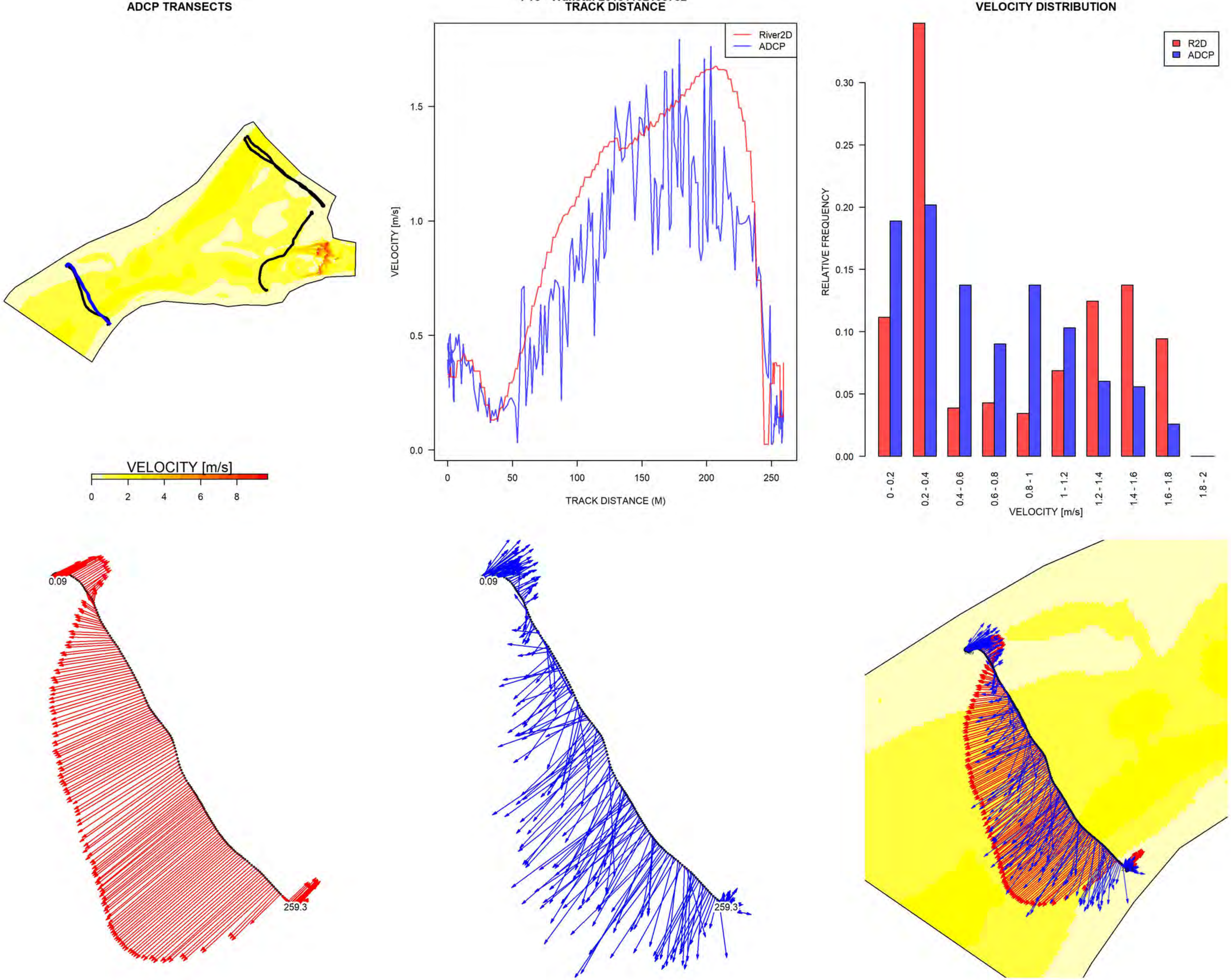
FT3 - Waneta: 20181102100529



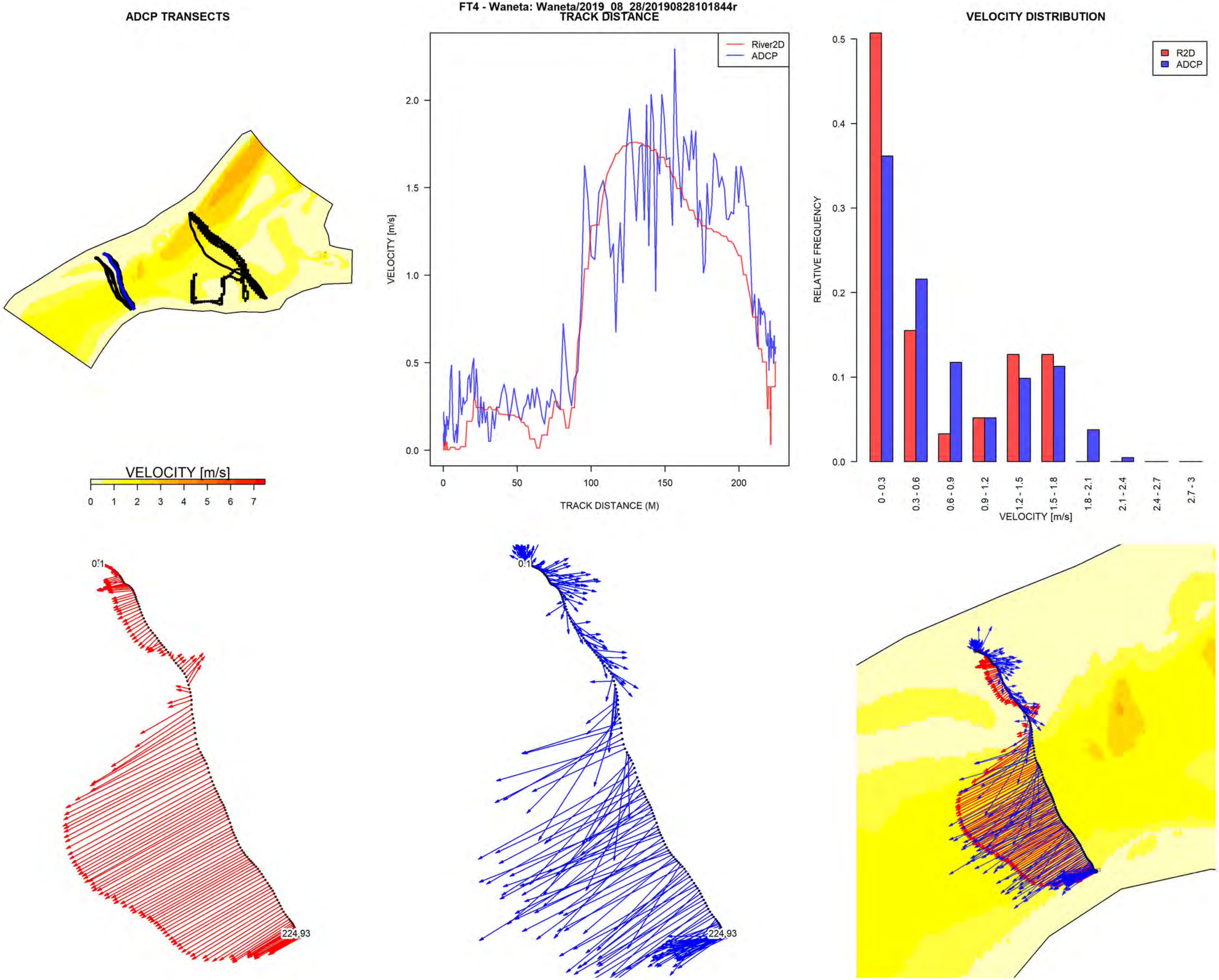
FT3 - Waneta: 20181102103328

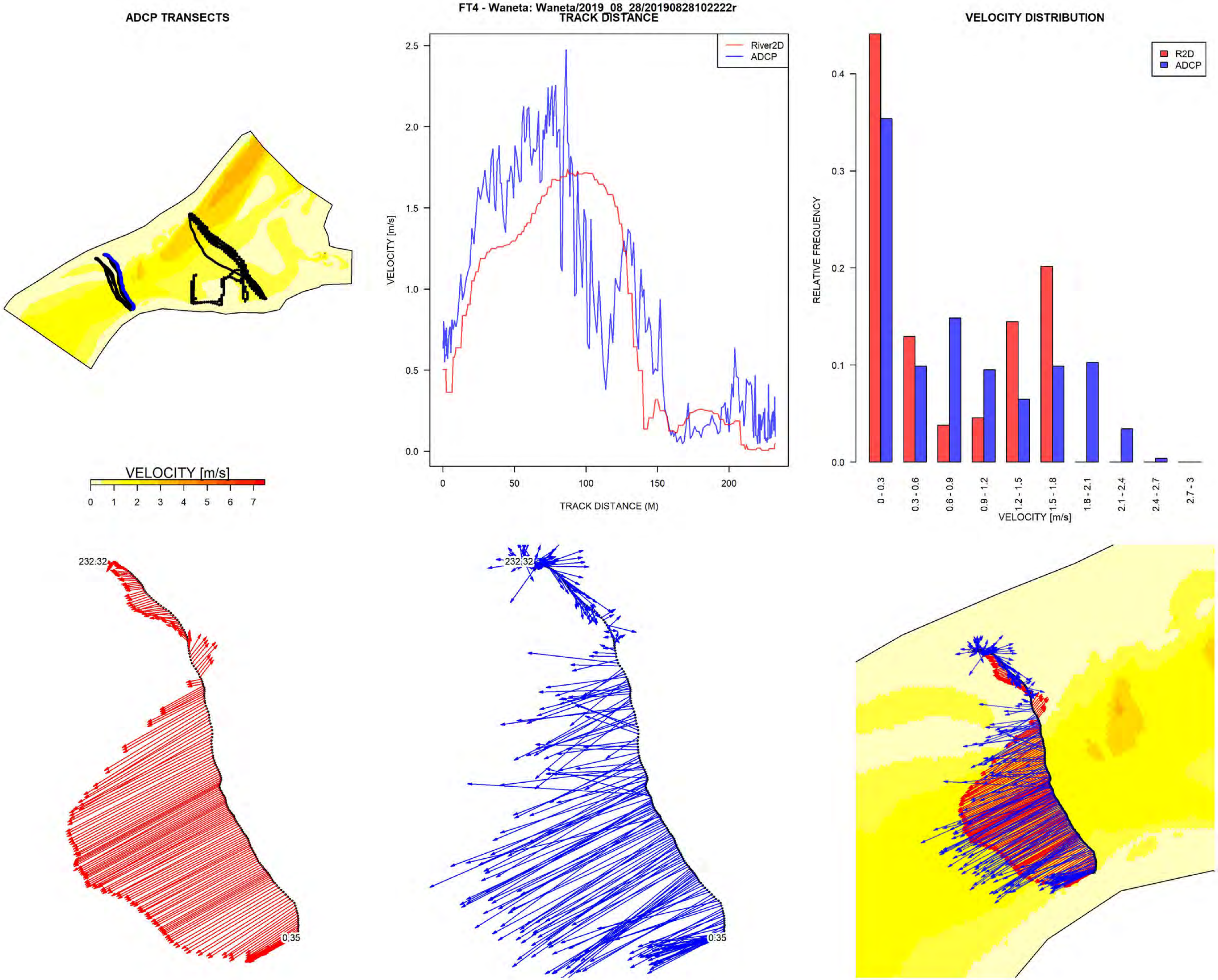


FT3 - Waneta: 20181102103732

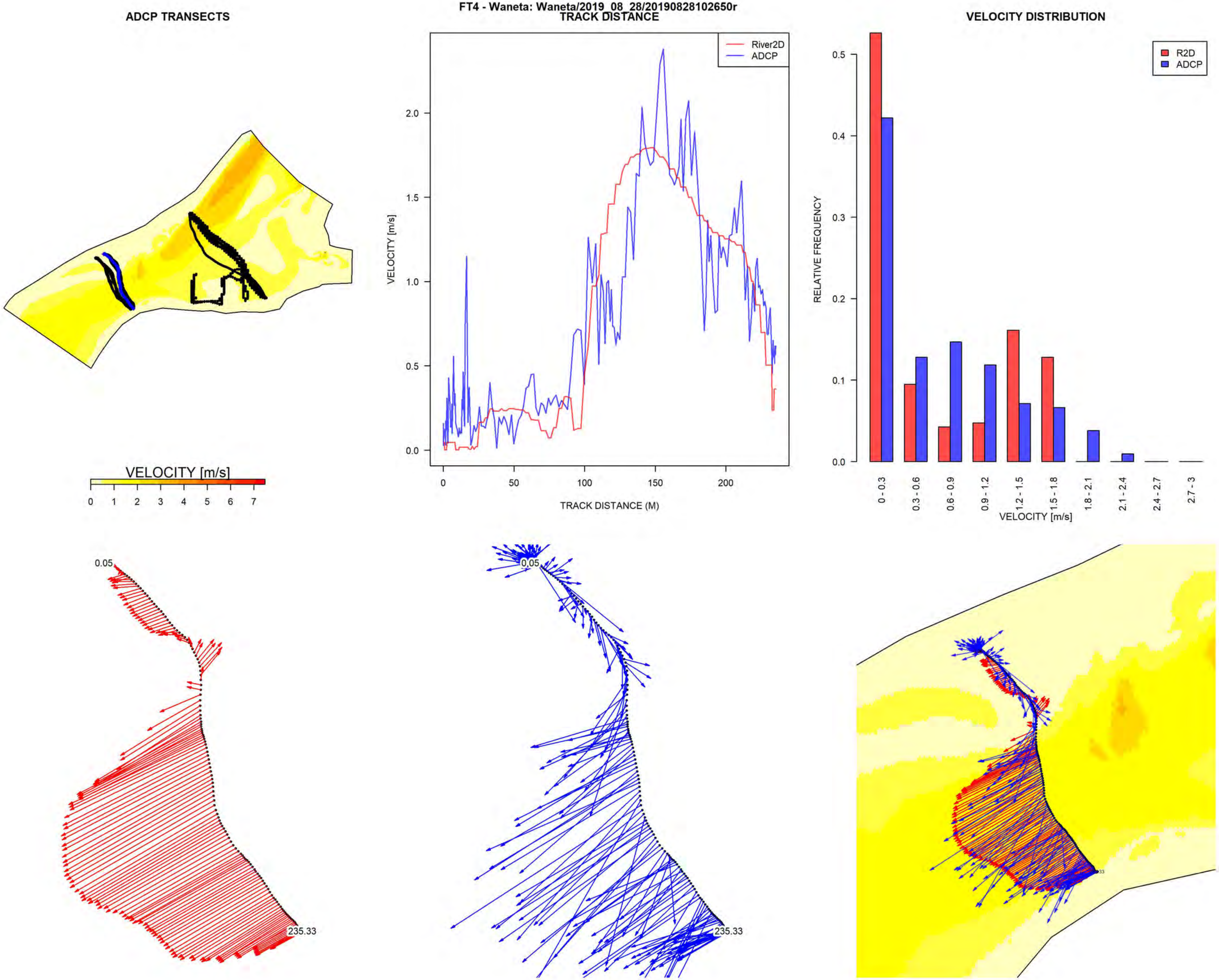


FT4 - Waneta: Waneta/2019_08_28/20190828101844r

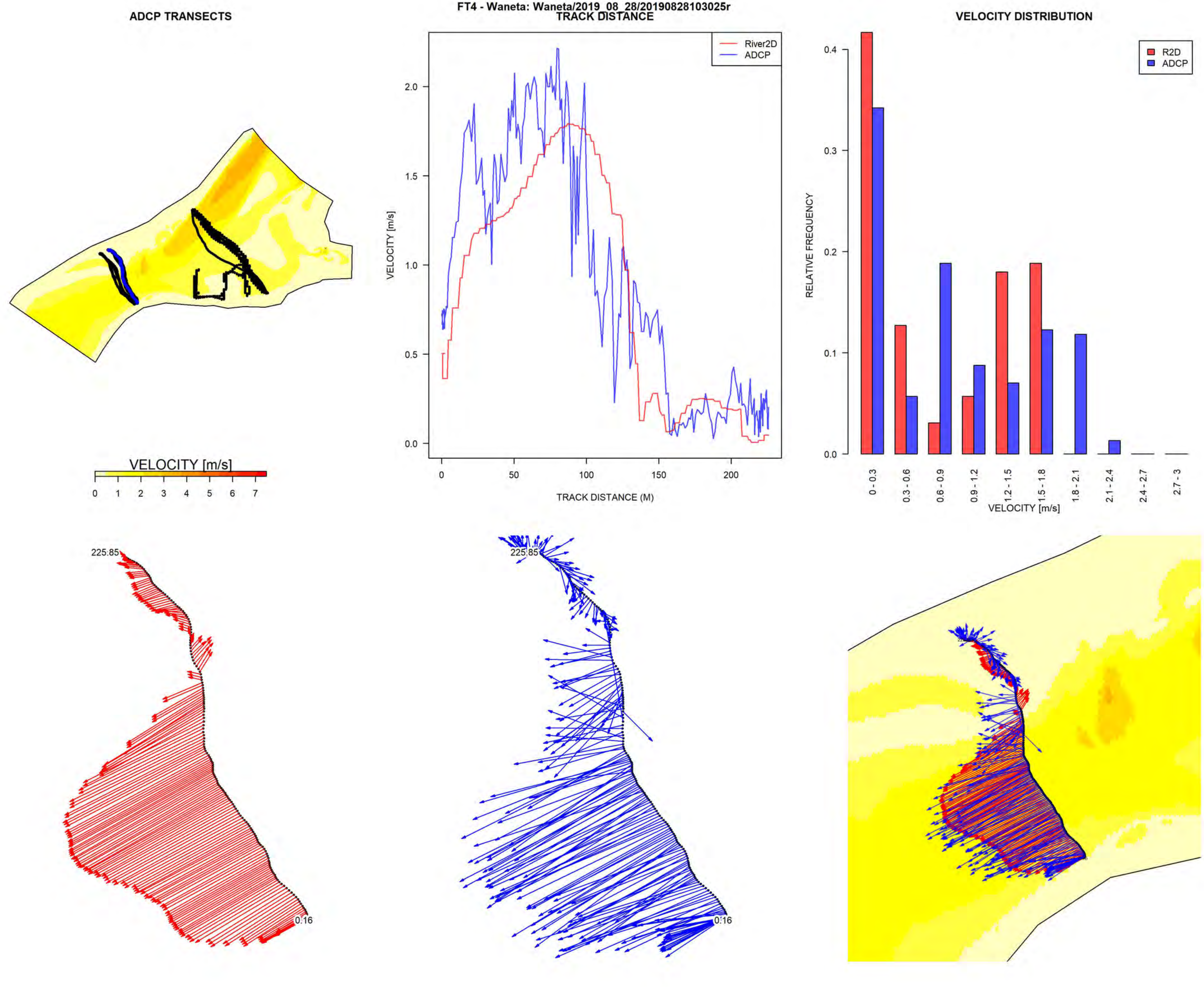



FT4 - Waneta: Waneta/2019_08_28/20190828102222r
ADCP TRANSECTS
TRACK DISTANCE
VELOCITY DISTRIBUTION
VELOCITY [m/s]
0 1 2 3 4 5 6 7
River2D
ADCP
VELOCITY [m/s]
TRACK DISTANCE (M)
0.0 0.5 1.0 1.5 2.0 2.5
0 50 100 150 200
R2D
ADCP
RELATIVE FREQUENCY
0.0 0.1 0.2 0.3 0.4
0 - 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
2.4 - 2.7
2.7 - 3
VELOCITY [m/s]
232.32
0.35
232.32
0.35

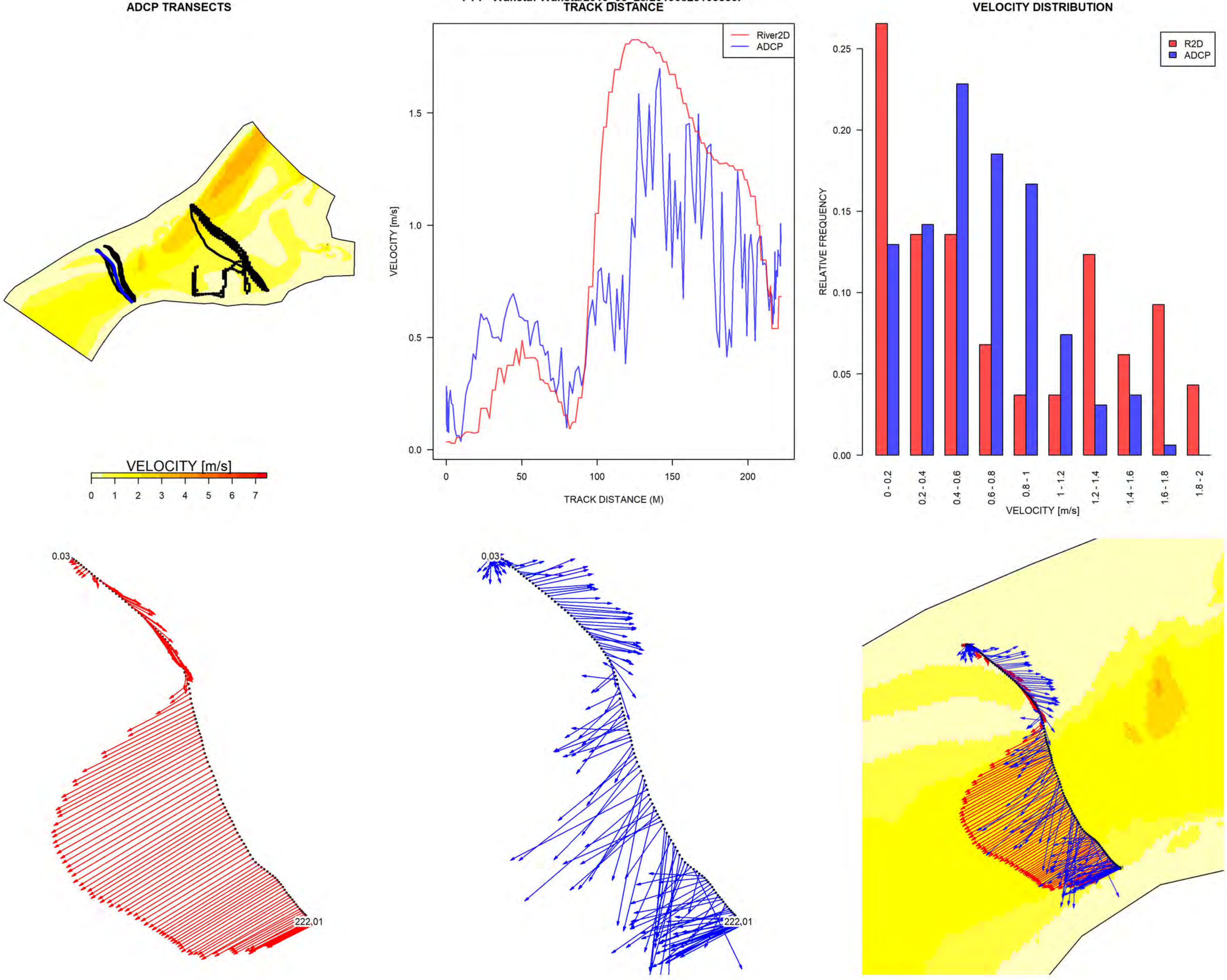
FT4 - Waneta: Waneta/2019_08_28/20190828102650r



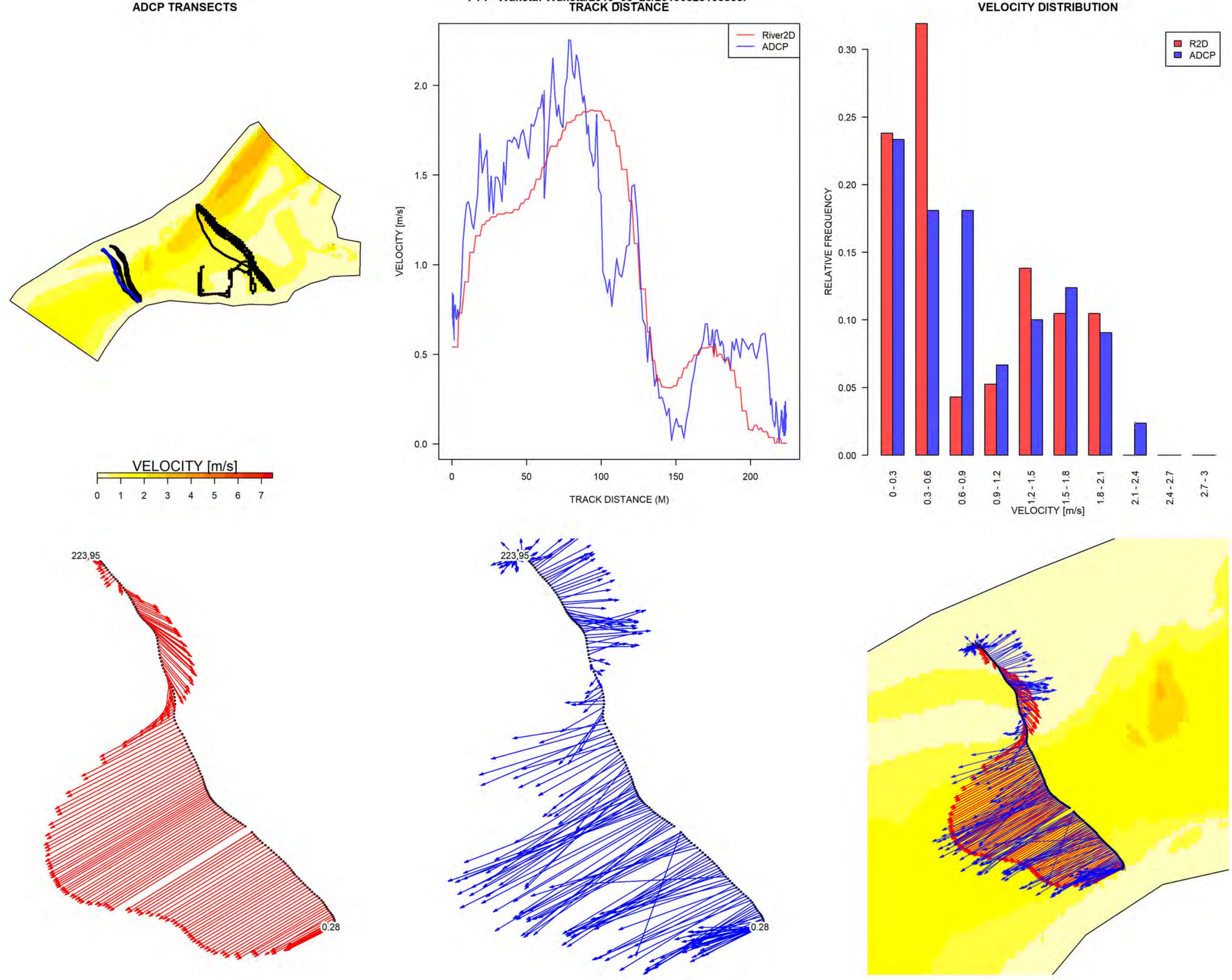
FT4 - Waneta: Waneta/2019_08_28/20190828103025r



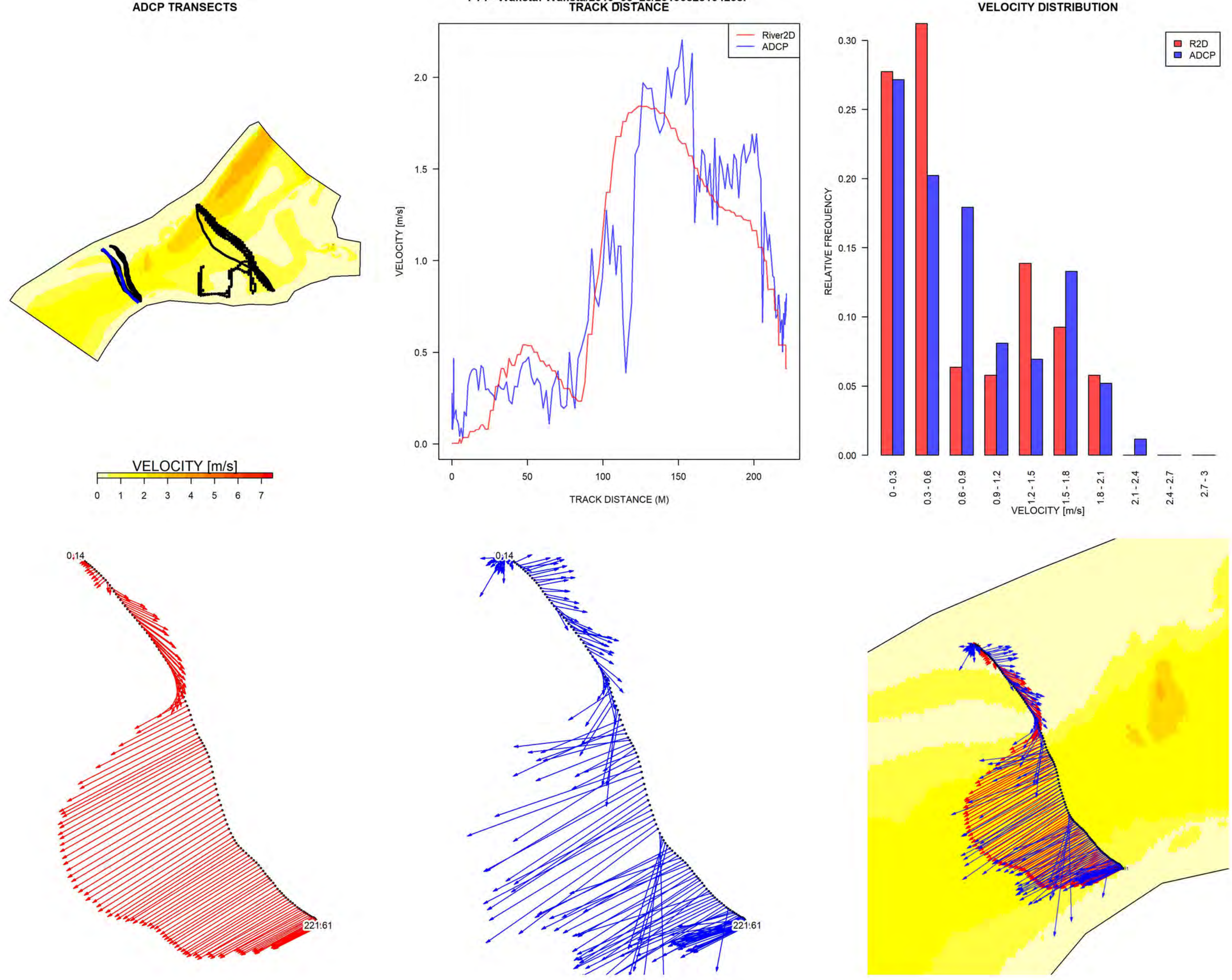
FT4 - Waneta: Waneta/2019_08_28/20190828103550r

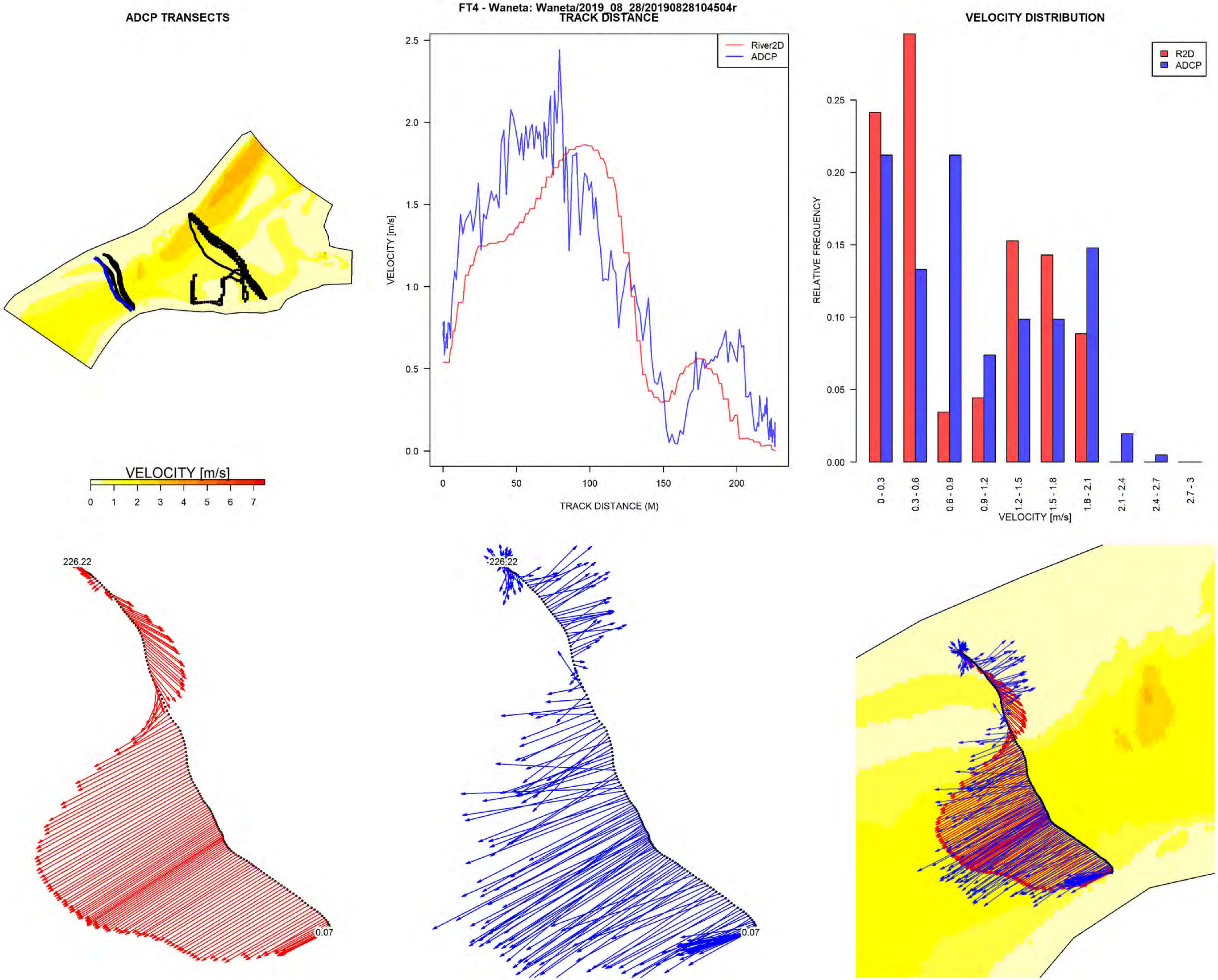


FT4 - Waneta: Waneta/2019_08_28/20190828103835r



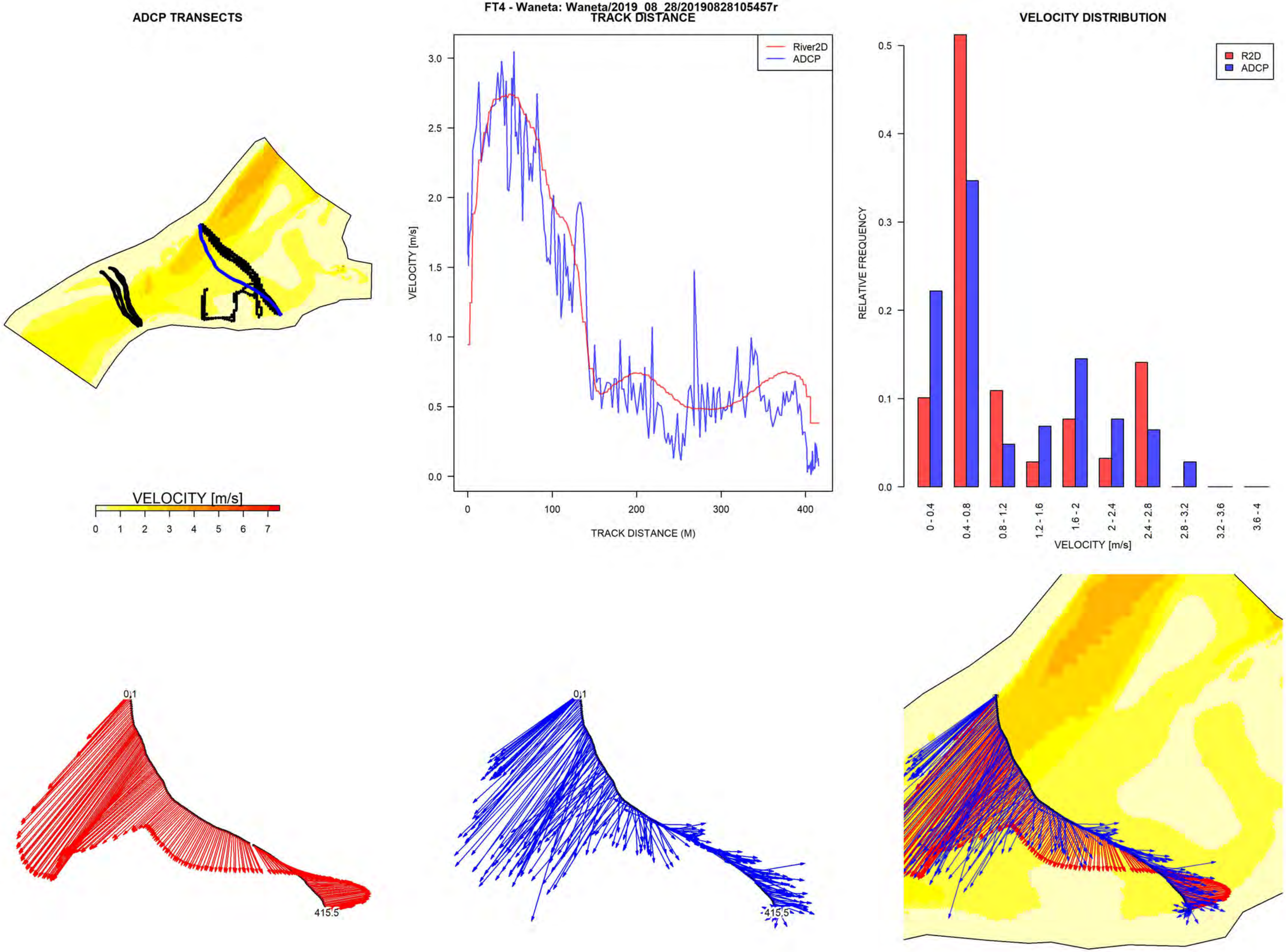
FT4 - Waneta: Waneta/2019_08_28/20190828104208r



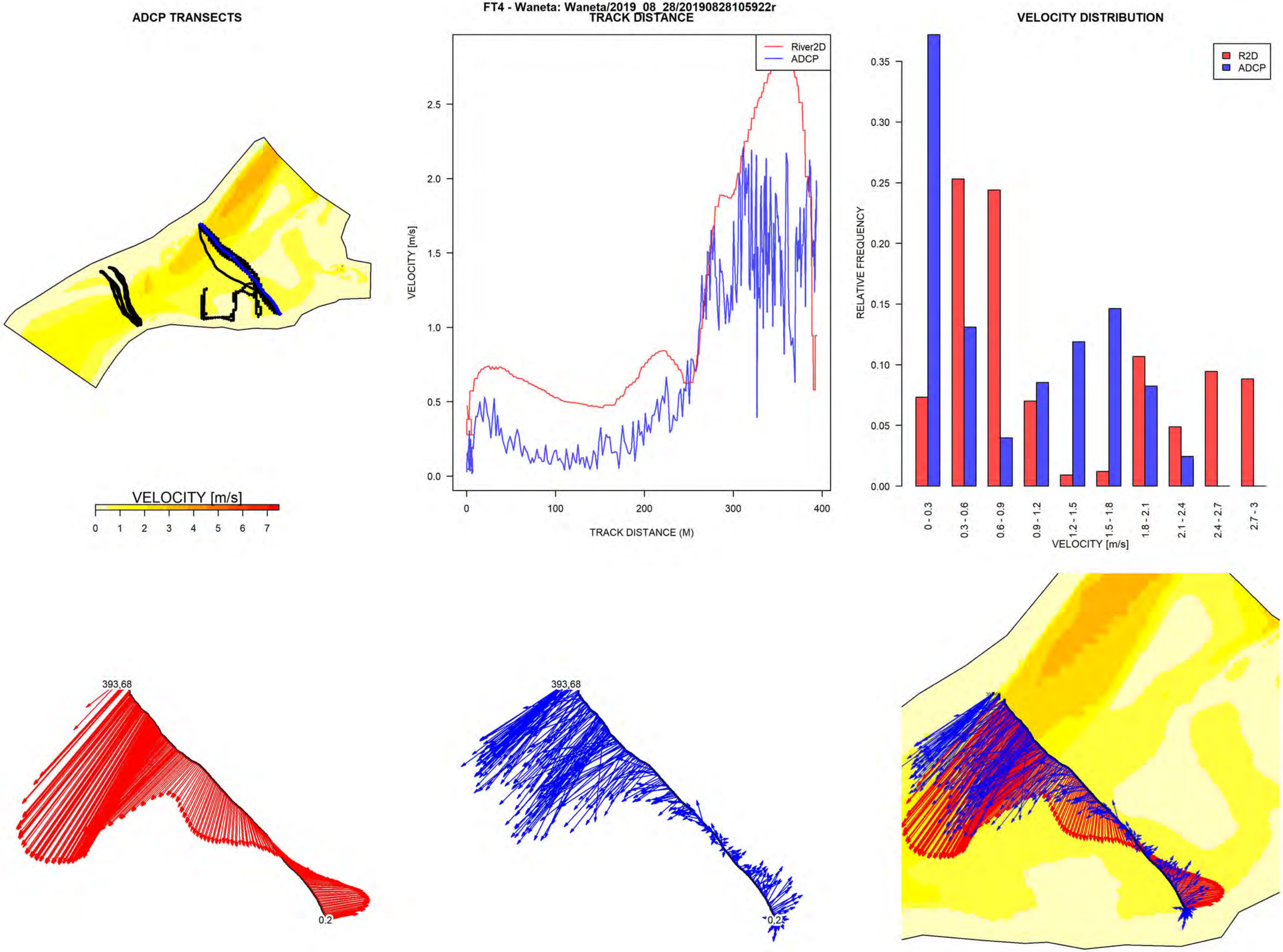


FT4 - Waneta: Waneta/2019_08_28/20190828104504r
ADCP TRANSECTS
VELOCITY [m/s]
0
1
2
3
4
5
6
7
TRACK DISTANCE
River2D
ADCP
VELOCITY [m/s]
TRACK DISTANCE (M)
0.0
0.5
1.0
1.5
2.0
2.5
0
50
100
150
200
VELOCITY DISTRIBUTION
R2D
ADCP
RELATIVE FREQUENCY
0.00
0.05
0.10
0.15
0.20
0.25
0 - 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
2.4 - 2.7
2.7 - 3
VELOCITY [m/s]
226.22
0.07
226.22
0.07

FT4 - Waneta: Waneta/2019_08_28/20190828105457r

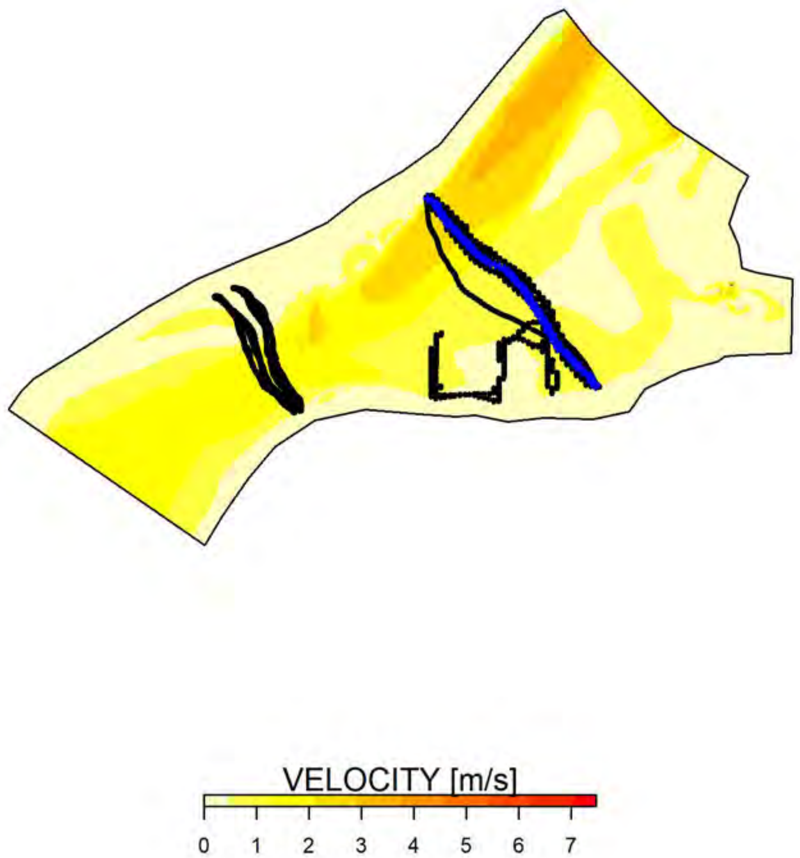


FT4 - Waneta: Waneta/2019_08_28/20190828105922r

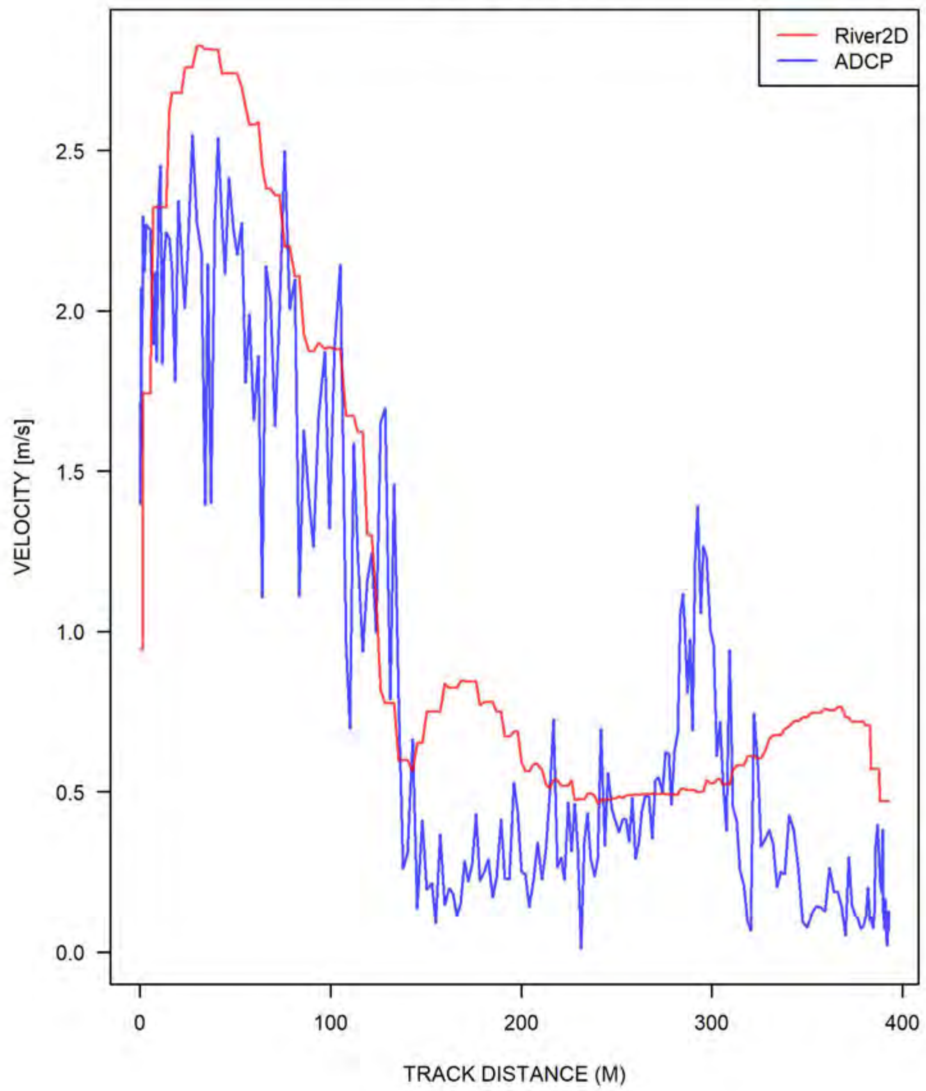


FT4 - Waneta: Waneta/2019_08_28/20190828110830r

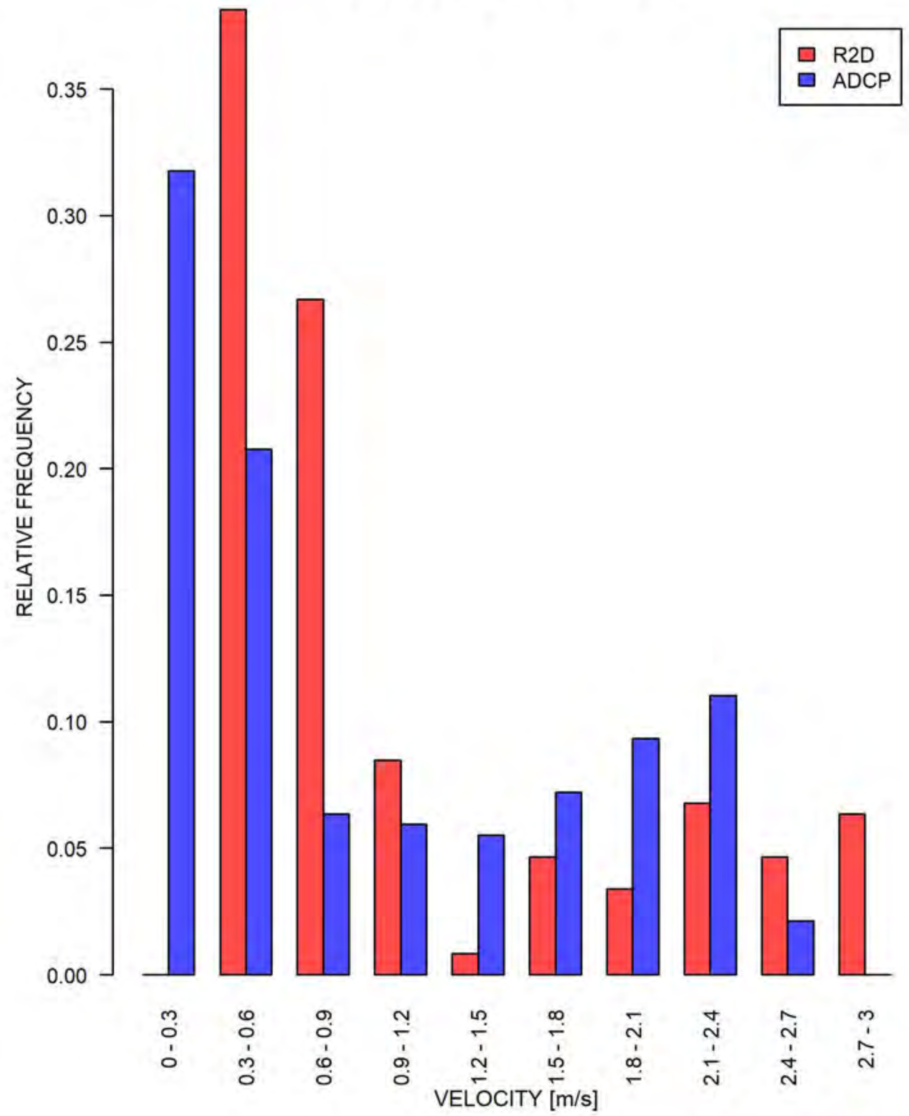
ADCP TRANSECTS

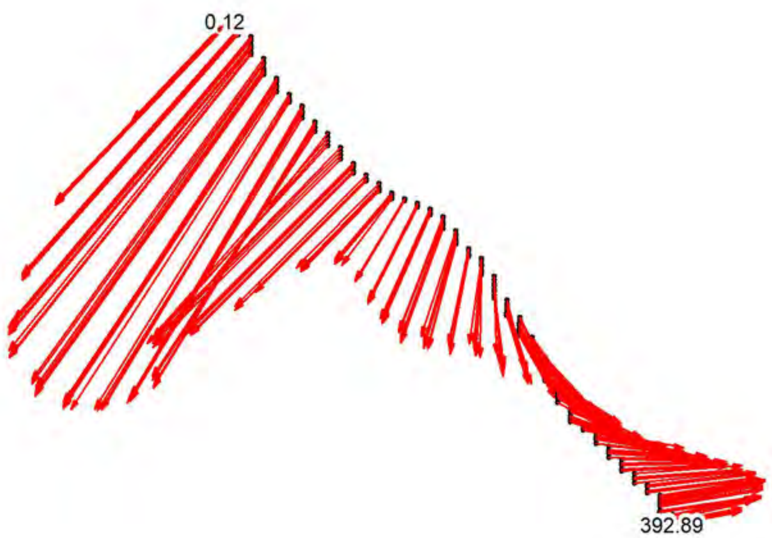


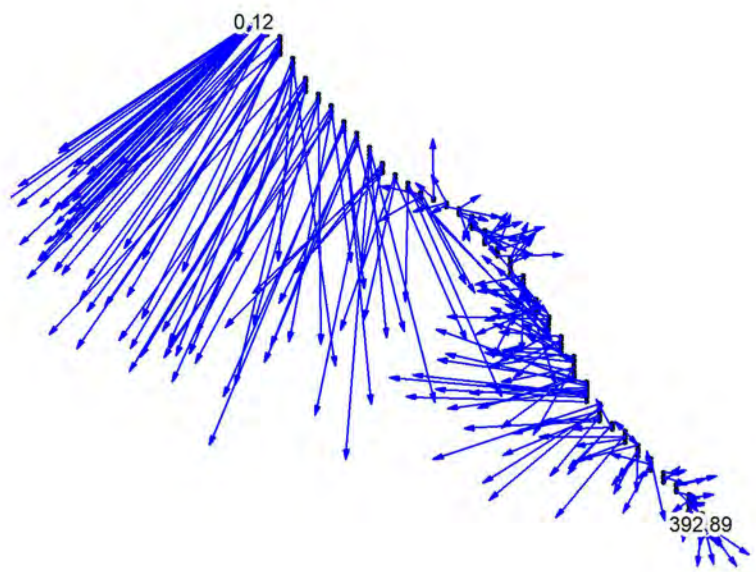
TRACK DISTANCE

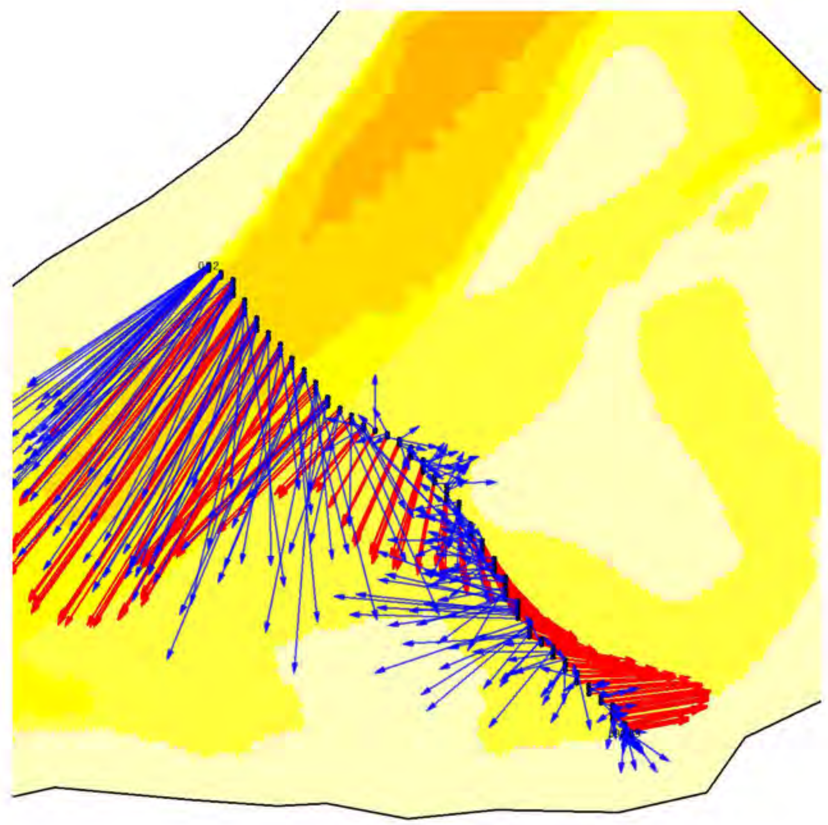


VELOCITY DISTRIBUTION

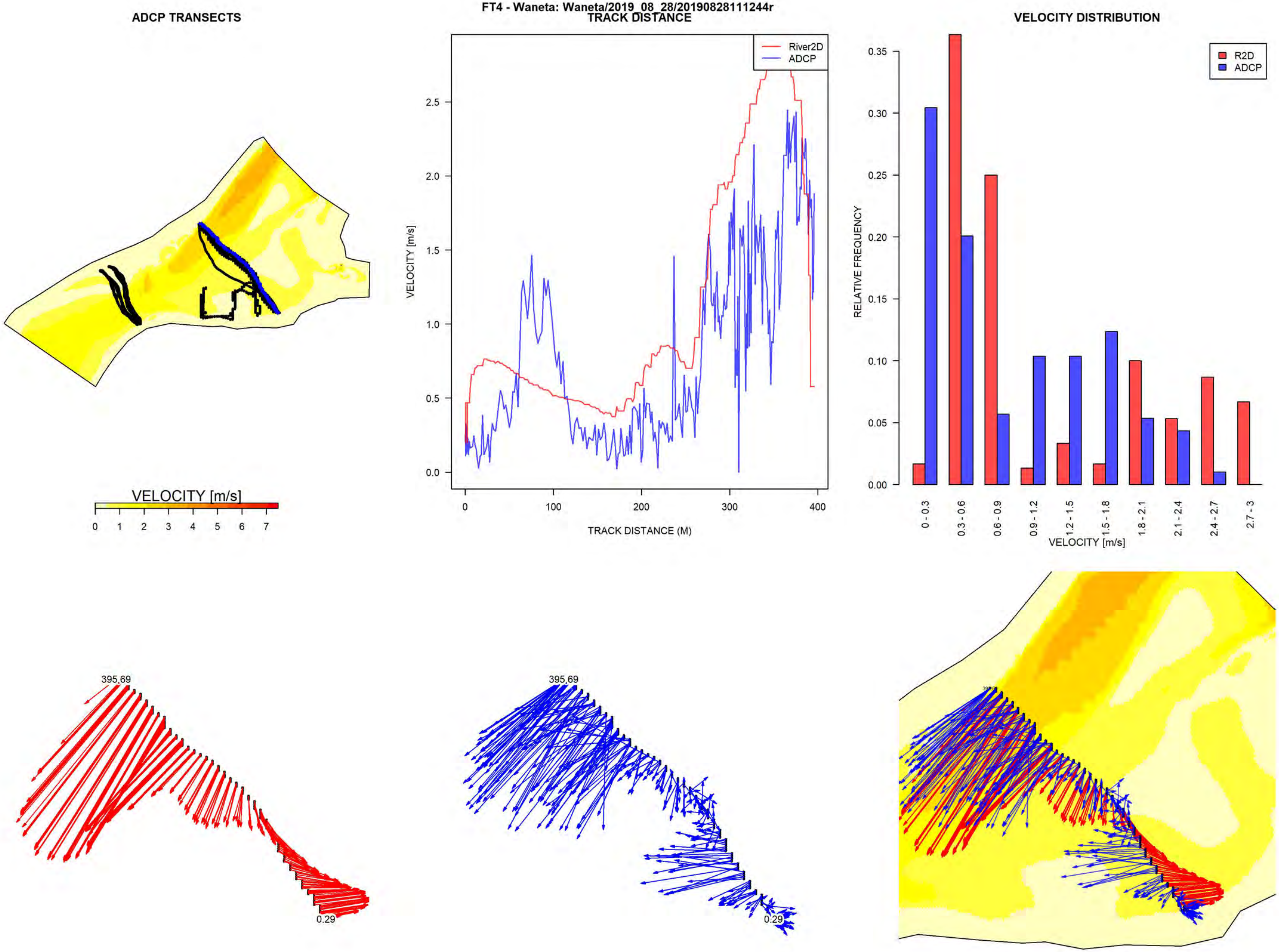


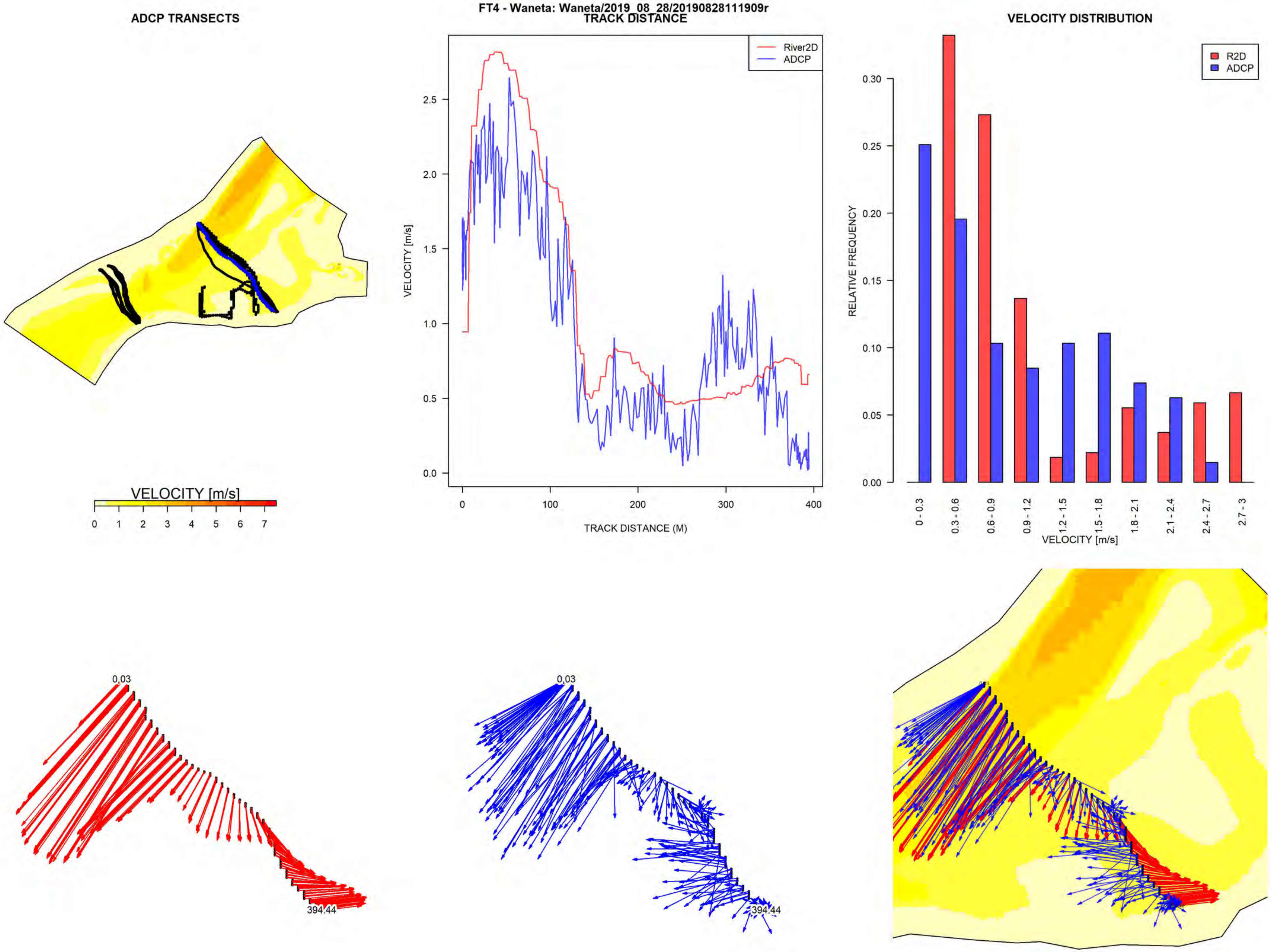


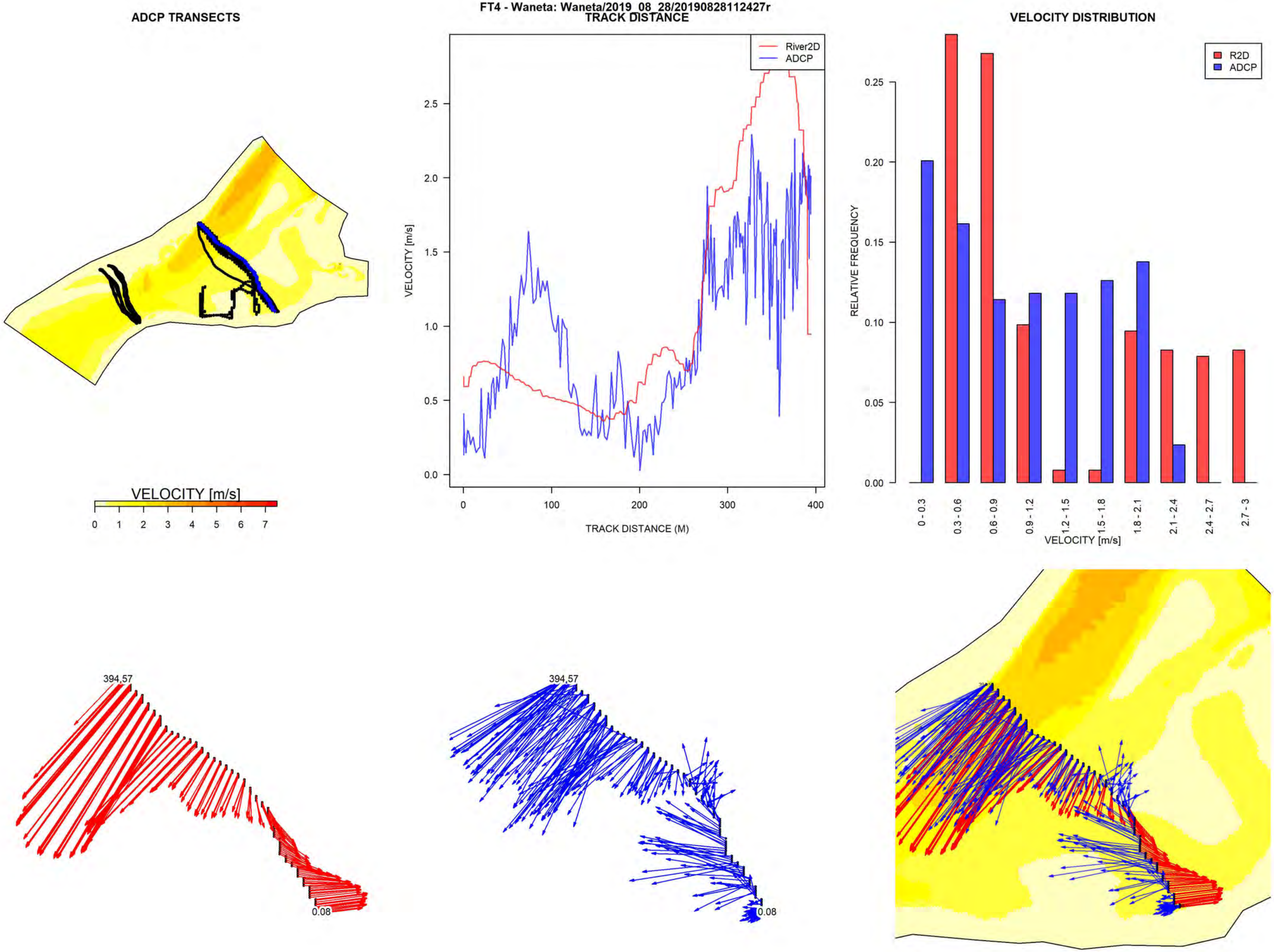




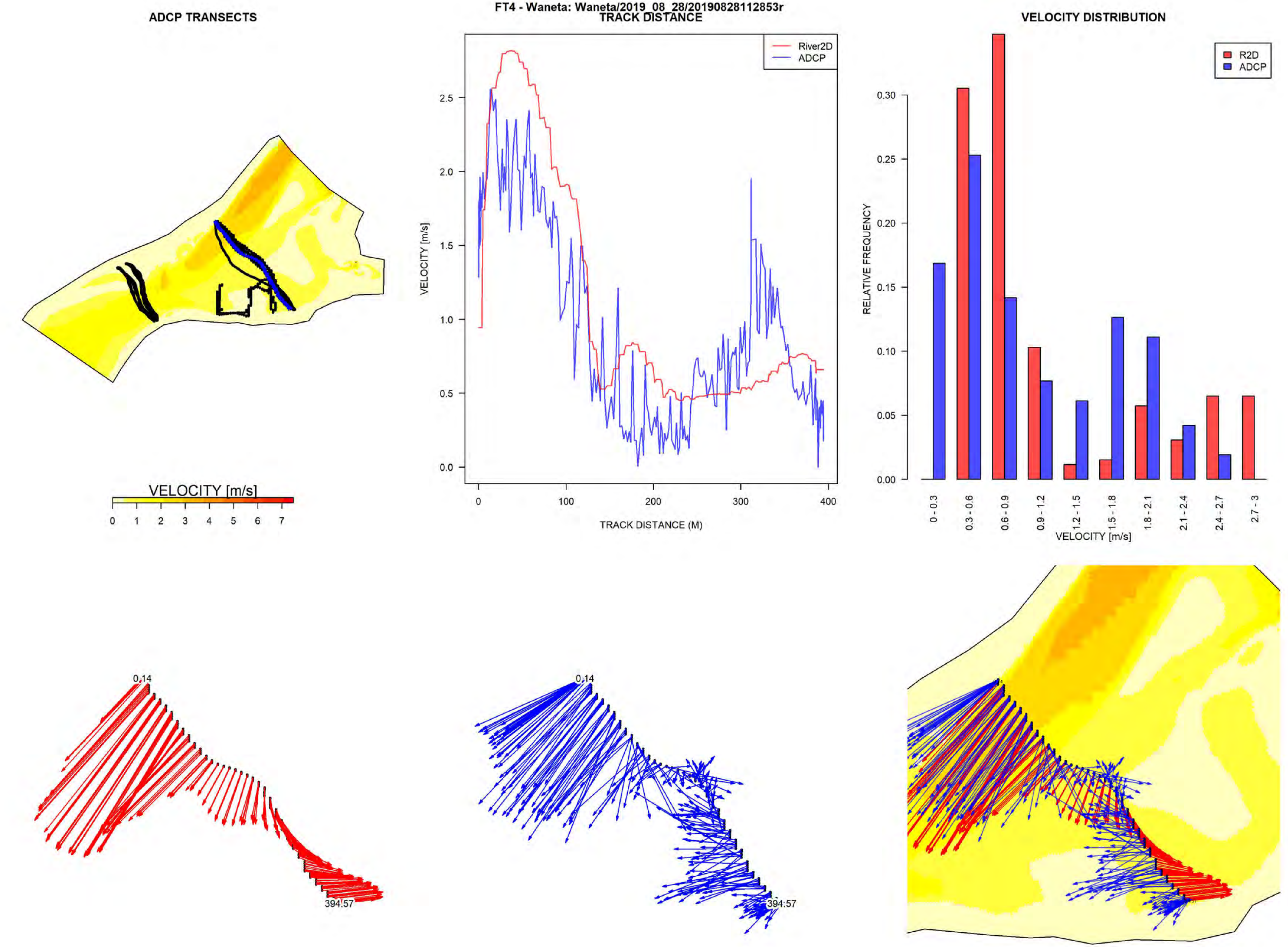
FT4 - Waneta: Waneta/2019_08_28/20190828111244r




FT4 - Waneta: Waneta/2019_08_28/20190828111909r
ADCP TRANSECTS
VELOCITY [m/s]
0 1 2 3 4 5 6 7
TRACK DISTANCE
River2D
ADCP
VELOCITY [m/s]
TRACK DISTANCE (M)
0.0 0.5 1.0 1.5 2.0 2.5
0 100 200 300 400
VELOCITY DISTRIBUTION
R2D
ADCP
RELATIVE FREQUENCY
0.00 0.05 0.10 0.15 0.20 0.25 0.30
0 - 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
2.4 - 2.7
2.7 - 3
VELOCITY [m/s]
0.03
394.44
0.03
394.44


FT4 - Waneta: Waneta/2019_08_28/20190828112427r
ADCP TRANSECTS
VELOCITY [m/s]
0 1 2 3 4 5 6 7
TRACK DISTANCE
River2D
ADCP
VELOCITY [m/s]
TRACK DISTANCE (M)
0.0 0.5 1.0 1.5 2.0 2.5
0 100 200 300 400
VELOCITY DISTRIBUTION
R2D
ADCP
RELATIVE FREQUENCY
0.00 0.05 0.10 0.15 0.20 0.25
0 - 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 2.4
2.4 - 2.7
2.7 - 3
VELOCITY [m/s]
394,57
0.08
394,57
0.08

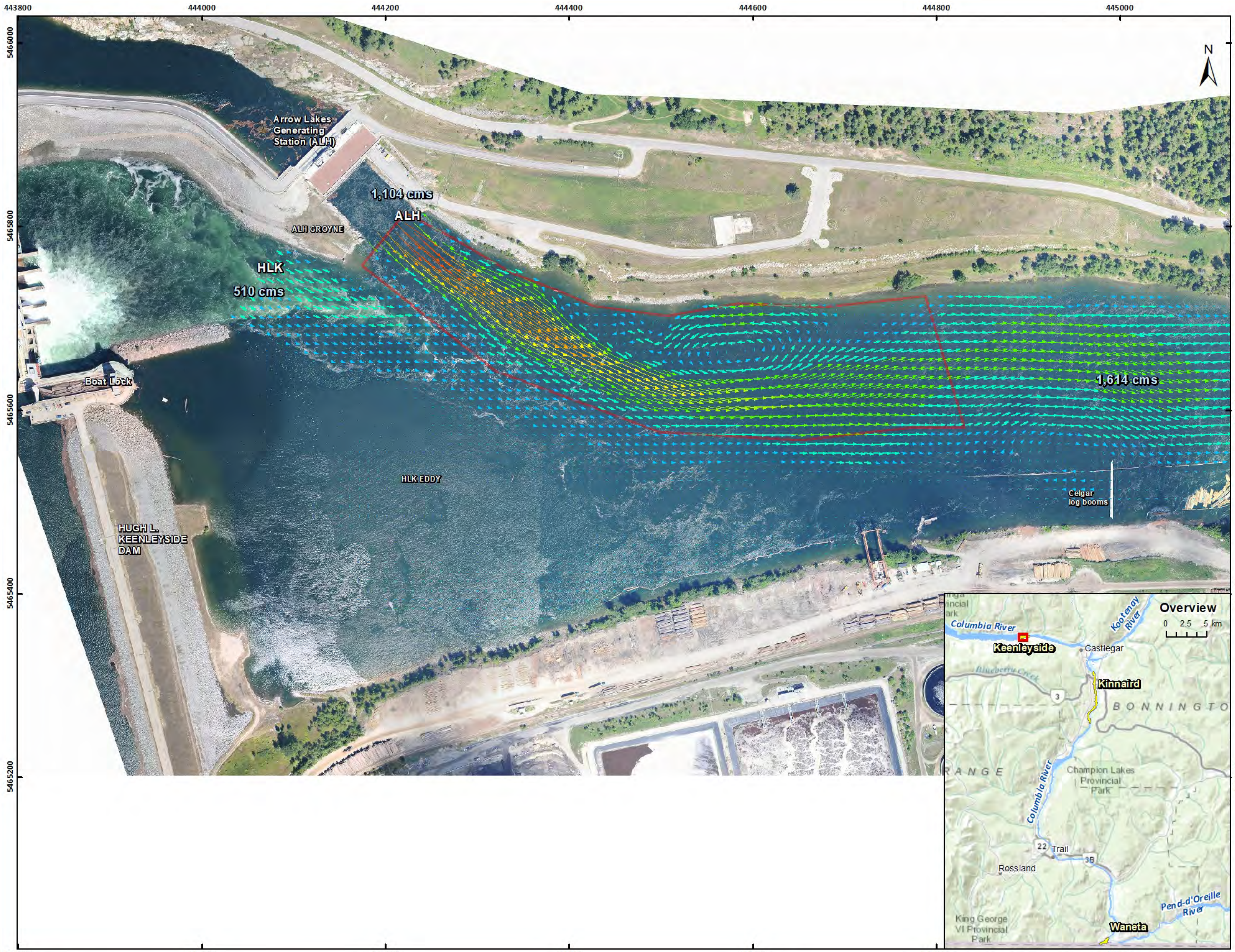
FT4 - Waneta: Waneta/2019_08_28/20190828112853r



Appendix F. Simulated velocity vectors for Field Trip 1

CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Keenleyside R2D Velocity Field Trip 1 July Typical Spawning Flows



Legend

Known Spawning Area

River2D Velocity (m/s)

- 0 - 0.10
- 0.10 - 0.50
- 0.50 - 1.00
- 1.00 - 1.50
- 1.50 - 1.75
- 1.75 - 2.00
- 2.00 - 2.50
- >2.50

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

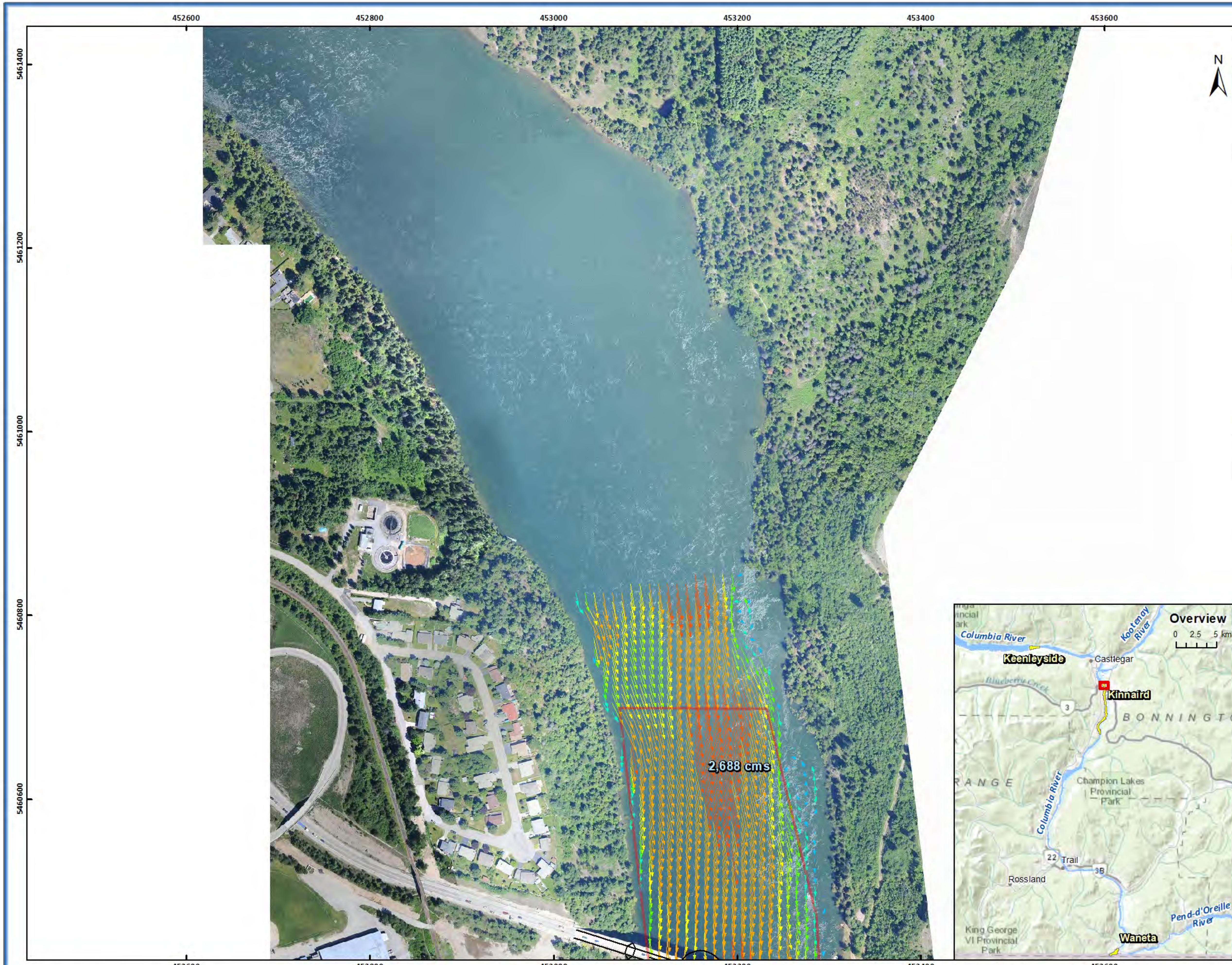
NO.	DATE	REVISION	BY
1	4/12/2019	1210_Engagement_FT1_Flow_190404	
2			
3			
4			
5			

Date Saved: 4/12/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map F1

Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_FT1_Flow_190404.mxd



CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Kinnaird - Upper
R2D Velocity Field Trip 1 July
Typical Spawning Flows

Legend

Known Spawning Area

River2D Velocity (m/s)

- 0 - 0.10
- 0.10 - 0.50
- 0.50 - 1.00
- 1.00 - 1.50
- 1.50 - 1.75
- 1.75 - 2.00
- 2.00 - 2.50
- >2.50

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

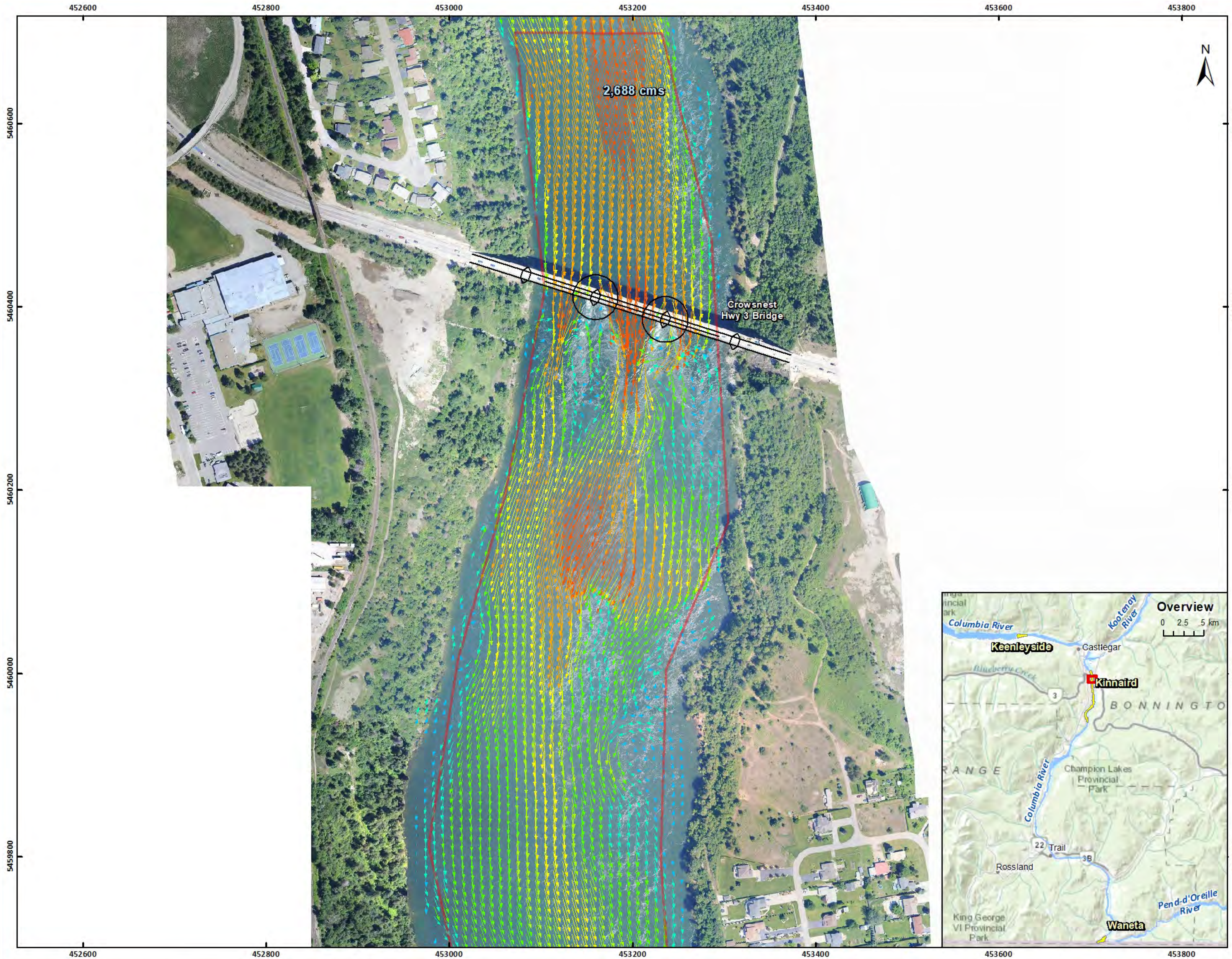
NO.	DATE	REVISION	BY
1	4/12/2019	1210_Engagement_FT1_Flow_190404	
2			
3			
4			
5			

Date Saved: 4/12/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map F2

Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_FT1_Flow_190404.mxd



CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Kinnaird - Upper
R2D Velocity Field Trip 1 July
Typical Spawning Flows

Legend

Known Spawning Area

River2D Velocity (m/s)

- 0 - 0.10
- 0.10 - 0.50
- 0.50 - 1.00
- 1.00 - 1.50
- 1.50 - 1.75
- 1.75 - 2.00
- 2.00 - 2.50
- >2.50

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
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Date Saved: 4/12/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map F3

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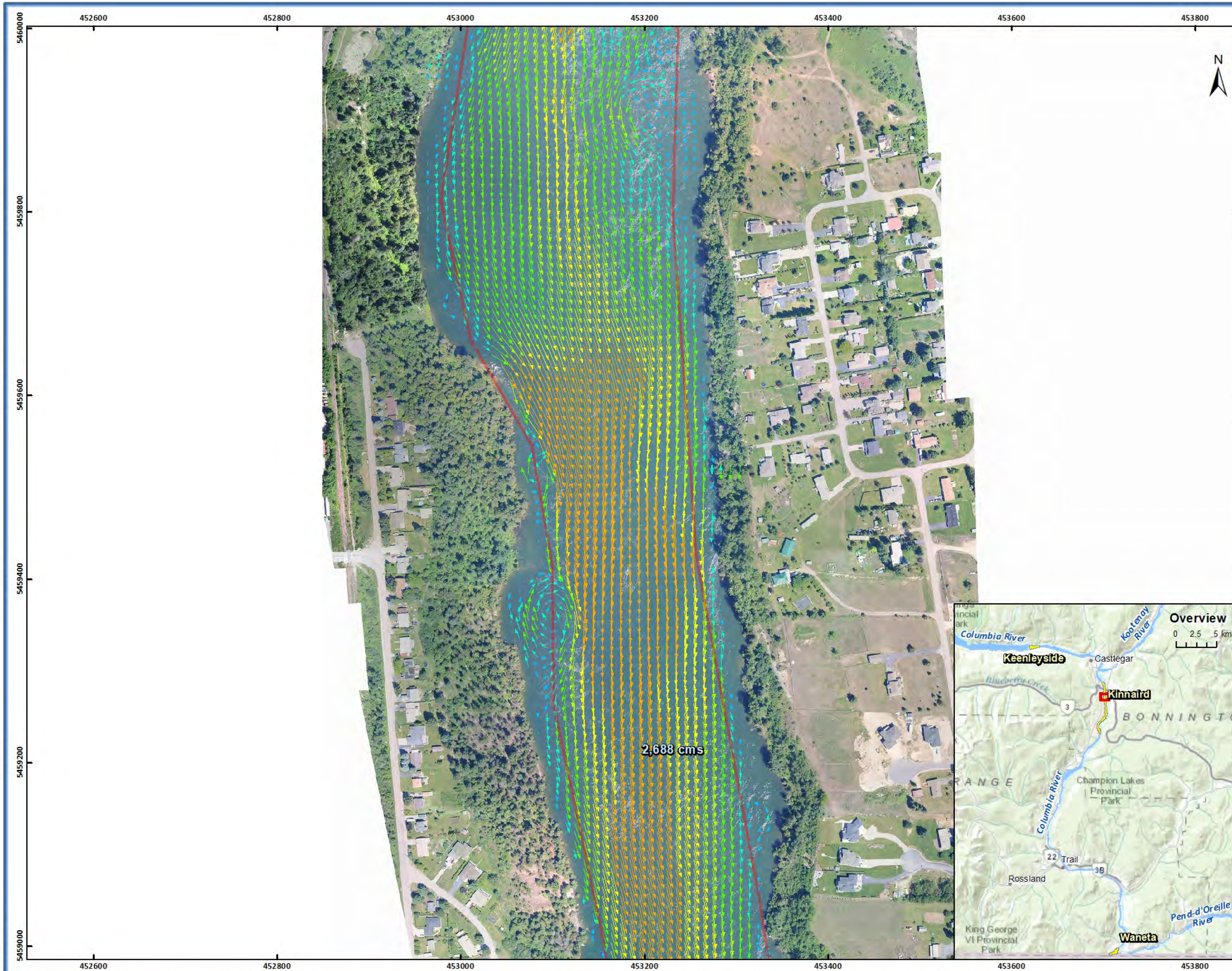

CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Kinnaird - Upper
R2D Velocity Field Trip 1 July
Typical Spawning Flows

Legend

Known Spawning Area

River2D Velocity (m/s)

- 0 - 0.10
- 0.10 - 0.50
- 0.50 - 1.00
- 1.00 - 1.50
- 1.50 - 1.75
- 1.75 - 2.00
- 2.00 - 2.50
- >2.50

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
1	4/12/2019	1210_Engagement_FT1_Flow_190404	
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Date Saved: 4/12/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map F4

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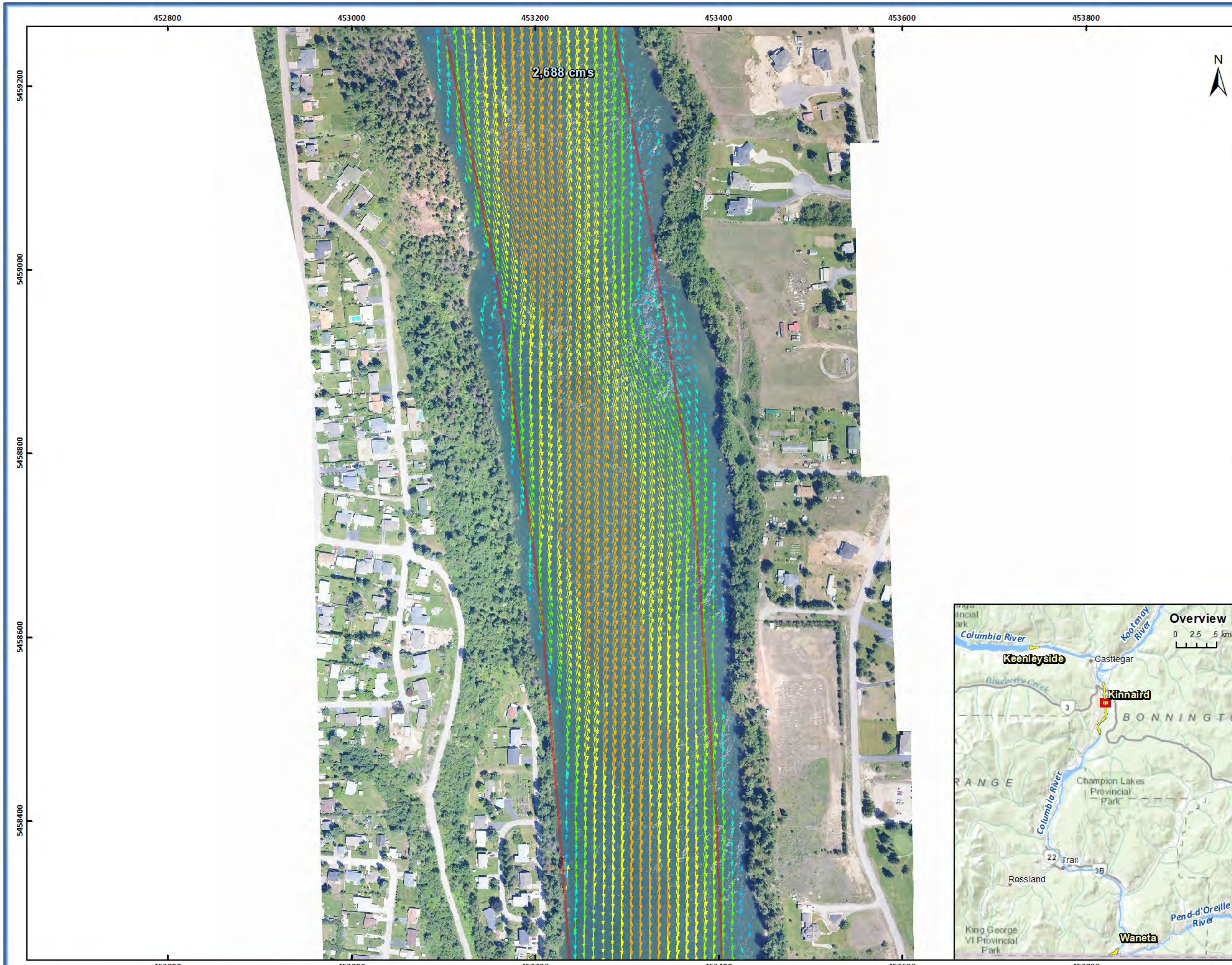

CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Kinnaird - Upper
R2D Velocity Field Trip 1 July Typical Spawning Flows

Legend

Known Spawning Area

River2D Velocity (m/s)

- 0 - 0.10
- 0.10 - 0.50
- 0.50 - 1.00
- 1.00 - 1.50
- 1.50 - 1.75
- 1.75 - 2.00
- 2.00 - 2.50
- >2.50

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
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Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

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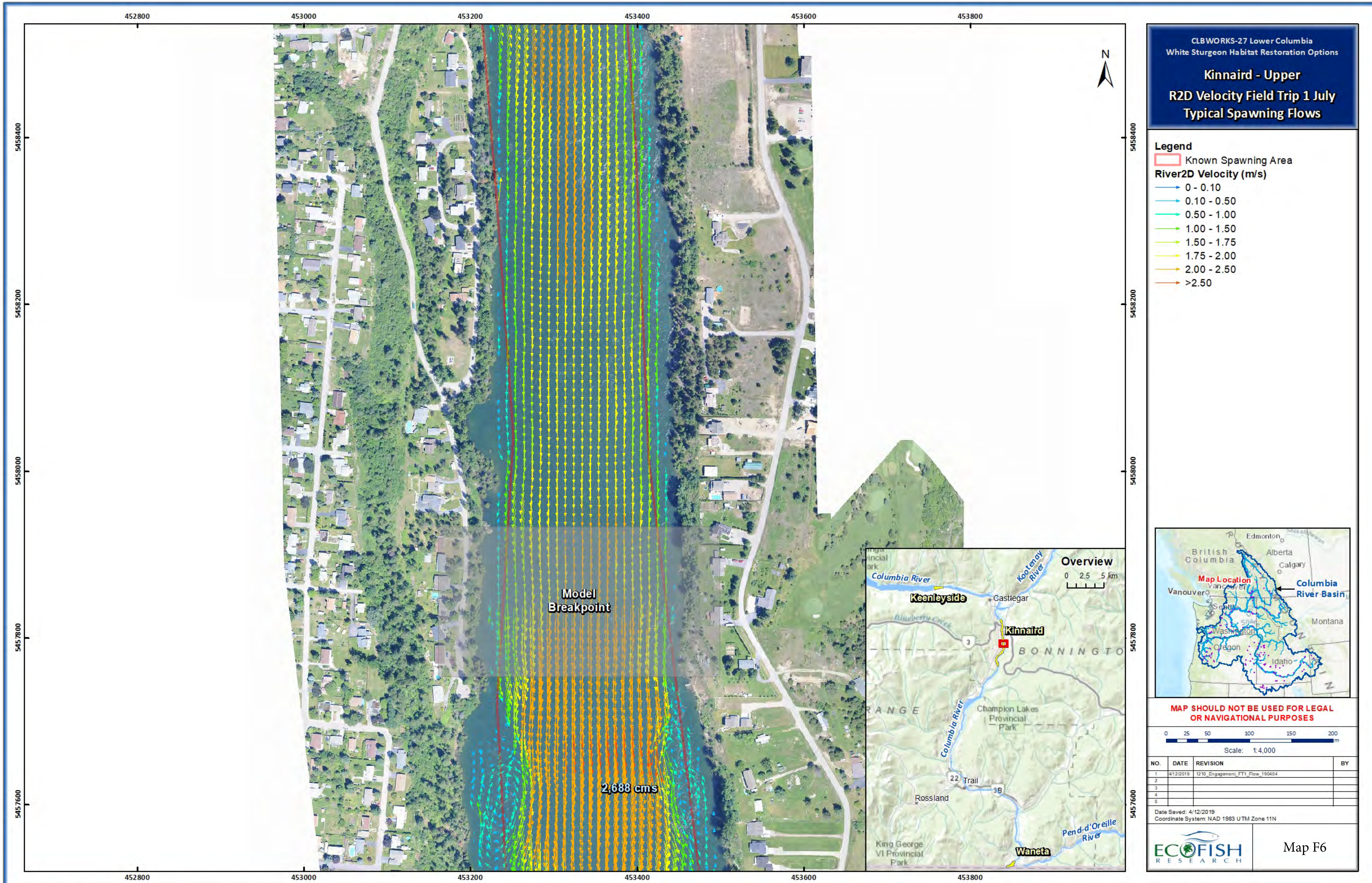

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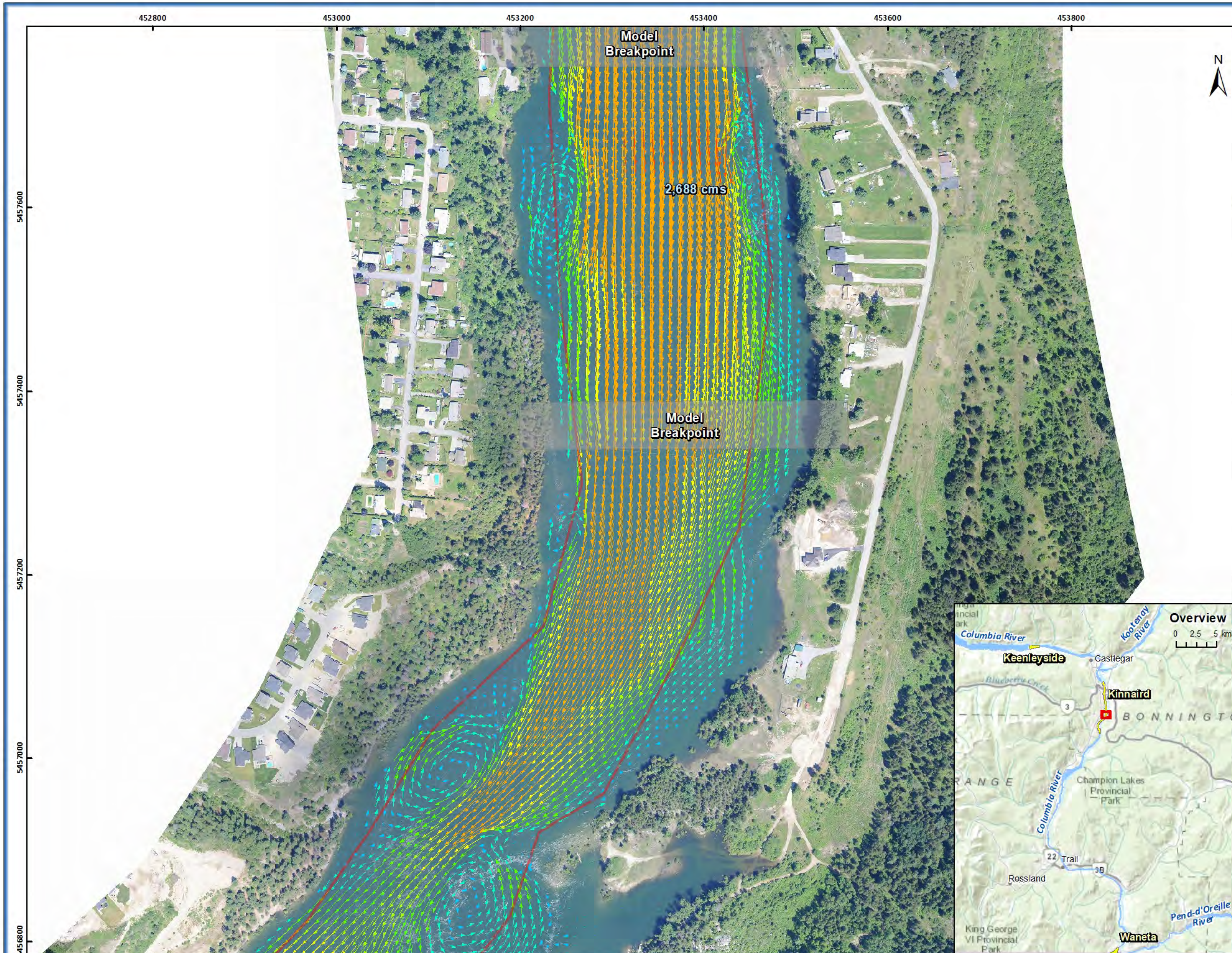

CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Kinnaird - Lower
R2D Velocity Field Trip 1 July
Typical Spawning Flows

Legend

Known Spawning Area

River2D Velocity (m/s)

- 0 - 0.10
- 0.10 - 0.50
- 0.50 - 1.00
- 1.00 - 1.50
- 1.50 - 1.75
- 1.75 - 2.00
- 2.00 - 2.50
- >2.50

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

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Date Saved: 4/12/2019
Coordinate System: NAD 1983 UTM Zone 11N

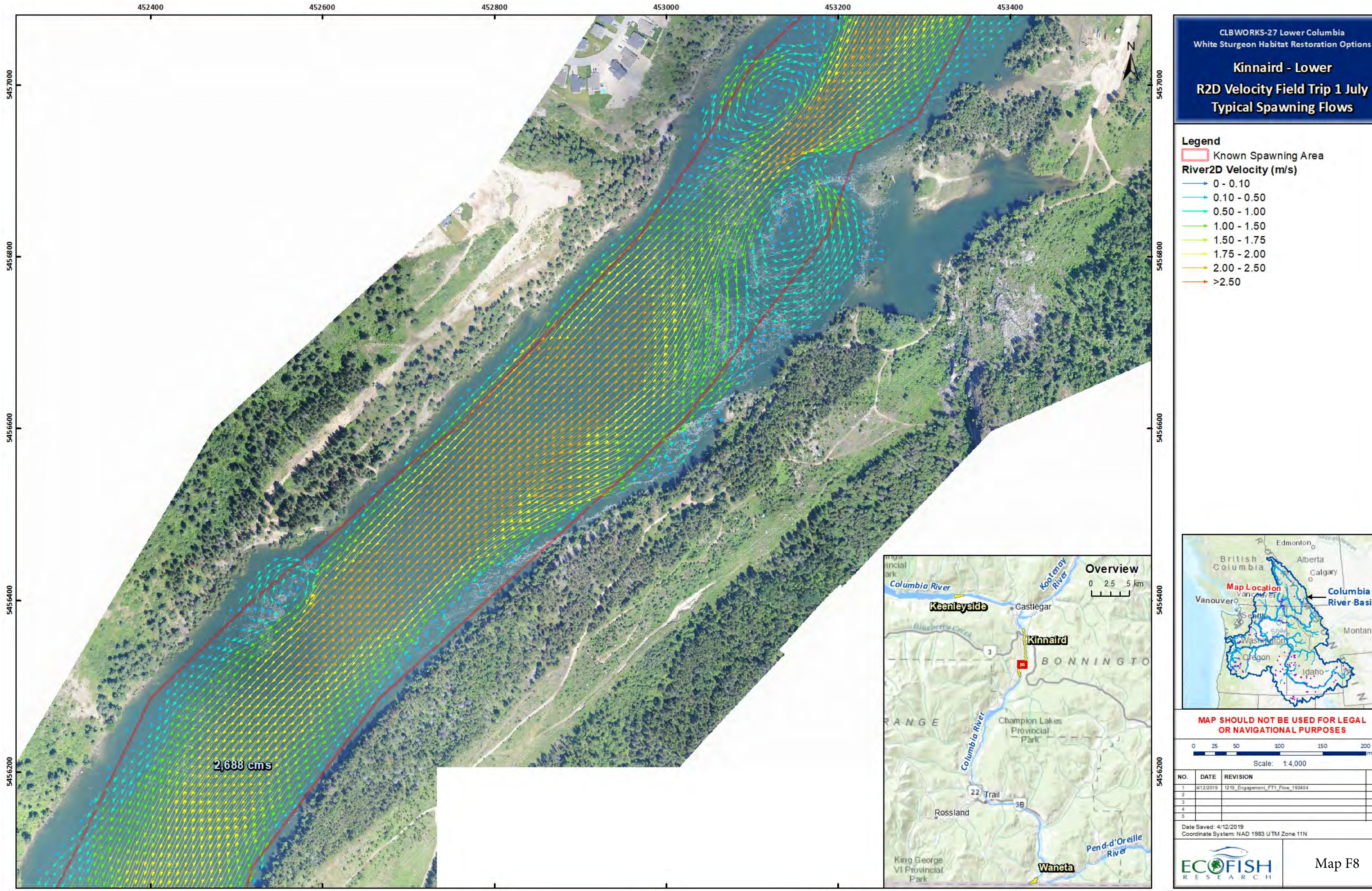
ECOFISH RESEARCH

Map F7

Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_FT1_Flow_190404.mxd

CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Kinnaird - Lower
R2D Velocity Field Trip 1 July
Typical Spawning Flows



Legend

Known Spawning Area

River2D Velocity (m/s)

- 0 - 0.10
- 0.10 - 0.50
- 0.50 - 1.00
- 1.00 - 1.50
- 1.50 - 1.75
- 1.75 - 2.00
- 2.00 - 2.50
- >2.50

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

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Date Saved: 4/12/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map F8

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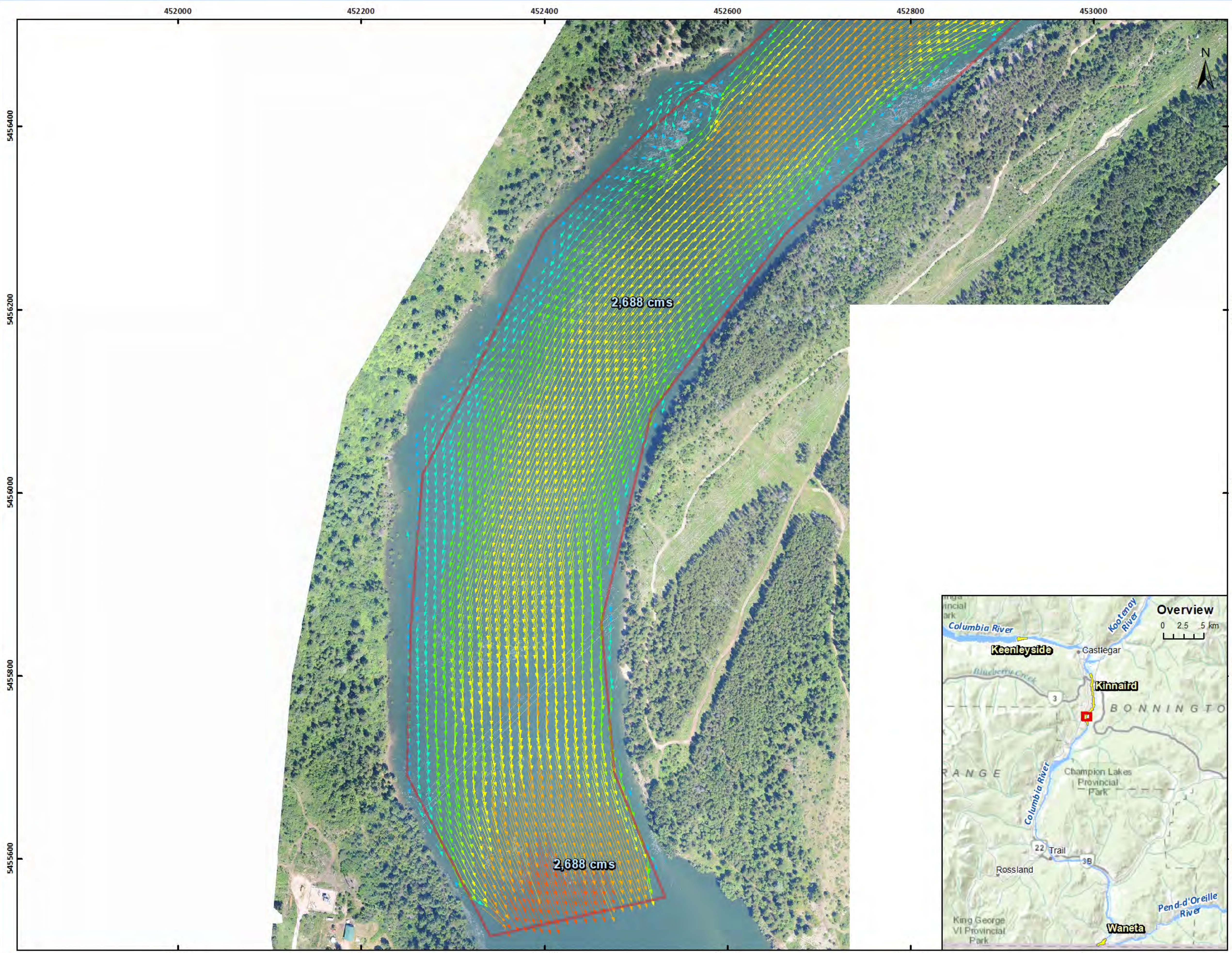
CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Kinnaird - Lower
R2D Velocity Field Trip 1 July
Typical Spawning Flows



Legend

Known Spawning Area

River2D Velocity (m/s)

- 0 - 0.10
- 0.10 - 0.50
- 0.50 - 1.00
- 1.00 - 1.50
- 1.50 - 1.75
- 1.75 - 2.00
- 2.00 - 2.50
- >2.50

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

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Date Saved: 4/12/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map F9

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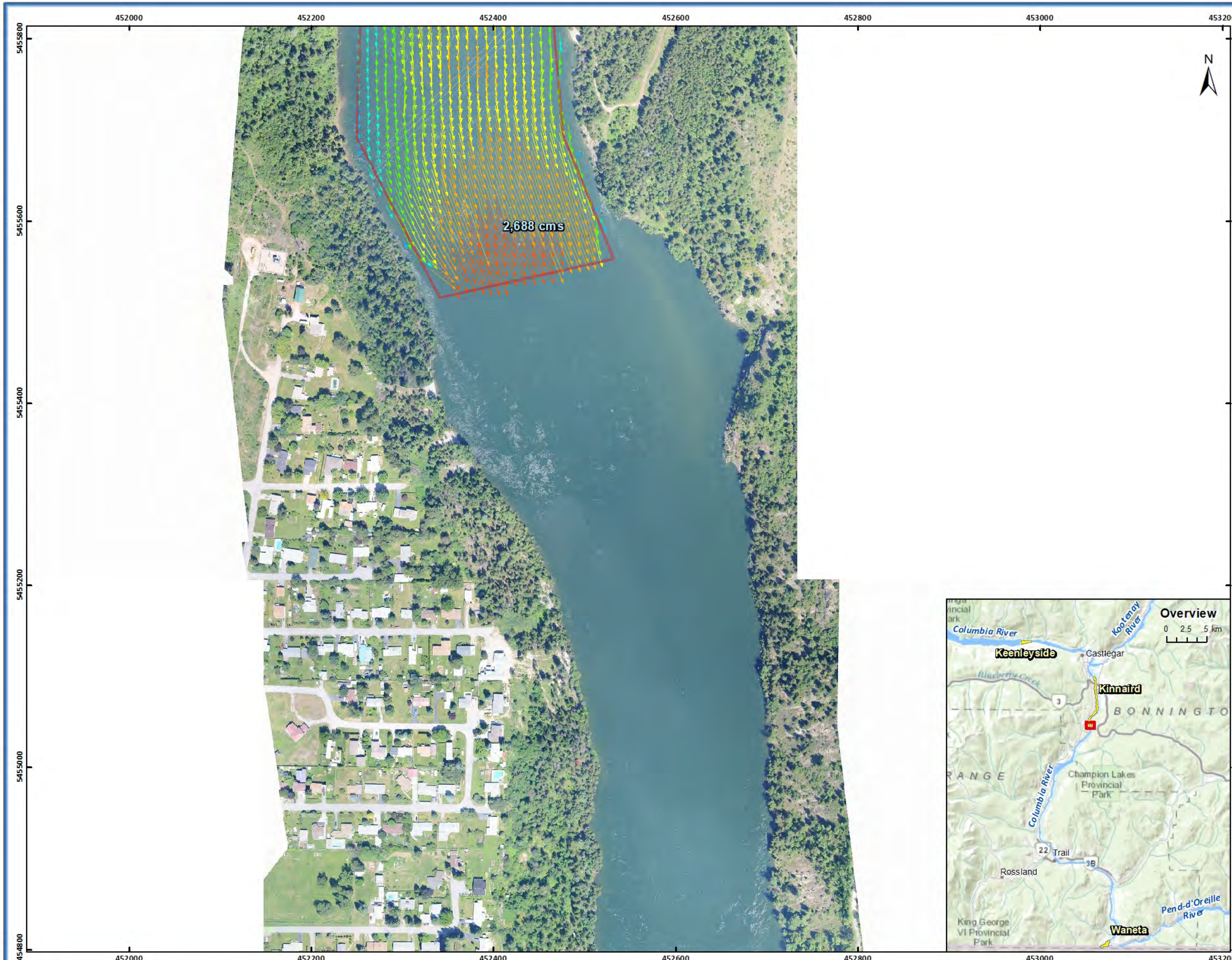

CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Kinnaird - Lower
R2D Velocity Field Trip 1 July
Typical Spawning Flows

Legend

Known Spawning Area

River2D Velocity (m/s)

- 0 - 0.10
- 0.10 - 0.50
- 0.50 - 1.00
- 1.00 - 1.50
- 1.50 - 1.75
- 1.75 - 2.00
- 2.00 - 2.50
- >2.50

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
1	4/12/2019	1210_Engagement_FT1_Flow_190404	
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Date Saved: 4/12/2019
Coordinate System: NAD 1983 UTM Zone 11N

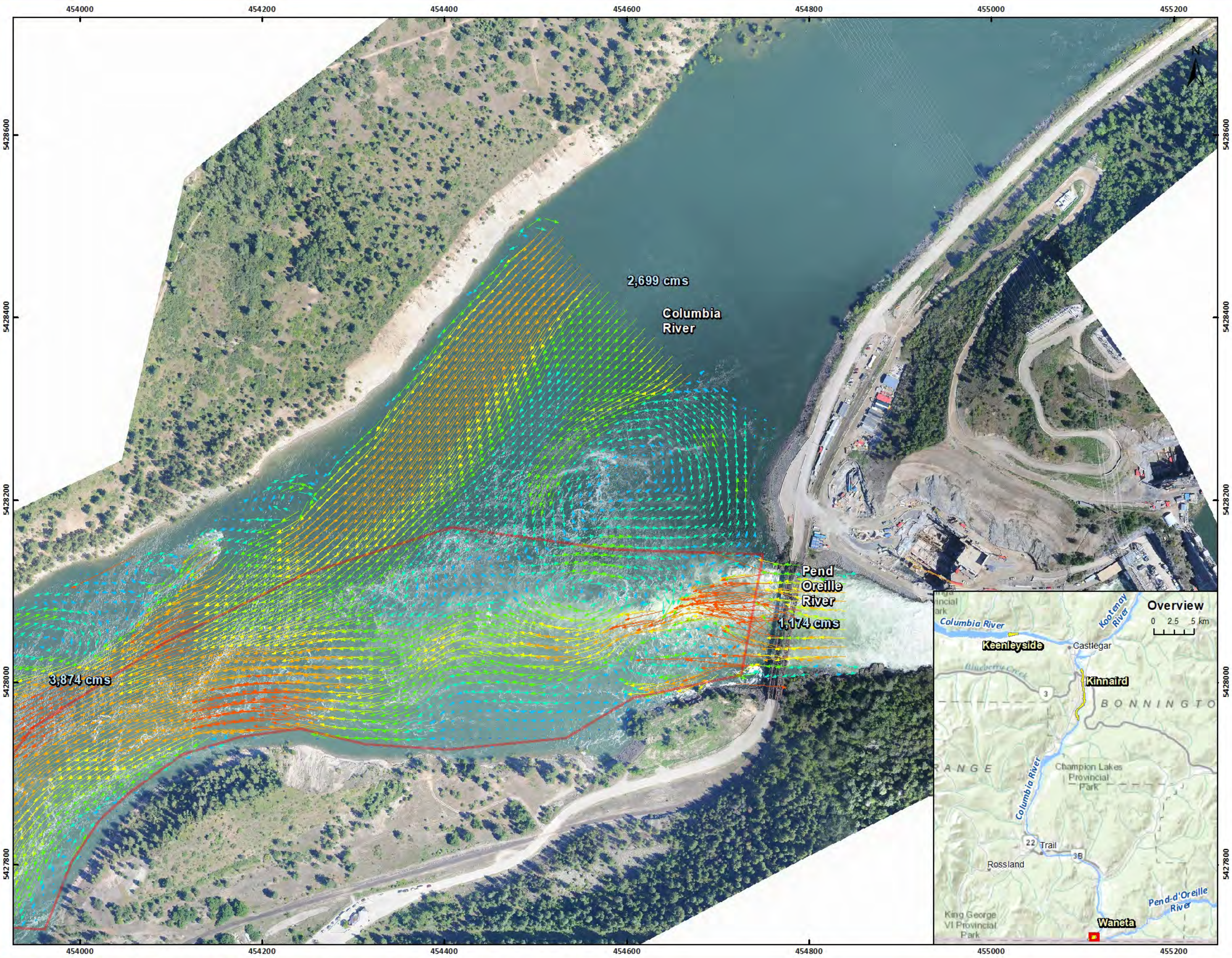
ECOFISH RESEARCH

Map F10

Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_FT1_Flow_190404.mxd

CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Waneta
R2D Velocity Field Trip 1 July Typical Spawning Flows



Legend

- Known Spawning Area

River2D Velocity (m/s)

- 0 - 0.10
- 0.10 - 0.50
- 0.50 - 1.00
- 1.00 - 1.50
- 1.50 - 1.75
- 1.75 - 2.00
- 2.00 - 2.50
- >2.50

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
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Date Saved: 4/12/2019
Coordinate System: NAD 1983 UTM Zone 11N

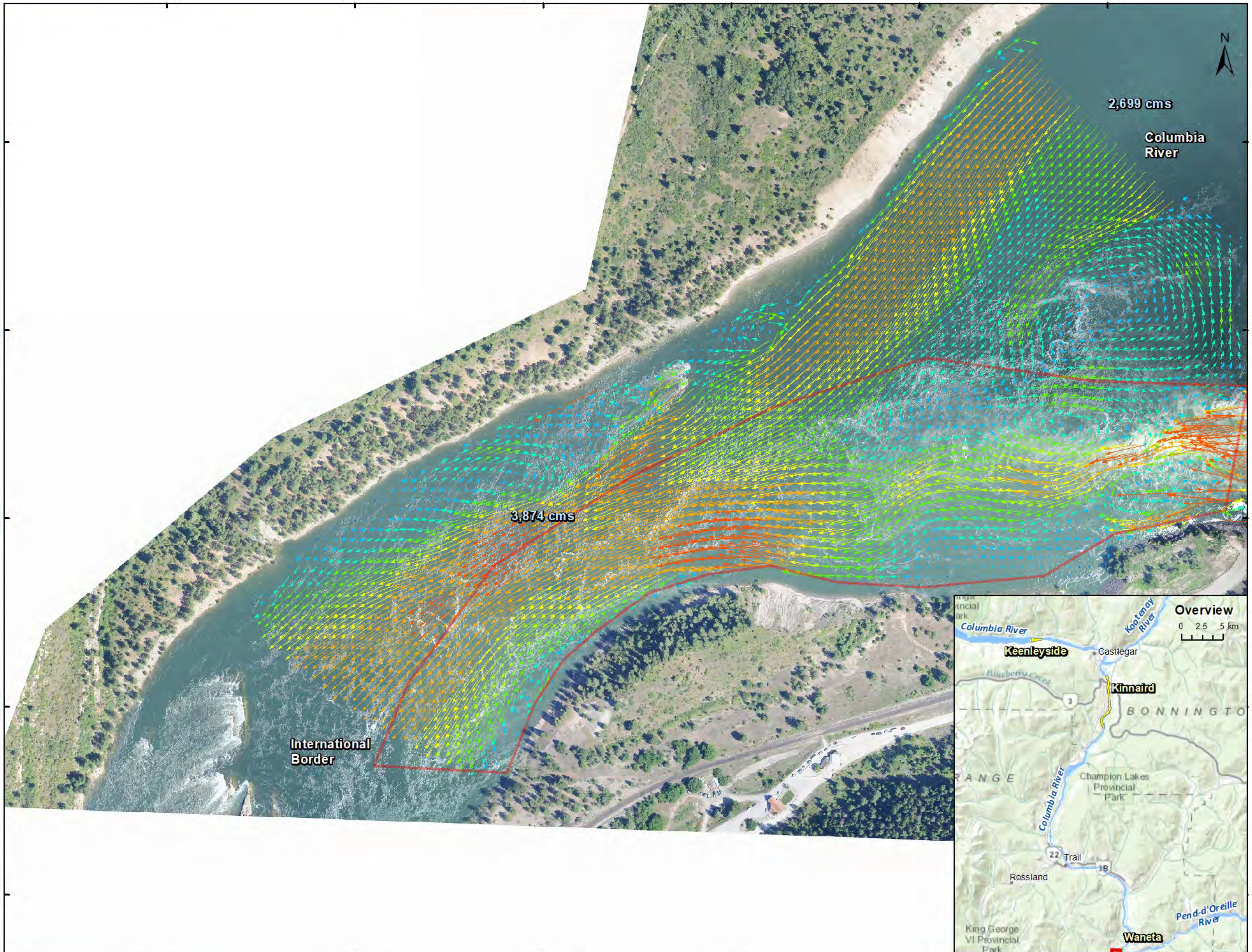
ECOFISH RESEARCH

Map F11

Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_FT1_Flow_190404.mxd

CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Waneta
R2D Velocity Field Trip 1 July
Typical Spawning Flows



Legend

Known Spawning Area

River2D Velocity (m/s)

- 0 - 0.10
- 0.10 - 0.50
- 0.50 - 1.00
- 1.00 - 1.50
- 1.50 - 1.75
- 1.75 - 2.00
- 2.00 - 2.50
- >2.50

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
1	4/11/2019	1210_Engagement_FT1_Flow_190404	
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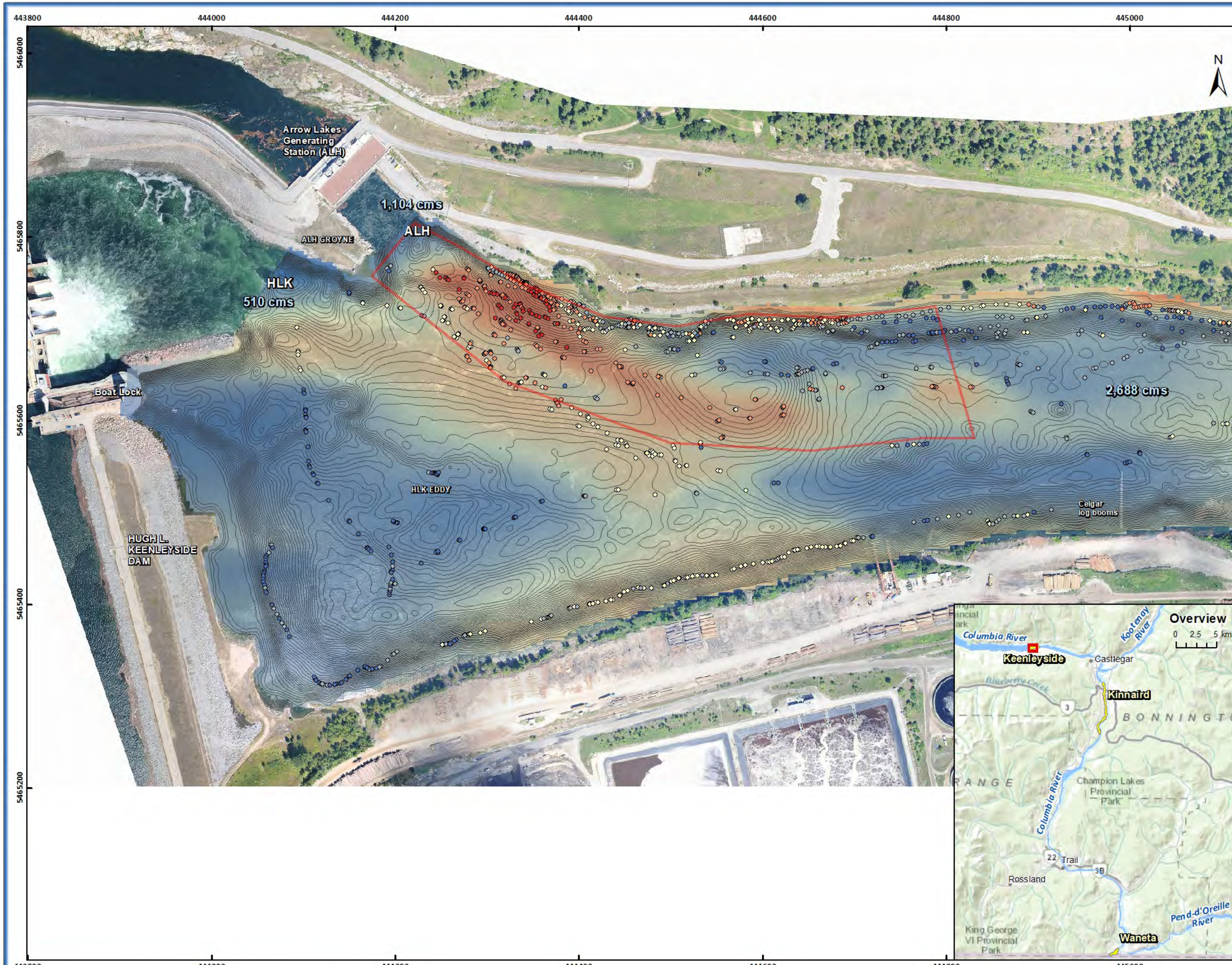
Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map F12

Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_FT1_Flow_190404.mxd

Appendix G. Habitat suitability maps



CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Keenleyside Recruitment Suitability (Hatten et al 2018) Typical Spawning Flows Field Trip 1 (July)

Legend

Known Spawning Area

Contour 0.5 m

Recruitment Suitability (0-1)

Value

High : 1

0.8

0.6

0.4

0.2

Low : 0

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
1	4/11/2019	1210_Engagement_BioMod_FT1_190404	
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Coordinate System: NAD 1983 UTM Zone 11N

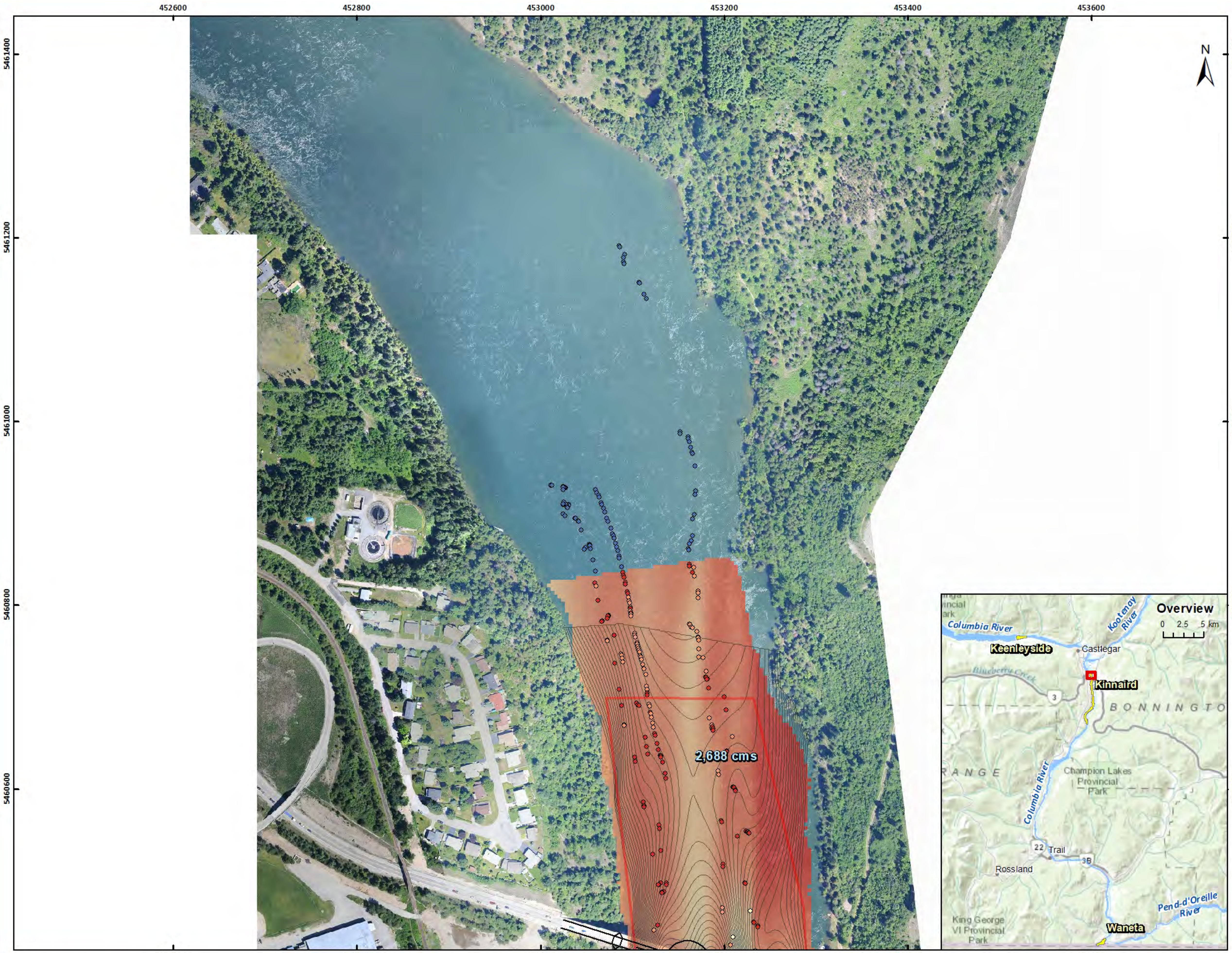
ECOFISH RESEARCH

Map G1

Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_BioMod_FT1_190404.mxd

CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Kinnaird - Upper Recruitment Suitability (Hatten et al 2018) Typical Spawning Flows Field Trip 1 (July)



Legend

Known Spawning Area

Contour 0.5 m

Recruitment Suitability (0-1)

Value

High : 1

0.8

0.6

0.4

0.2

Low : 0

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
1	4/11/2019	1210_Engagement_BioMod_FT1_190404	
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Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map G2

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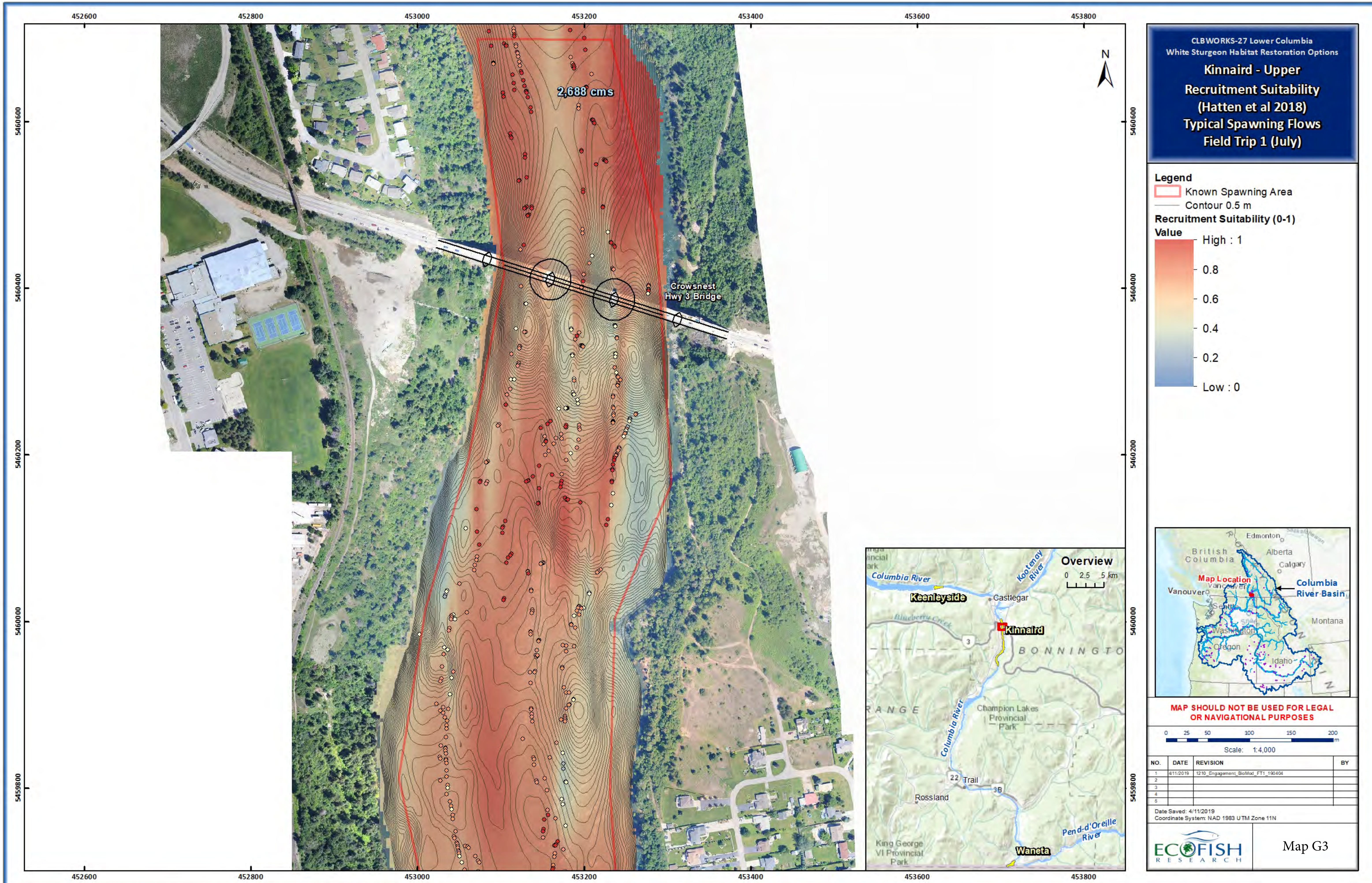

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CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Kinnaird - Upper
Recruitment Suitability (Hatten et al 2018)
Typical Spawning Flows
Field Trip 1 (July)

Legend
- Known Spawning Area
- Contour 0.5 m

Recruitment Suitability (0-1)
Value
- High : 1
- 0.8
- 0.6
- 0.4
- 0.2
- Low : 0

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m
Scale: 1:4,000

NO.	DATE	REVISION	BY
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4			
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Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map G4

Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_BioMod_FT1_190404.mxd

CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Kinnaird - Upper
Recruitment Suitability
(Hatten et al 2018)
Typical Spawning Flows
Field Trip 1 (July)

Legend

Known Spawning Area
Contour 0.5 m

Recruitment Suitability (0-1)

Value

High : 1
0.8
0.6
0.4
0.2
Low : 0

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

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Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map G5

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CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Kinnaird - Upper Recruitment Suitability (Hatten et al 2018) Typical Spawning Flows Field Trip 1 (July)

Legend

- Known Spawning Area
- Contour 0.5 m

Recruitment Suitability (0-1)

Value

High : 1

0.8

0.6

0.4

0.2

Low : 0

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
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Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map G6

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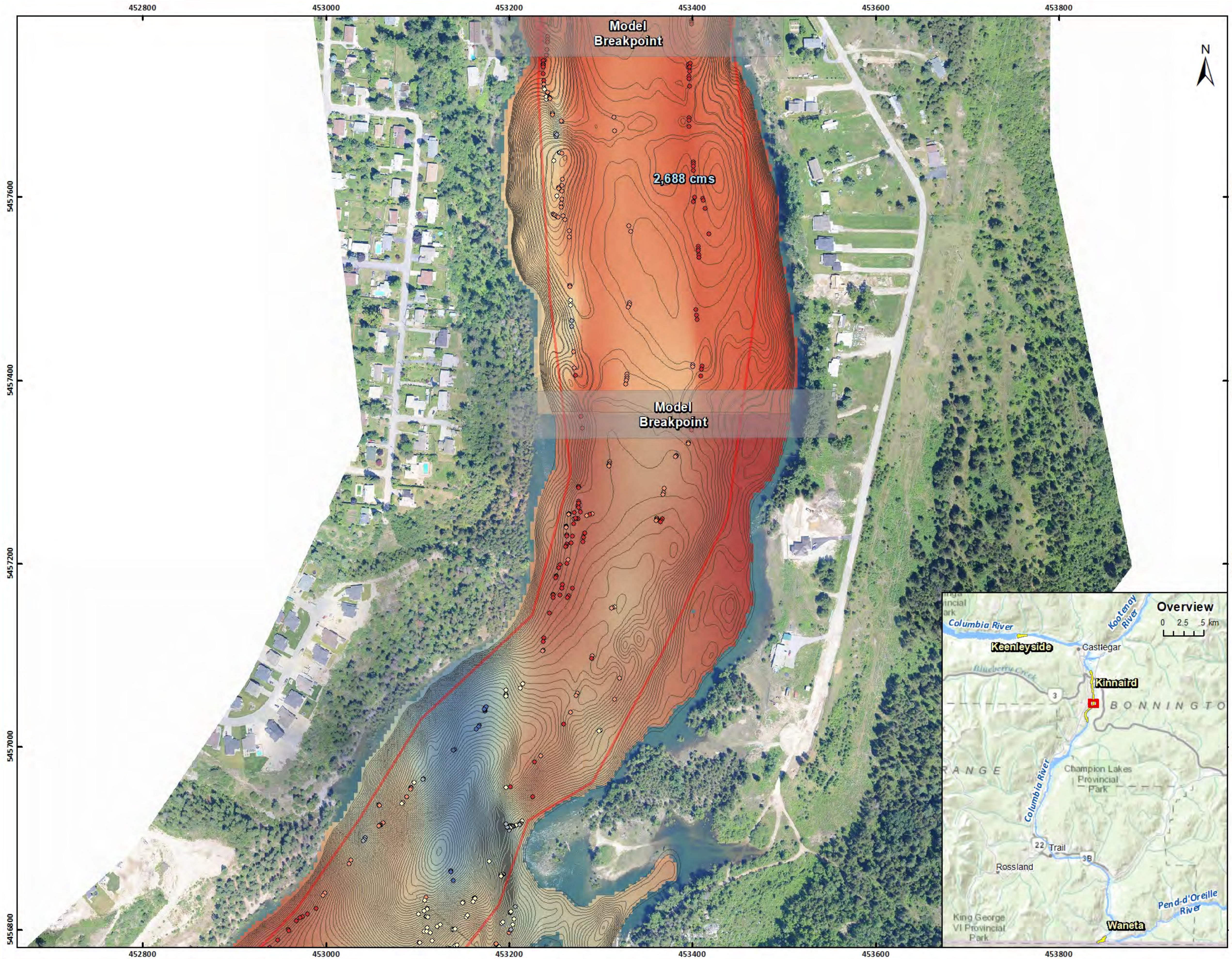
CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Kinnaird - Lower Recruitment Suitability (Hatten et al 2018) Typical Spawning Flows Field Trip 1 (July)



Legend
Known Spawning Area
Contour 0.5 m
Recruitment Suitability (0-1)
Value
High : 1
0.8
0.6
0.4
0.2
Low : 0

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

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Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map G7

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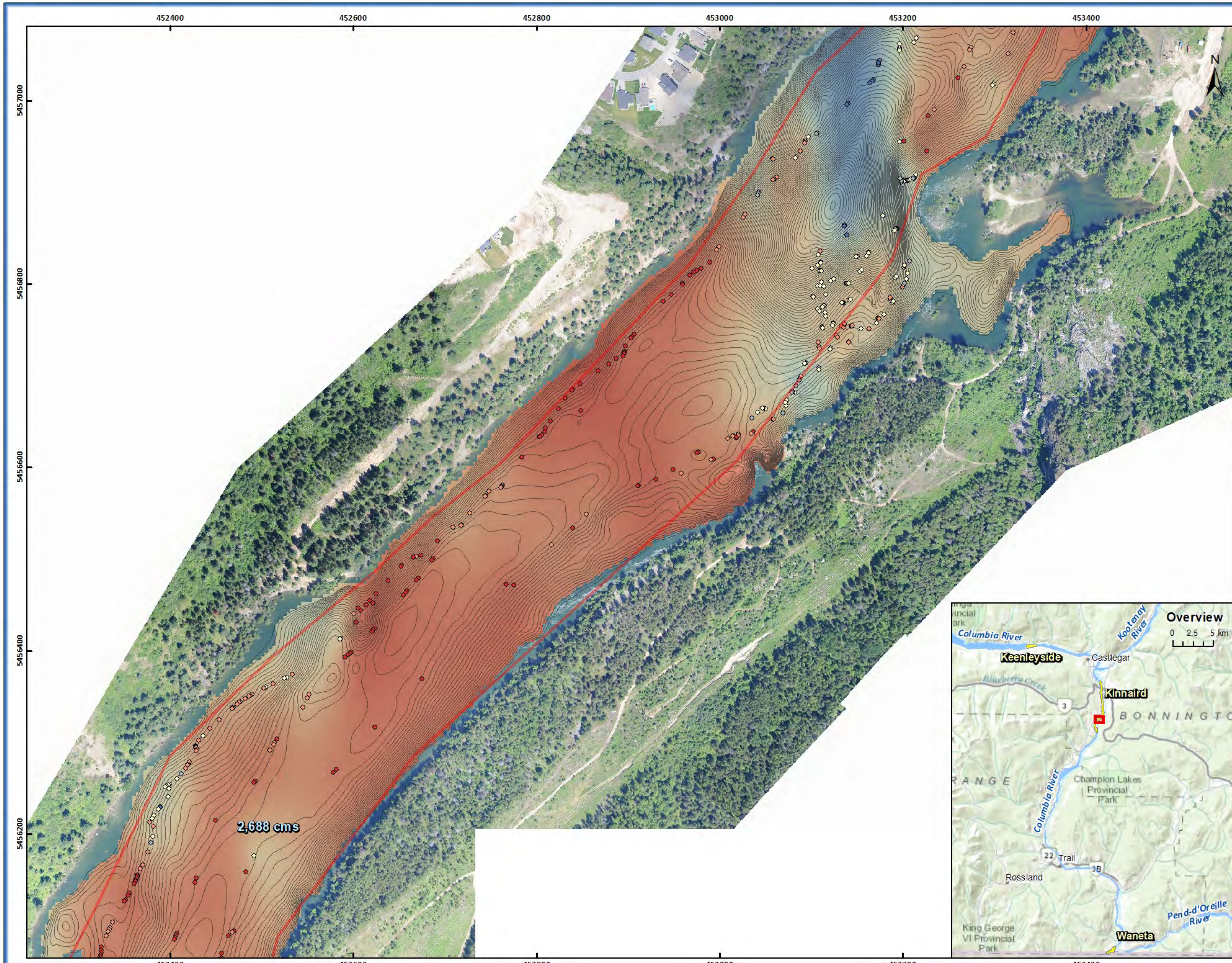

CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Kinnaird - Lower Recruitment Suitability (Hatten et al 2018) Typical Spawning Flows Field Trip 1 (July)

Legend

- Known Spawning Area
- Contour 0.5 m

Recruitment Suitability (0-1)

Value

High : 1

0.8

0.6

0.4

0.2

Low : 0

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
1	4/11/2019	1210_Engagement_BioMod_FT1_190404	
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Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map G8

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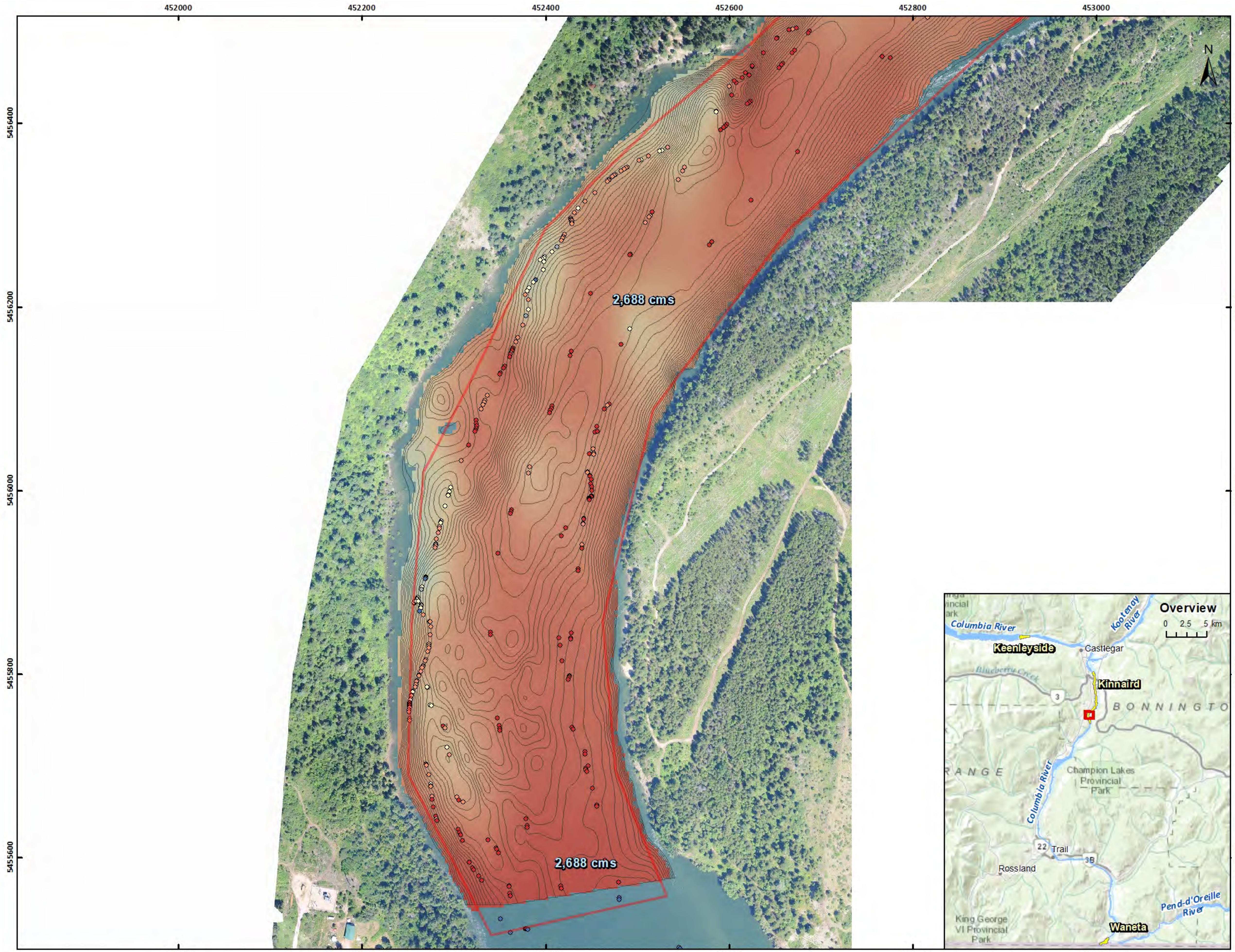

CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Kinnaird - Lower
Recruitment Suitability
(Hatten et al 2018)
Typical Spawning Flows
Field Trip 1 (July)

Legend
Known Spawning Area
Contour 0.5 m
Recruitment Suitability (0-1)
Value
High : 1
0.8
0.6
0.4
0.2
Low : 0

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m
Scale: 1:4,000

NO.	DATE	REVISION	BY
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Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map G9

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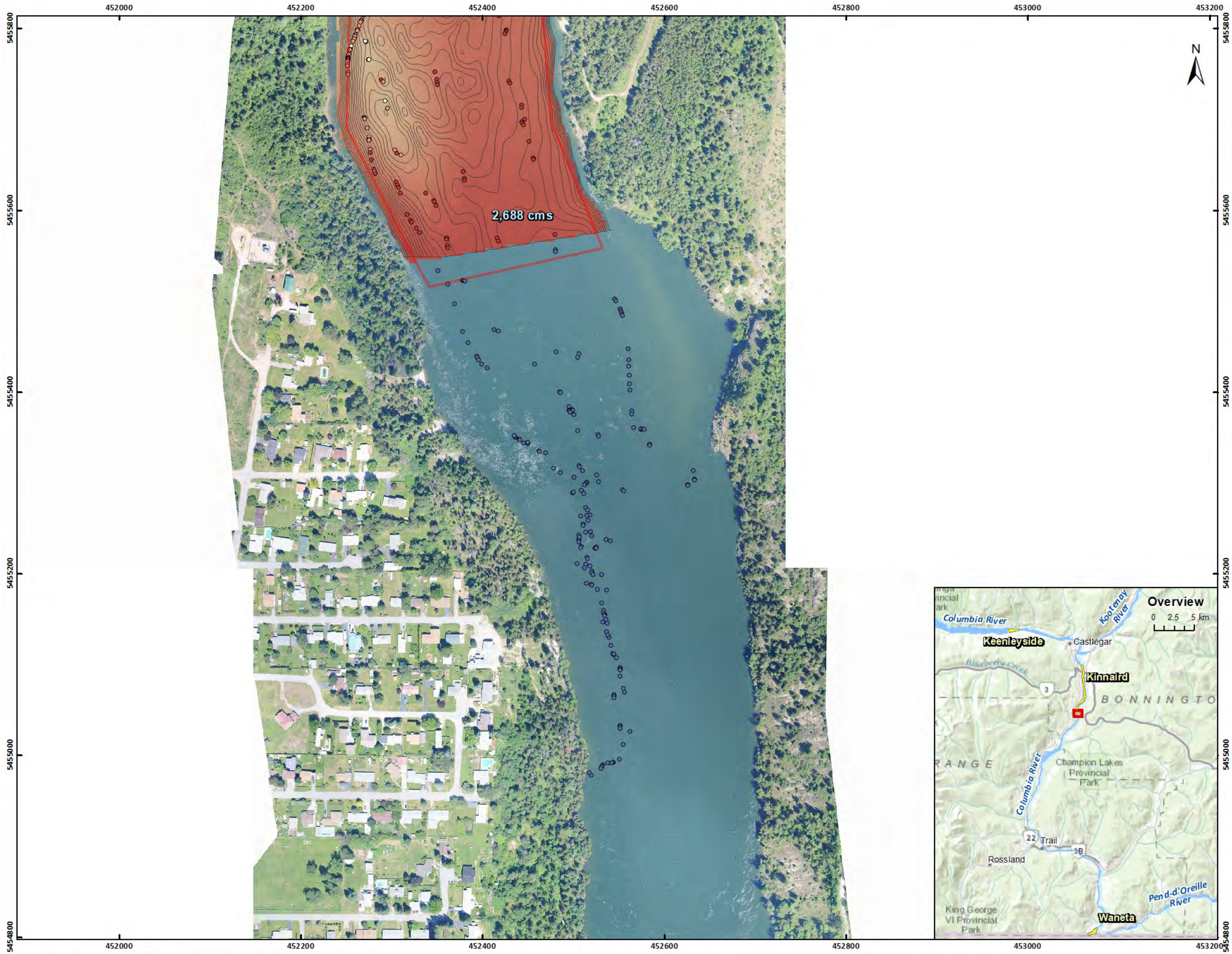

CLBWORKS-27 Lower Columbia
White Sturgeon Habitat Restoration Options

Kinnaird - Lower
Recruitment Suitability
(Hatten et al 2018)
Typical Spawning Flows
Field Trip 1 (July)

Legend

Known Spawning Area
Contour 0.5 m

Recruitment Suitability (0-1)

Value

High : 1
0.8
0.6
0.4
0.2
Low : 0

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m
Scale: 1:4,000

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Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

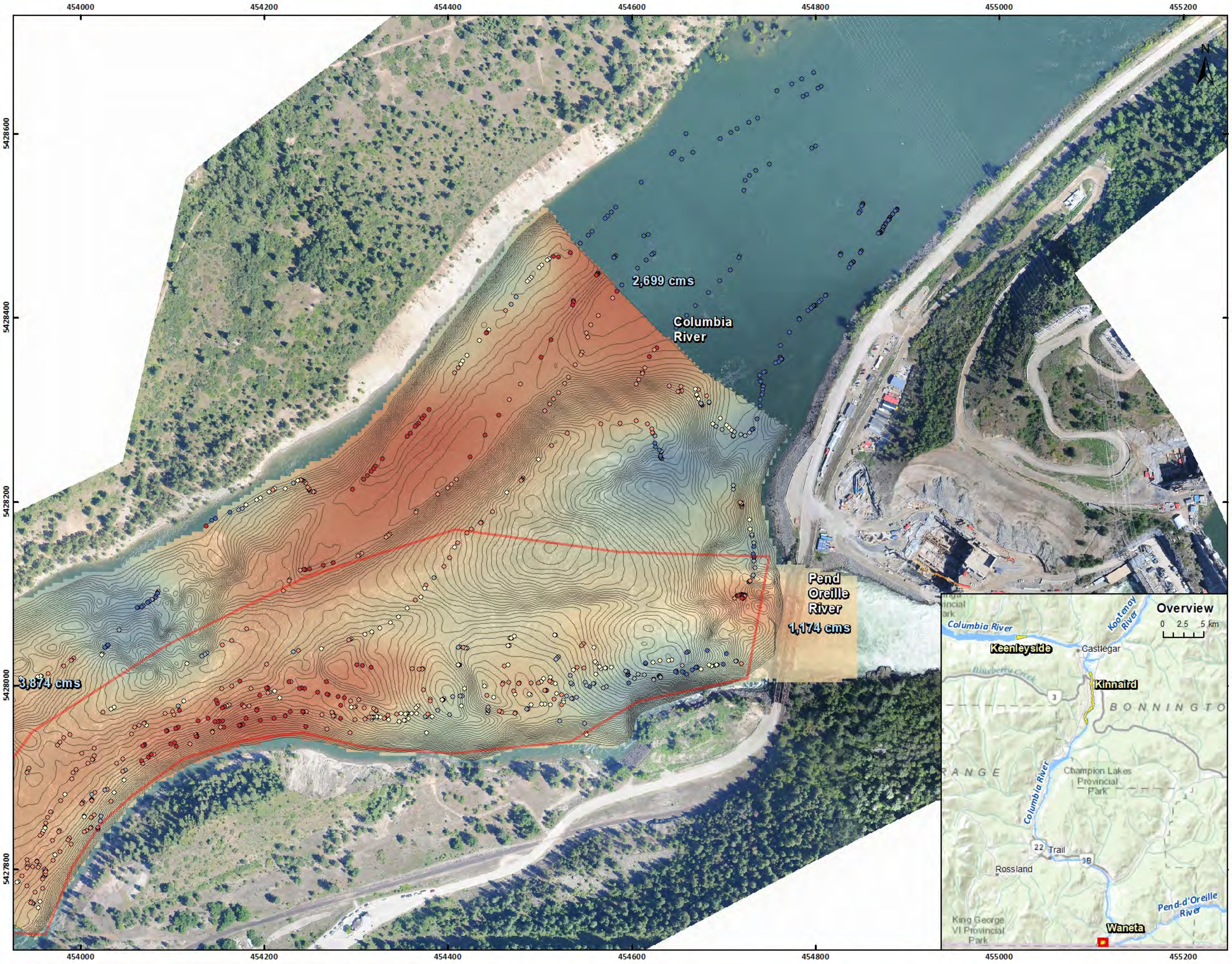
ECOFISH RESEARCH

Map G10

Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_BioMod_FT1_190404.mxd

CLBWORKS-27 Lower Columbia White Sturgeon Habitat Restoration Options

Waneta
Recruitment Suitability (Hatten et al 2018)
Typical Spawning Flows
Field Trip 1 (July)



Legend

Known Spawning Area
Contour 0.5 m

Recruitment Suitability (0-1)
Value
High : 1
0.8
0.6
0.4
0.2
Low : 0

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 25 50 100 150 200 m

Scale: 1:4,000

NO.	DATE	REVISION	BY
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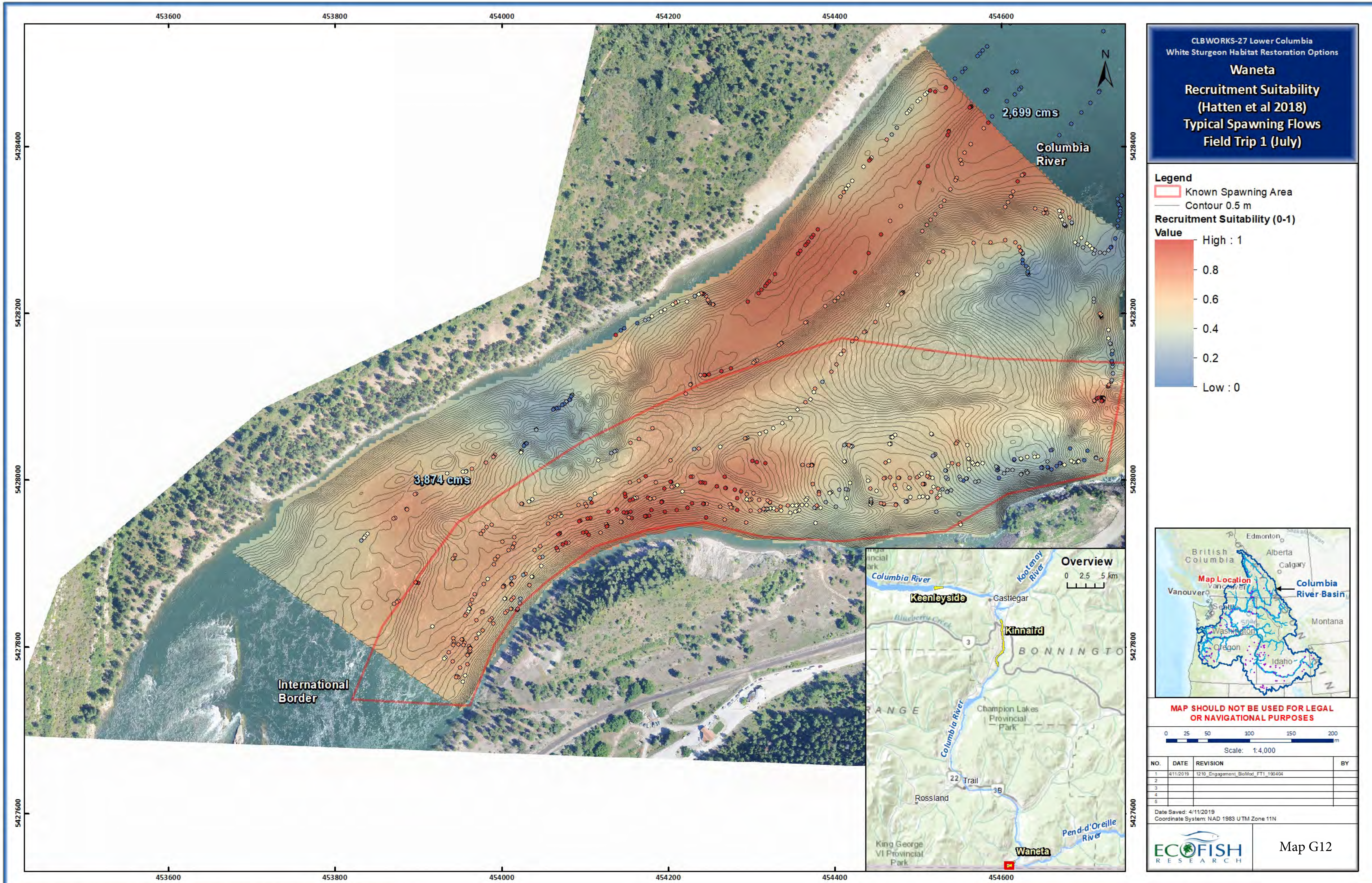
Date Saved: 4/11/2019
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map G11

Path: M:\Projects-Active\1210\MXD\BCH Progress Update 190412\1210_Engagement_BioMod_FT1_190404.mxd



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Appendix H. Detailed results from preliminary restoration alternative prioritization process

LIST OF TABLES

Table 1. Longlist of performance measures for each objective. Colours indicate proximity of score to ideal range, with low as yellow, orange as moderate, and green as high. Colour ramps are shown where fixed categories were not selected.

			ALH					WAN
Performance Measures	Unit	Flow Sim.	Ideal Mix Placement at EDZ DS	Ideal Mix Placement at EDZ and EDZ DS	Ideal Mix Placement at EDZ	Clean EDZ and EDZ DS	Gravel Placement at EDZ and EDZ DS	Ideal Mix Placement at Restoration Area
Existing Mobility in Restoration Area								
Mobile coarse fraction - typical freshet (W&C)	%	K09,W05	28.6	47.8	56.3	47.8	47.8	9.1
Mobile coarse fraction - typical freshet (Shields)	%	K09,W05	28.6	39.1	43.8	39.1	39.1	0.0
Mobile fines fraction - typical freshet	%	K09,W05	28.6	47.8	56.3	47.8	47.8	9.1
Mobile fines fraction during low flows	%	K12,W02	0.0	0.0	0.0	0.0	0.0	9.1
Mobile coarse fraction with max shear (W&C)	%	K09, W07	28.6	47.8	56.3	47.8	47.8	27.3
Mobile coarse fraction with max shear (Shields)	%	K09, W07	28.6	39.1	43.8	39.1	39.1	27.3
Mobile fines fraction with max shear (W&C)	%	K09, W07	28.6	47.8	56.3	47.8	47.8	45.5
Mobile fines fraction - PDO/ALH 5-yr peak	%	K09, W08	28.6	47.8	56.3	47.8	47.8	27.3
Mobile coarse fraction - PDO/ALH 5-yr peak	%	K09, W08	28.6	47.8	56.3	47.8	47.8	18.2
Mobile coarse fraction - CLB/ALH 5-yr peak	%	K09, W10	28.6	47.8	56.3	47.8	47.8	18.2
Mobile fines fraction - CLB/ALH 5-yr peak	%	K09, W10	28.6	47.8	56.3	47.8	47.8	27.3
Mobile fines fraction - 5-yr low freshet	%	K09, W03	28.6	47.8	56.3	47.8	47.8	9.1
Existing Mobility in Spawning Area								
Mobile coarse fraction - typical freshet (W&C)	%	K09,W05	29.3	29.3	29.3	29.3	29.3	16.7
Mobile coarse fraction - typical freshet (Shields)	%	K09,W05	24.4	24.4	24.4	24.4	24.4	8.3
Mobile fines fraction - typical freshet	%	K09,W05	29.3	29.3	29.3	29.3	29.3	30.6
Mobile fines fraction during low flows	%	K12,W02	0.0	0.0	0.0	0.0	0.0	11.1
Mobile coarse fraction with max shear (W&C)	%	K09, W07	29.3	29.3	29.3	29.3	29.3	52.8
Mobile coarse fraction with max shear (Shields)	%	K09, W07	24.4	24.4	24.4	24.4	24.4	30.6
Mobile fines fraction with max shear (W&C)	%	K09, W07	29.3	29.3	29.3	29.3	29.3	69.4
Mobile fines fraction - PDO/ALH 5-yr peak	%	K09, W08	29.3	29.3	29.3	29.3	29.3	50.0
Mobile coarse fraction - PDO/ALH 5-yr peak	%	K09, W08	29.3	29.3	29.3	29.3	29.3	36.1
Mobile coarse fraction - CLB/ALH 5-yr peak	%	K09, W10	29.3	29.3	29.3	29.3	29.3	33.3
Mobile fines fraction - CLB/ALH 5-yr peak	%	K09, W10	29.3	29.3	29.3	29.3	29.3	47.2
Mobile fines fraction - 5-yr low freshet	%	K09, W03	29.3	29.3	29.3	29.3	29.3	36.1
Treatment Mobility in Restoration Area								
Mobile coarse fraction - typical freshet (W&C)	%	K09,W05	5.6	21.3	35.7	43.5	42.5	0.0
Mobile coarse fraction - typical freshet (Shields)	%	K09,W05	0.0	3.0	5.7	39.1	41.2	0.0
Mobile fines fraction - typical freshet	%	K09,W05	24.9	41.7	57.0	47.8	49.8	0.0
Mobile fines fraction during low flows	%	K12,W02	0.0	0.0	0.0	0.0	0.0	0.0
Mobile coarse fraction with max shear (W&C)	%	K09, W07	5.6	21.3	35.7	43.5	42.5	1.9
Mobile coarse fraction with max shear (Shields)	%	K09, W07	0.0	3.0	5.7	39.1	41.2	0.0
Mobile fines fraction with max shear (W&C)	%	K09, W07	24.9	41.7	57.0	47.8	49.8	22.6
Mobile fines fraction - PDO/ALH 5-yr peak	%	K09, W08	24.9	41.7	57.0	47.8	49.8	0.4
Mobile coarse fraction - PDO/ALH 5-yr peak	%	K09, W08	5.6	21.3	35.7	43.5	42.5	0.0
Mobile coarse fraction - CLB/ALH 5-yr peak	%	K09, W10	5.6	21.3	35.7	43.5	42.5	0.0
Mobile fines fraction - CLB/ALH 5-yr peak	%	K09, W10	24.9	41.7	57.0	47.8	49.8	0.5
Mobile fines fraction - 5-yr low freshet	%	K09, W03	24.9	41.7	57.0	47.8	49.8	0.0

Table 1. Continued.

			ALH					WAN
Performance Measures	Unit	Flow Sim.	Ideal Mix Placement at EDZ DS	Ideal Mix Placement at EDZ and EDZ DS	Ideal Mix Placement at EDZ	Clean EDZ and EDZ DS	Gravel Placement at EDZ and EDZ DS	Ideal Mix Placement at Restoration Area
Mobility in Restoration Area after-before								
Mobile coarse fraction - typical freshet (W&C)	%	K09,W05	-23.0	-26.5	-20.6	-4.4	-5.3	-9.09
Mobile coarse fraction - typical freshet (Shields)	%	K09,W05	-28.6	-36.1	-38.0	0.0	2.1	0
Mobile fines fraction - typical freshet	%	K09,W05	-3.7	-6.2	0.8	0.0	2.0	-9.09
Mobile fines fraction during low flows	%	K12,W02	0.0	0.0	0.0	0.0	0.0	-9.09
Mobile coarse fraction with max shear (W&C)	%	K09, W07	-23.0	-26.5	-20.6	-4.4	-5.3	-25.34
Mobile coarse fraction with max shear (Shields)	%	K09, W07	-28.6	-36.1	-38.0	0.0	2.1	-27.27
Mobile fines fraction with max shear (W&C)	%	K09, W07	-3.7	-6.2	0.8	0.0	2.0	-22.87
Mobile fines fraction - PDO/ALH 5-yr peak	%	K09, W08	-3.7	-6.2	0.8	0.0	2.0	-26.85
Mobile coarse fraction - PDO/ALH 5-yr peak	%	K09, W08	-23.0	-26.5	-20.6	-4.4	-5.3	-18.18
Mobile coarse fraction - CLB/ALH 5-yr peak	%	K09, W10	-23.0	-26.5	-20.6	-4.4	-5.3	-18.18
Mobile fines fraction - CLB/ALH 5-yr peak	%	K09, W10	-3.7	-6.2	0.8	0.0	2.0	-26.8
Mobile fines fraction - 5-yr low freshet	%	K09, W03	-3.7	-6.2	0.8	0.0	2.0	-9.09
Existing Substrate Condition (Restoration area):								
Coarse material supply	-		low	low	low	low	low	high
Supply of fines (total sources)	-		High	Low	Low	Low	Low	High
Embeddedness (% High) - Mike P	%		9.5	18.6	23.7	18.6	18.6	0
Embeddedness (Average Score) - Mike P	0-5		1.3	1.5	1.6	1.5	1.5	0.60
Armouring evidence	%		80.0	81.1	79.4	81.1	81.1	46.1
Evidence of Recent Transport	%		52.6	73.6	90.9	73.6	73.6	81.8
Substrate fouling	-		Low	Low	Low	Low	Low	Low
Bottom roughness (near bottom velocity)	1-3		2.0	1.8	1.7	1.8	1.8	2.81
Fines percentage (M Parsley)	%		10.0	16.9	17.8	16.9	16.9	5.83
General rearing suitability	1-3		2.4	2.2	2.1	2.2	2.2	2.83
Substrate Condition (Spawning area):								
D50 from GSD	m		0.04	0.04	0.04	0.04	0.04	0.08
D84 from GSD	m		0.09	0.09	0.09	0.09	0.09	0.14
Fines fraction (A Tamminga)	%		7.4	7.4	7.4	7.4	7.4	4.6
Ex. Habitat suitability (Restoration Area)								
Spawning Suitability - Velocity (% area suitable)	%	K10/W05	59.9	44.6	30.9	44.6	44.6	64.4
Spawning Suitability - Depth (% area suitable)	%	K10/W05	1.0	1.0	1.0	1.0	1.0	1.0
Recruitment Suitability	%	K10/W05	67.2	65.9	62.1	65.9	65.9	47.8
Recruitment Suitability (% area suitable)	%	K10/W05	77.1	65.2	54.4	65.2	65.2	14.1
Ex. Habitat suitability (Spawning Area)								
Recruitment Suitability	%	K10/W05	49.7	49.7	49.7	49.7	49.7	58.5
Recruitment Suitability (% area high)	%	K10/W05	31.1	31.1	31.1	31.1	31.1	47.4
Restored Habitat suitability (Restoration Area)								
Recruitment Suitability (% area high)	%		85.9	80.3	75.1	80.3	80.3	49.8
Recruitment Suitability After-Before	%		8.8	15.1	20.7	15.1	15.1	35.7
Expected Biological Response:								
Biological risk (e.g. to spawning adults)	-		low	low-med	low-med	med	low	low
Magnitude of response	-		med	high	med	med	low-med	low
Response of other species	-		pos	pos	pos	neg?	neutral	neutral
Biological uncertainty	-		med	low-med	med	med	low-med	low
Food	-		high	high	high	high	high	med-high
Feasibility								
Constructability	-		high	high	high	low	high	med
Longevity of works	-		med	med	med	low	low	low
Risks to generation	-		low	med	med	low	low	low
Cost -access	-		low	low	low	low	low	med
Cost (Size)	-		low	med	low	med	med	low
Public visibility (e.g. of signage)	-		high	high	high	high	high	low
Ease of substrate monitoring	-		med	med	med	med	med	low

Table 2. Longlist of performance measures for each objective, and incidation of rationale for inclusion in shortlist. Scoring range for L/M/H, purpose, targets, and difference between lowest and highest value for each alternative are also shown.

Performance measures	Rationale for removal or inclusion in final table	Primary purpose	Unit	Score assignment	Target	Diference between best and worst (%)
Existing Mobility in Restoration Area						
Mobile coarse fraction - typical freshet (W&C)	Redundant with after treatment results	Coarse scour	%	L: <10 & >40, M: 10-20 & 30-40, H: 20-30	specific	47
Mobile coarse fraction - typical freshet (Shields)	Remove because redundant	Coarse scour	%	L: <10 & >40, M: 10-20 & 30-40, H: 20-30	specific	44
Mobile fines fraction - typical freshet	Redundant with after treatment results	Fines flushing	%	Spectrum	+	47
Mobile fines fraction during low flows	Remove because difference is <20%	Fines deposition	%	Spectrum	+	9
Mobile coarse fraction with max shear (W&C)	Similar to freshet results, but lower in magnitude	Coarse scour	%	L: <20 & >80, M: 20-40 & 60-80, H: 40-60	specific	29
Mobile coarse fraction with max shear (Shields)	Remove because redundant and <20% difference	Coarse scour	%	L: <20 & >80, M: 20-40 & 60-80, H: 40-60	specific	16
Mobile fines fraction with max shear (W&C)	Redundant with before-after comparison	Fines flushing	%	Spectrum	+	28
Mobile fines fraction - PDO/ALH 5-yr peak	Redundant with before-after comparison	Fines flushing	%	Spectrum	+	29
Mobile coarse fraction - PDO/ALH 5-yr peak	Redundant with before-after comparison	Coarse scour	%	L: <10 & >40, M: 10-20 & 30-40, H: 20-30	specific	38
Mobile coarse fraction - CLB/ALH 5-yr peak	Redundant with before-after comparison	Coarse scour	%	L: <10 & >40, M: 10-20 & 30-40, H: 20-30	specific	38
Mobile fines fraction - CLB/ALH 5-yr peak	Redundant with before-after comparison	Fines flushing	%	Spectrum	+	29
Mobile fines fraction - 5-yr low freshet	Redundant with before-after comparison	Fines flushing	%	Spectrum	+	47
Existing Mobility in Spawning Area						
Mobile coarse fraction - typical freshet (W&C)	Remove because difference is <20%	Coarse scour	%	L: <10 & >40, M: 10-20 & 30-40, H: 20-30	specific	13
Mobile coarse fraction - typical freshet (Shields)	Remove because redundant and <20% difference	Coarse scour	%	L: <10 & >40, M: 10-20 & 30-40, H: 20-30	specific	16
Mobile fines fraction - typical freshet	Remove because difference is <20%	Fines flushing	%	Spectrum	+	1
Mobile fines fraction during low flows	Remove because difference is <20%	Fines deposition	%	Spectrum	+	11
Mobile coarse fraction with max shear (W&C)	Redundant with PDO 5-yr fines flushing	Coarse scour	%	L: <20 & >80, M: 20-40 & 60-80, H: 40-60	specific	24
Mobile coarse fraction with max shear (Shields)	Remove because redundant and <20% difference	Coarse scour	%	L: <20 & >80, M: 20-40 & 60-80, H: 40-60	specific	6
Mobile fines fraction with max shear (W&C)	Similar result to PDO 5-yr, but more useful	Fines flushing	%	Spectrum	+	40
Mobile fines fraction - PDO/ALH 5-yr peak	Indicates where mobility of fines is better	Fines flushing	%	L: 0-33, M: 33-66, H:66-100	+	21
Mobile coarse fraction - PDO/ALH 5-yr peak	Remove because difference is <20%	Coarse scour	%	L: <10 & >40, M: 10-20 & 30-40, H: 20-30	specific	7
Mobile coarse fraction - CLB/ALH 5-yr peak	Remove because difference is <20%	Coarse scour	%	L: <10 & >40, M: 10-20 & 30-40, H: 20-30	specific	4
Mobile fines fraction - CLB/ALH 5-yr peak	Redundant with PDO 5-yr and <20% difference	Fines flushing	%	Spectrum	+	18
Mobile fines fraction - 5-yr low freshet	Remove because difference is <20%	Fines flushing	%	Spectrum	+	7
Treatment Mobility in Restoration Area						
Mobile coarse fraction - typical freshet (W&C)	Shows areas where most mobility occurs	Coarse scour	%	L: <10 & >40, M: 10-20 & 30-40, H: 20-30	specific	43
Mobile coarse fraction - typical freshet (Shields)	Remove because redundant	Coarse scour	%	L: <10 & >40, M: 10-20 & 30-40, H: 20-30	specific	41
Mobile fines fraction - typical freshet	Shows spectrum of where fines flsuhing is worst	Fines flushing	%	L: 0-33, M: 33-66, H:66-100	+	57
Mobile fines fraction during low flows	Remove because difference is <20%	Fines deposition	%	spectrum	+	0
Mobile coarse fraction with max shear (W&C)	Similar to freshet results, which are more	Coarse scour	%	L: <20 & >80, M: 20-40 & 60-80, H: 40-60	specific	42
Mobile coarse fraction with max shear (Shields)	Remove because redundant	Coarse scour	%	L: <20 & >80, M: 20-40 & 60-80, H: 40-60	specific	41
Mobile fines fraction with max shear (W&C)	Similar information as freshet result	Fines flushing	%	spectrum	+	34
Mobile fines fraction - PDO/ALH 5-yr peak	Similar result to freshet and CLB 5-yr	Fines flushing	%	spectrum	+	57
Mobile coarse fraction - PDO/ALH 5-yr peak	Similar to freshet results	Coarse scour	%	L: <10 & >40, M: 10-20 & 30-40, H: 20-30	specific	43
Mobile coarse fraction - CLB/ALH 5-yr peak	Similar to freshet results	Coarse scour	%	L: <10 & >40, M: 10-20 & 30-40, H: 20-30	specific	43
Mobile fines fraction - CLB/ALH 5-yr peak	Similar result to freshet and PDO 5-yr	Fines flushing	%	spectrum	+	57
Mobile fines fraction - 5-yr low freshet	Similar to freshet results	Fines flushing	%	spectrum	+	57

Table 2. Continued.

Performance measures	Rationale for removal or inclusion in final table	Primary purpose	Unit	Score assignment	Target	Diference between best and worst (%)
Mobility in Restoration Area after-before						
Mobile coarse fraction - typical freshet (W&C)	Shows areas that are less mobile after treatment	Coarse scour	%	L: <-10 & 20-30, M: -10 -0 & 10-20, H: 0-1(	specific	22
Mobile coarse fraction - typical freshet (Shields)	Remove because redundant	Coarse scour	%	L: <-10 & 20-30, M: -10 -0 & 10-20, H: 0-1(	specific	40
Mobile fines fraction - typical freshet	Remove because difference is <20%	Fines flushing	%	spectrum	+	11
Mobile fines fraction during low flows	Remove because difference is <20%	Fines deposition	%	spectrum	+	9
Mobile coarse fraction with max shear (W&C)	Results are similar to typical freshet conditions	Coarse scour	%	L: <-20 & 10-20, M: -20 -10 & 0-10, H: -10-	specific	22
Mobile coarse fraction with max shear (Shields)	Remove because redundant	Coarse scour	%	L: <-20 & 10-20, M: -20 -10 & 0-10, H: -10-	specific	40
Mobile fines fraction with max shear (W&C)	Results are similar to PDO 5-yr condition	Fines flushing	%	spectrum	+	25
Mobile fines fraction - PDO/ALH 5-yr peak	Fines become less mobile in WAN after treatment	Fines flushing	%	L: ≤0, M 1-20, H: >20	+	29
Mobile coarse fraction - PDO/ALH 5-yr peak	Results are similar to typical freshet conditions	Coarse scour	%	L: <-10 & 20-30, M: -10 -0 & 10-20, H: 0-1(	specific	22
Mobile coarse fraction - CLB/ALH 5-yr peak	Results are similar to typical freshet conditions	Coarse scour	%	L: <-10 & 20-30, M: -10 -20 & 10-20, H: 0-1	specific	22
Mobile fines fraction - CLB/ALH 5-yr peak	Results are similar to PDO 5-yr condition	Fines flushing	%	spectrum	+	29
Mobile fines fraction - 5-yr low freshet	Remove because difference is <20%	Fines flushing	%	spectrum	+	11
Existing Substrate Condition (Restoration area):						
Coarse material supply	Offset by supply of fines		-	professional judgement	+	-
Supply of fines (total sources)	Offset by supply of coarse material		-	professional judgement	neg	-
Embeddedness (% High) - Mike P	Redundant with Embeddedness average		%	L: 0-10, 40-50 M: 10-20,30-40 H: 20-30	specific	24
Embeddedness (Average Score) - Mike P	Greatest range and most important		0-5	L: 1-1.5, -3.5 M: 1.5-2, 2.5-3 H: 2-2.5	specific	62
Armouring evidence	Less important than others		%	L: 0-20,80-100 M: 20-40,60-80 H: 40-60	specific	35
Evidence of Recent Transport	Less important than others		%	L: 0-20,80-100 M: 20-40,60-80 H: 40-60	specific	38
Substrate fouling	No variation		-	professional judgement	neg	-
Bottom roughness (near bottom velocity)	Less important than others		1-3	L: 1-1.5, -3.5 M: 1.5-2, 2.5-3 H: 2-2.5	specific	41
Fines percentage (M Parsley)	Remove because difference is <20%		%	L: 0-5, 20-25; M: 5-10, 15-20; H: 10-15	specific	12
General rearing suitability	WAN is currently very good		1-3	L: <1.5 M: 1.5-2, 2.5-3 H: 2-2.5	specific	27
Substrate Condition (Spawning area):						
D50 from GSD	Less important than other substrate metrics		m	L: fines, M: gravel, H: >cobble	specific	49
D84 from GSD	Less important than other substrate metrics		m	L: fines, M: gravel, H: >cobble	specific	39
Fines fraction (A Tamminga)	Remove because difference is <20%		%	L: 0-5, 20-25; M: 5-10, 15-20; H: 10-15	specific	3
Ex. Habitat suitability (Restoration Area)						
Spawning Suitability - Velocity (% area suitable)	Less important than recruitment suitability		%	Spectrum	+	34
Spawning Suitability - Depth (% area suitable)	No variation		%	Manual	+	0
Recruitment Suitability	Less variation than % area		%	Spectrum	+	19
Recruitment Suitability (% area suitable)	redundant with after-before		%	Spectrum	+	63
Ex. Habitat suitability (Spawning Area)						
Recruitment Suitability	Remove because difference is <20%		%	L: <30%, M: 30-50%, H: >60%	+	15
Recruitment Suitability (% area high)	Remove because difference is <20%		%	L: <30%, M: 30-40%, H: >50%	+	16
Restored Habitat suitability (Restoration Area)						
Recruitment Suitability (% area high)	Shows overall suitability after treatment		%	L: <60%, M: 60-80%, H: >80%	+	36
Recruitment Suitability After-Before	Shows what is limited by substrate		%	L: <20%, M: 20-40%, H >40%	+	27
Expected Biological Response:						
Biological risk (e.g. to spawning adults)	Minimal variation		-	Selected during workshop	neg	-
Magnitude of response	Important variable		-	Selected during workshop	+	-
Response of other species	Limited importance		-	Selected during workshop	neg	-
Biological uncertainty	Minimal variation		-	Selected during workshop	neg	-
Food	Minimal variation		-	Selected by sturgeon expert	+	-
Feasibility						
Constructability	Varies substantially		-	Professional judgement	+	-
Longevity of works	Longevity is redundant with the substrate metrics		-	Professional judgement	+	-
Risks to generation	Risks are likely low in general		-	Professional judgement	neg	-
Cost -access	Costs are likely fairly similar		-	Professional judgement	neg	-
Cost (Size)	Costs are likely fairly similar		-	Professional judgement	neg	-
Public visibility (e.g. of signage)	Minimal importance		-	Professional judgement	+	-
Ease of substrate monitoring	Minimal variation		-	Professional judgement	+	-

Appendix I. Embeddedness classification comparison

LIST OF FIGURES

Table 1. Substrate Embeddedness Ranking from Underwater Camera Imagery.

Class	Embeddedness Amounts
0 - Negligible	<5% of interstitial spaces covered by fines
1 - Low	6-25% of interstitial spaces covered by fines
2 - Moderate	26-50% of interstitial spaces covered by fines
3 - High	51-75% of interstitial spaces covered by fines
4 - Very High	>75% of interstitial spaces covered by fines
5 - N/A	Continuous fines

Figure 1. High agreement between three people for a high embeddedness ranking.

a) Photo ID 1333 (Rankings: 3, 3, 3)

b) Photo ID 795 (Rankings: 4, 3, 4)

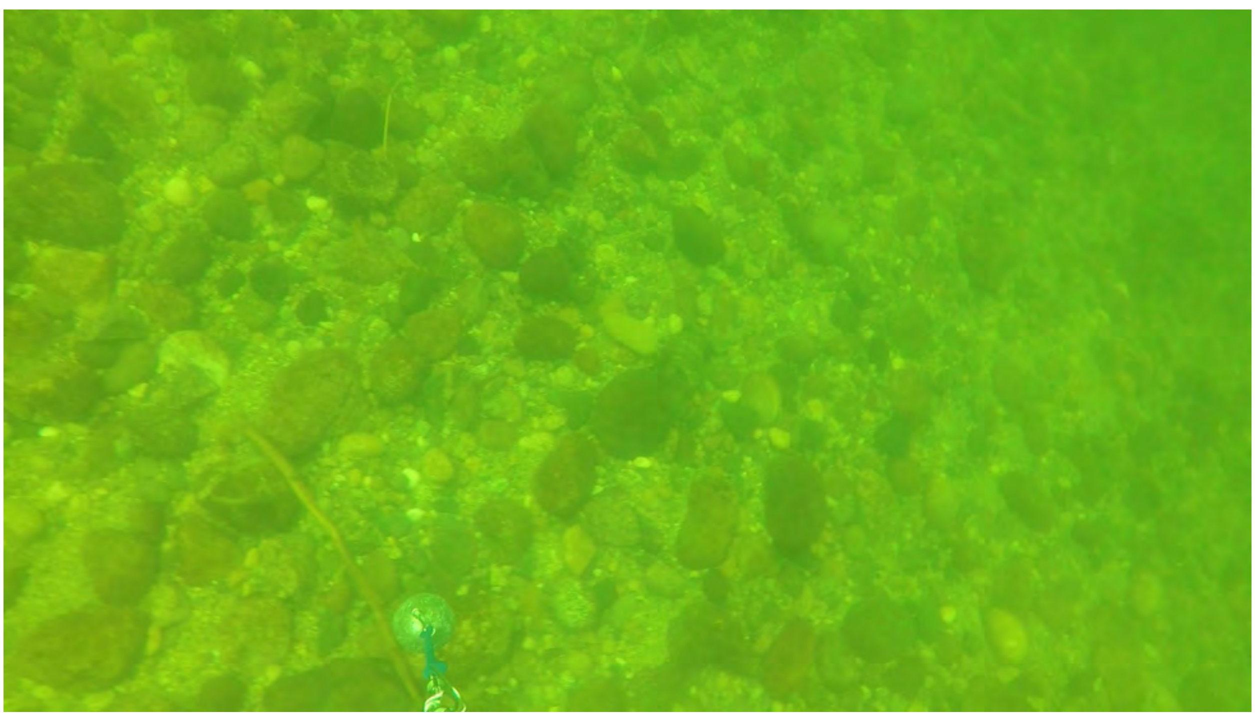
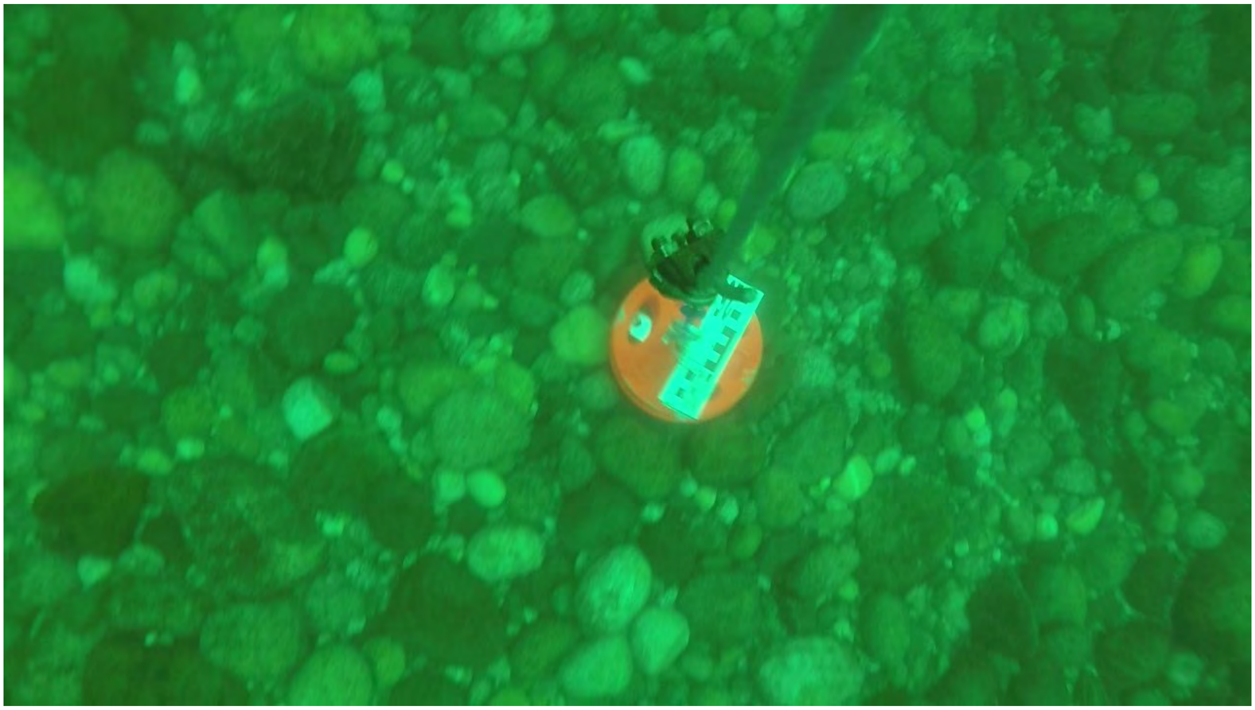


Figure 2. High agreement between three people for a low embeddedness ranking.

a) Photo ID 1305 (Rankings: 0, 1, 1)



b) Photo ID 2340 (Rankings: 1, 1, 1)

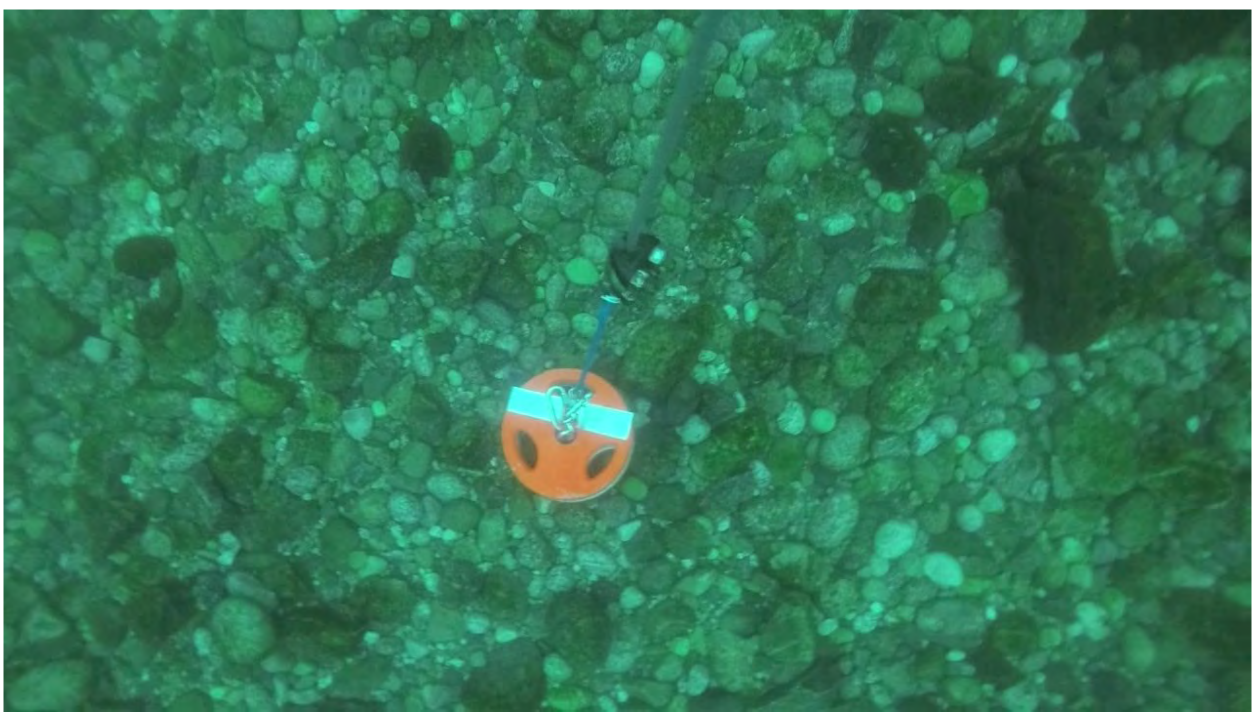
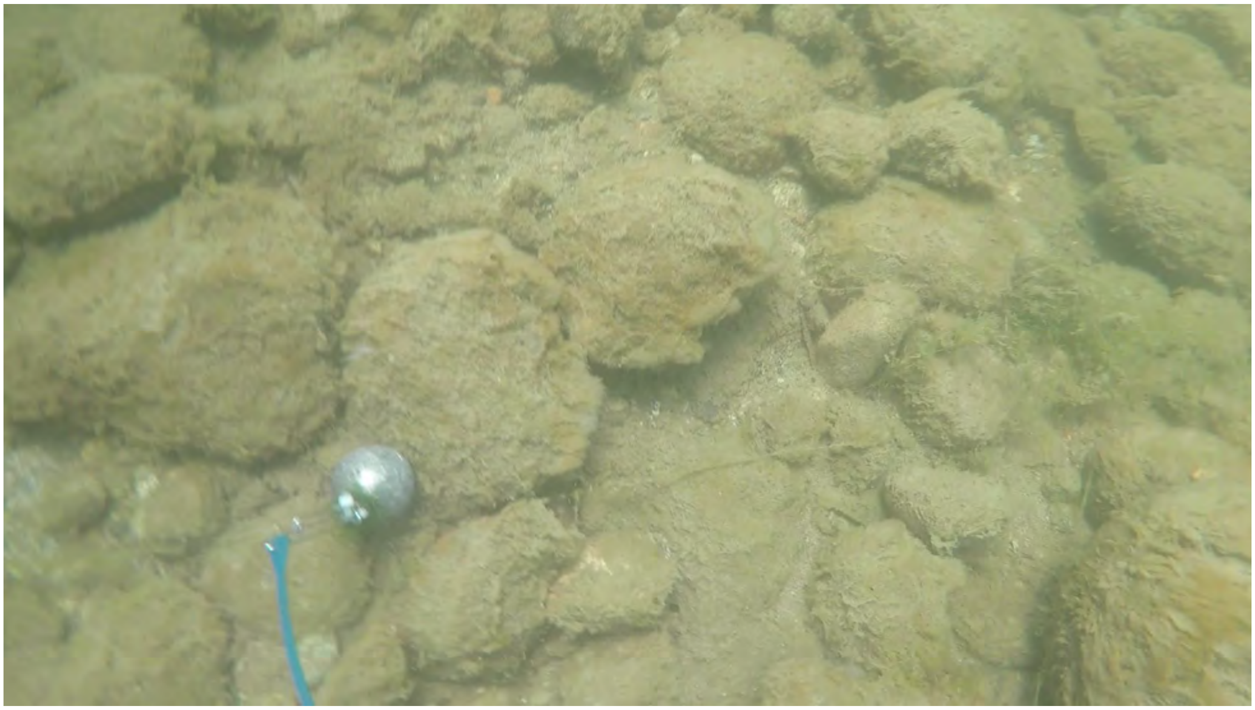


Figure 3. Low agreement between three people for a high embeddedness ranking.

a) Photo ID 735 (Rankings: 4, 1, 4)



b) Photo ID 1240 (Rankings: 1, 3, 3)

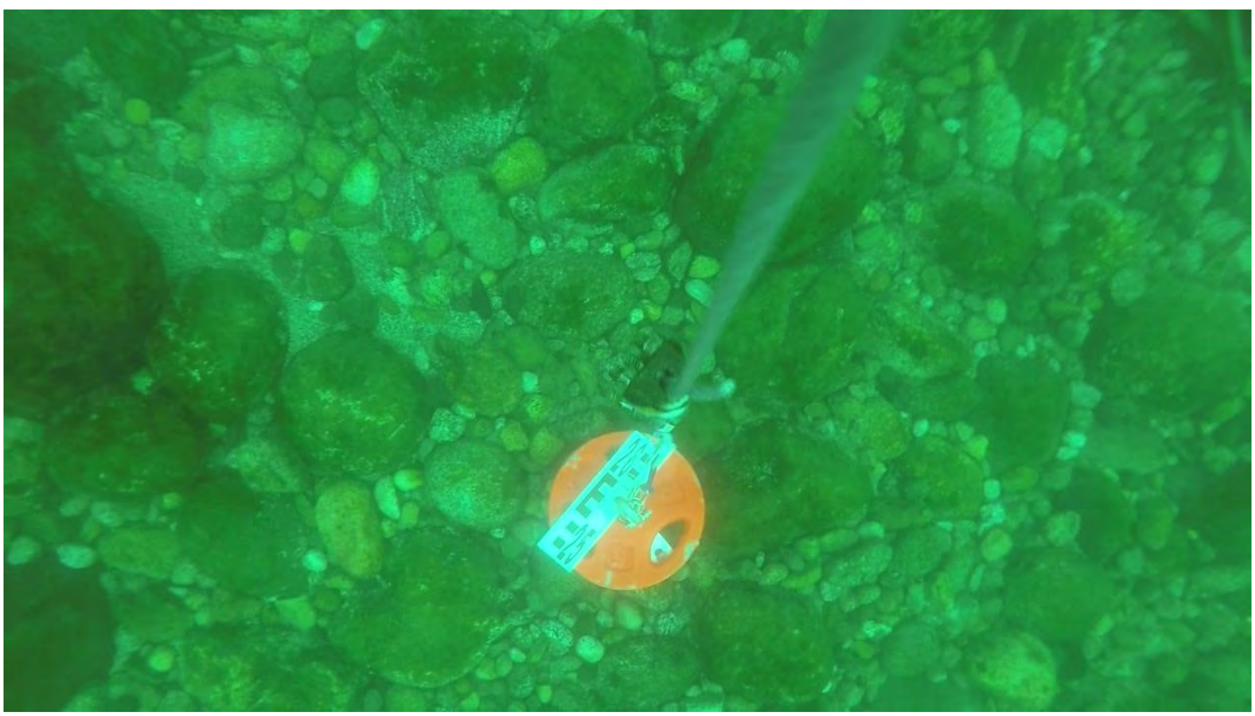
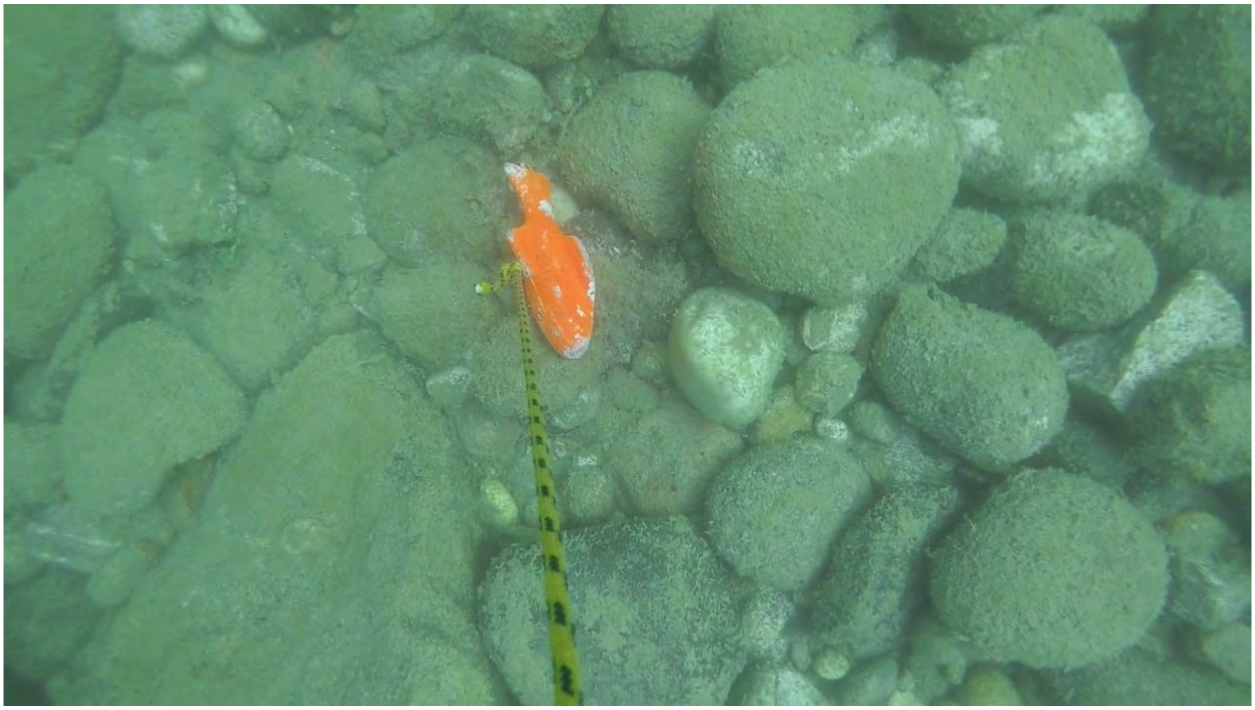


Figure 4. Low agreement between three people for a low embeddedness ranking.

a) Photo ID 125 (Rankings: 2, 0, 2)



b) Photo ID 683 (Rankings: 0, 1, 2)