Columbia River Project Water Use Plan

Columbia White Sturgeon Management Plan

Mid Columbia River White Sturgeon Spawning Habitat Assessment and
Mid Columbia River Effects of Flow Changes on Incubation and Early Rearing Sturgeon

Implementation Years 1-4

Reference: CLBMON-20 and CLBMON-54
(Appendices are listed in a separate file)

Effects of Flow Changes on White Sturgeon Spawning, Incubation, and Early Rearing Habitats in the Middle Columbia River

Study Period: June 2010 to August 2014

Golder Associates
ASL Environmental Sciences

September 12, 2014

September 12, 2014

Effects of Flow Changes on White Sturgeon Spawning, Incubation, and Early Rearing Habitats in the Middle Columbia River (CLBMON-20 and CLBMON-54).

Submitted to:
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REPORT

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1.0 INTRODUCTION

Studies initiated in the mid-1990s identified the presence of a remnant population of wild adult White Sturgeon (*Acipenser transmontanus*) in the Arrow Lakes Reservoir (ALR) Reach of the middle Columbia River (Golder 2006). The population was estimated at 52 (95% CI = 37 to 92) adults, that spawned in the flowing section of the middle Columbia River approximately 6 km downstream from Revelstoke Dam near the city of Revelstoke, BC (Figure 1). White Sturgeon in the ALR/middle Columbia River are listed as endangered under the Species At Risk Act (SARA) and the Revelstoke spawning area has been designated as critical habitat by Fisheries and Oceans Canada (2014).

Studies have documented White Sturgeon spawning activity at a location downstream of Revelstoke Dam with egg incubation and potential early rearing habitats located within a few kilometres downstream of the spawning grounds (Golder 2012). Spawned eggs have been collected upstream from the Jordan River mouth and adjacent to the Revelstoke Golf Course, but at present, there is no evidence that spawning presently or in the past has resulted in recruitment to the population in ALR. Since 1999, spawning has occurred intermittently and has been documented in eight out of thirteen years of monitoring effort with one to three spawning events per year (Table 1). Spawning has occurred in late July to late August, which represents the latest spawn timing recorded for this species throughout its range. The delayed onset of spawning has been attributed to naturally cold water temperatures in this section of the Columbia River that have been exacerbated by hypolimnetic flow releases from Revelstoke Dam. Low numbers of fertilized eggs and post-hatch larvae have been captured, which indicates some successful fertilization and survival to hatch has occurred, but recruitment to the juvenile stage from these spawning events has not been detected.

During the BC Hydro Water Use Planning (WUP) Process for the mainstem Columbia River facilities, the WUP Consultative Committee (CC) identified the need to better understand White Sturgeon spawning, incubation, and early rearing habitat in the middle Columbia River, and how dam and reservoir operations influence habitat availability and suitability. Revelstoke Dam is operated as a load-following facility and therefore, hydraulic conditions in the riverine section below the dam are highly variable and complex, and prior to 2010, varied from dam seepage flows (zero discharge) to an about 1700 m^3/s. BC Hydro added a fifth generation unit (REV5) at Revelstoke Dam in 2009 (operational in October 2010) that resulted in the implementation of a minimum discharge of 142 m^3/s and a maximum discharge of approximately 2124 m^3/s, when all 5 units are operated at full capacity.

In addition, at the initiation of this study program in 2009, BC Hydro was in the process of installing a fifth generation unit (REV5) at the Revelstoke Dam. A component of this project involved an examination of flow effects from the fifth unit on the White Sturgeon spawning, egg deposition/incubation, and early rearing habitat situated in the mainstem Columbia River downstream from the dam.

2.0 BACKGROUND

Monitoring results to date have not provided insights into potential cues that trigger White Sturgeon spawn timing or activity in the Revelstoke spawning area. As a result, addressing management questions related to the effects of Revelstoke Dam and ALR operations on White Sturgeon egg and larval survival has been challenging. This is attributed to the small population size of potential spawners that results in both intermittent spawning among years and low number of spawning events within a year (Table 1). The resultant small sample size of collected eggs and larvae, in addition to sampling challenges related to the highly variable physical environment within the spawning area, has limited data collection, which in turn has resulted in limited ability to obtain answers to the management questions.

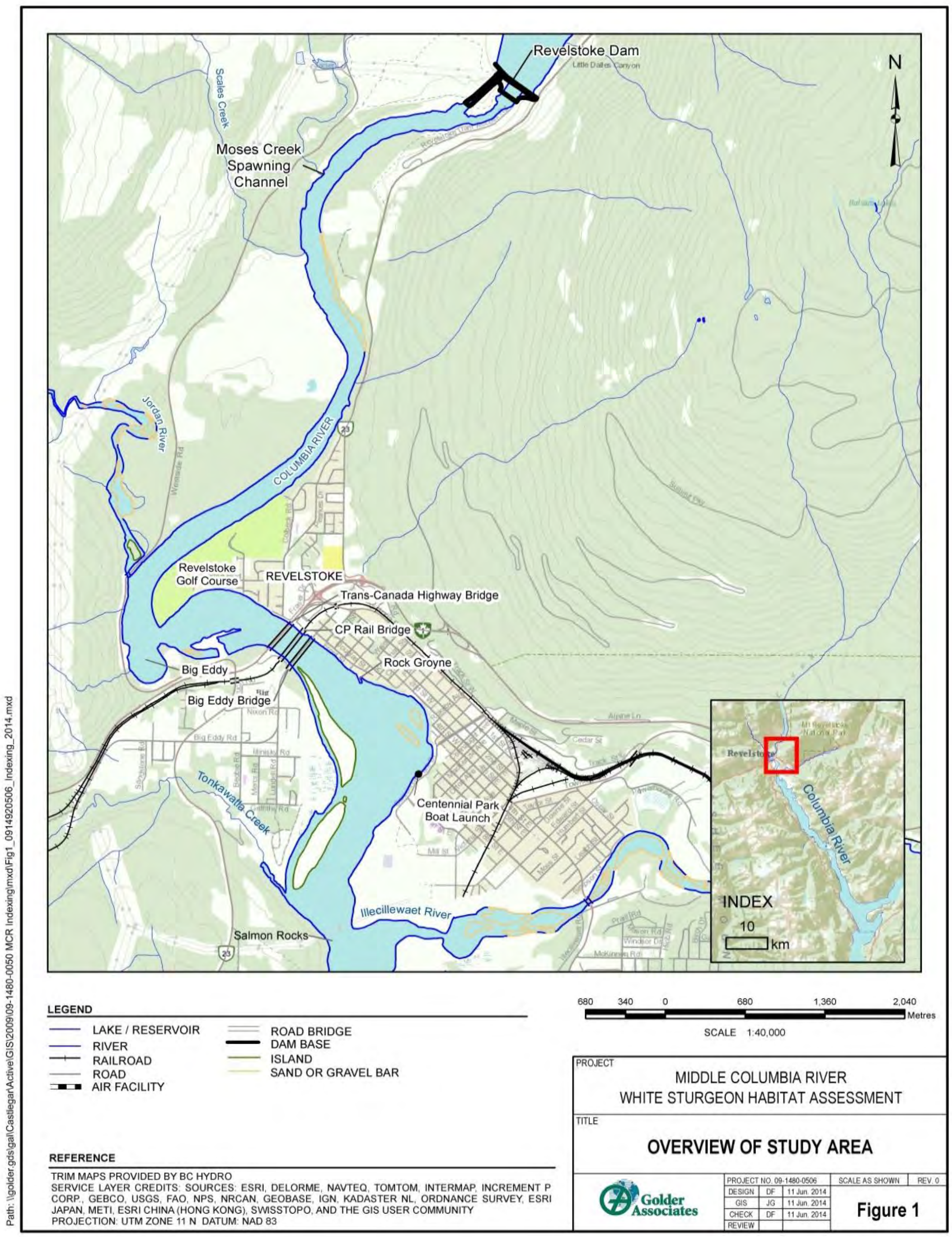


Figure 1: Study Area.

Table 1: Summary of White Sturgeon spawning events and physical parameters below Revelstoke Dam during the White Sturgeon spawning period (July and August) in years when spawn monitoring was conducted from 1999 to 2013 (from Golder 2012). Note: the ALR backwatering effect into the spawning area occurs when water elevations at the Nakusp gauge are 437 metres above sea level (masl) or greater.

Parameter		Sample Year (Shading denotes years when White Sturgeon spawning was detected)											
		1999	2000	2001	2003	2006	2007	2008	2009	2010	2011	2012	2013
No. Spawning Events		3	0	0	2	1	0	2	3	0	3	1	1
No. Eggs Captured		82	0	0	50	1	0	8	65	0	37	1	2
No. Larvae Caught		0	0	0	1	0	0	0	18	0	11	7	0
Discharge (m^3/s)	Mean	1230	1139	682	901	939	1185	712	744	540	957	1506	862
	Min.	0	0	0	0	0	0	0	0	0	145	150	253
	Max.	1838	1635	1612	1667	1630	1773	1752	1715	1757	2140	2573	2118
Water Temperature (°C)	Mean	10.3[a]	ND[b]	9.8	9.5	10.0	9.7	9.2	10.9	11.0	10.6	10.8	10.5
	Min.	9.2[a]		6.4	6.9	8.0	4.5	6.7	7.6	7.5	8.0	7.8	9.1
	Max.	11.6[a]		13.1	13.6	13.1	12.9	11.8	16.2	14.2	12.5	13.5	12.6
ALR Water Surface Elevation at Nakusp (m above sea level)	Mean	438.0	438.9	429.4	438.0	438.5	437.5	439.2	436.5	437.7	439.0	439.5	435.0
	Min.	437.2	437.6	427.3	436.2	435.2	435.3	438.7	435.8	436.1	438.0	436.6	432.9
	Max.	440.0	440.0	430.4	439.0	439.8	438.6	439.9	437.5	439.3	439.5	440.5	437.6
No. Zero or Minimum Flow Events[c]		25	8	36	36	12	8	49	42	39	25	20	0[d]

[a] Temperature data were only available from August 4-31.
[b] Data not available
[c] Prior to 2011, zero flow was the minimum; for 2011 and later, 142 m^3/s was the minimum
[d] In 2013, flows during July and August never were lower than 253 m3/s

3.0 OBJECTIVES

This report addresses two BC Hydro Water License Requirements (WLR) monitoring programs that overlap in their data collection needs and scope. These are: CLBMON-20: Middle Columbia River White Sturgeon spawning habitat assessment and CLBMON-54: Effects of flow changes on egg incubation and early rearing. The overall objective of these studies was to model the effects of Revelstoke Dam flows and ALR levels on velocity patterns in the White Sturgeon egg deposition/incubation and early rearing area. Using these results and what is known about White Sturgeon spawning and early rearing habitats, inferences on potential effects on White Sturgeon spawning suitability could then be drawn. The two monitoring programs are described below.

3.1 CLBMON-20: Middle Columbia River White Sturgeon Spawning Habitat Assessment

In order to determine how Revelstoke Dam and ALR operations influence the availability and suitability of white sturgeon spawning habitat in the middle Columbia River, the WUP CC recommended that detailed hydrometric surveys be undertaken in locations of known white sturgeon spawning. This data would then be used to validate the assumptions used to decide on and set white sturgeon spawning flow treatments, and assist in determining spawning habitat objectives for sturgeon for future rehabilitation activities.

Key management uncertainties encountered during development of the Columbia River Water Use Plan related to how current operation of Revelstoke Dam and Arrow Lakes Reservoir affects the quantity and quality of white sturgeon spawning habitat in the Columbia River below Revelstoke Dam. The fundamental management questions to be addressed through this monitoring program were:

1) What are the depth, hydraulic properties (velocity/turbulence) and substrate conditions in the known or identified white sturgeon spawning and incubation area(s) below Revelstoke Dam?

2) How do Revelstoke Dam and Arrow Lakes Reservoir operations affect hydraulic conditions in this/these area(s)?

3) How do these hydraulic conditions relate to spawning habitat suitability (quality and quantity) for white sturgeon?

4) Can modifications be made to operations of Revelstoke Dam and/or Arrow Lakes Reservoir to protect or enhance middle Columbia River white sturgeon spawning habitat?

3.2 CLBMON-54: Middle Columbia River Effects of Flow Changes on Incubation and Early Rearing Sturgeon

The completion and operation of the REV5 unit will result in increased daily maximum flows and the provision of a licensed minimum flow. The Upper Columbia White Sturgeon Recovery Initiative (UCWSRI) Technical Working Group (TWG) recommended an assessment be conducted of the effect that these discharge changes may have on the spawning/egg incubation and early rearing habitat of sturgeon downstream of Revelstoke Dam. To support this recommendation, the Comptroller of Water Rights required BC Hydro to “assess pre- and post-project flow changes in incubation and early rearing sturgeon habitat conditions” as these relate to operations of REV5. As defined by the TWG, “early rearing sturgeon habitat conditions” refers to that life stage where the free embryo or post-hatch larva hide in the substrate while undergoing further development prior to dispersing to feeding habitats. The Delphi technique (Crance 1987a) was originally proposed to develop habitat suitability indices based on the data collected and opinions of experts on habitat requirements for early life stages of white sturgeon. This method has previously been used to develop indices for shortnose sturgeon and paddlefish (Crance 1986 and 1987b) in the absence of information. However, given recent findings both in the field (Crossman and Hildebrand 2012) and laboratory settings (McAdam 2011; Bates et al. 2014; Boucher et al. 2014), the Delphi technique was not considered likely to add considerable information to the current state of knowledge. Given that substrate restoration will be a focus of the recovery program in the next few years for the upper Columbia River, the Delphi technique is likely more applicable for those works if an acceptable level of consensus cannot be reached during the development of those projects.

Key management uncertainties relate to how pre and post-REV5 operations of Revelstoke Dam and ALR presently and in the future will affect the quantity and quality of white sturgeon spawning/egg incubation and early rearing (free embryo hiding) habitat in the Columbia River below Revelstoke Dam. The fundamental management questions to be addressed through this monitoring program were:

1) What are the depth, hydraulic properties (velocity/turbulence) and substrate conditions in the identified white sturgeon egg incubation and suspected early rearing habitat area(s) below Revelstoke Dam?

2) How does Revelstoke Dam (including the addition of unit 5) and Arrow Lakes Reservoir operations affect hydraulic conditions in this/these area(s)?

3) How do these hydraulic conditions relate to incubation and early rearing habitat suitability (quality and quantity) for white sturgeon?

4) Can proposed minimum flows and spawning flow modifications to the operations of Revelstoke Dam protect or enhance middle Columbia River white sturgeon incubation and early rearing habitat?

3.3 Project Approach and Rationale

To address management questions related to flow effects on White Sturgeon habitat downstream from Revelstoke Dam (see Section 3.0), a 3D COCIRM-SED numerical flow model (hereafter called the 3D model) was developed. This model consists of six sub-modules, which include circulation, wave, multi-size sediment transport, morphodynamics, particle tracking, and water quality. More information on the ASL-COCIRM model definitions and components are provided in Fissel and Jiang (2008).

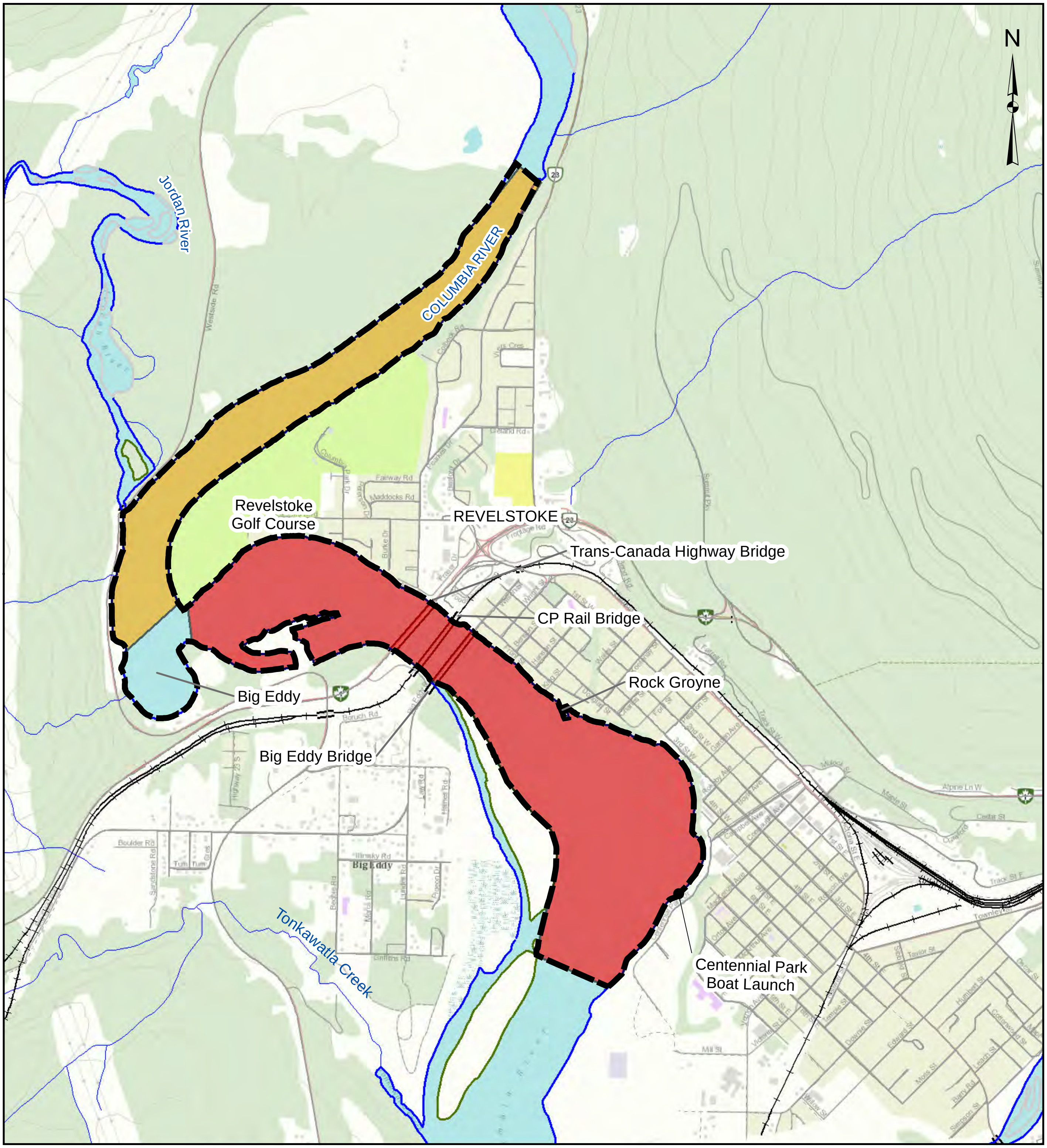
The 3D model was selected as the best approach to address BC Hydro's management questions related to flow effects on sturgeon spawning (CLBMON-20) and early rearing (CLBMON-54) habitats in the middle Columbia River for the following reasons:

- The 3D model has been previously used successfully for the Waneta Expansion Project to quantify changes to flow patterns in the White Sturgeon spawning area downstream from the Waneta Dam on the Pend d'Oreille River (Fissel and Jiang 2008; WEPC 2007). The model was accepted by DFO as the best tool available to identify and quantify changes in flow patterns and velocities in the White Sturgeon spawning and egg incubation area.
- The 3D model has the degree of resolution necessary to identify fine-scale changes adjacent to near-bottom areas of the river bed, which are the areas actually being used for spawning/egg incubation and early rearing. Turbulence, considered by many researchers to be an important determinant in spawning habitat selection, cannot be assessed using 1D and 2D models nor can these model types provide near bottom data. The 3D model can provide parameterized measures of both vertical and horizontal turbulence levels at different vertical levels within the water column, from near surface to near bottom.
- The 3D model is a proven quantitative tool that allows the identification of key habitat attributes, provides sufficient resolution, precision, and accuracy to predict conditions and identify changes to these conditions at different dam and reservoir operations, and generates mapping and graphical outputs to visually illustrate key parameters within important habitats.

- Portions of the egg incubation area and the free embryo rearing area are downstream from Jordan River. The Jordan and Columbia systems have different temperature regimes during the sturgeon spawning period, which could potentially influence spawning site selection and affect egg incubation and larval development (particularly during low discharge from Revelstoke Dam). The 3D model output includes 3D temperature distributions that address this issue.
- The 3D model allows the input of any combination of Revelstoke Dam discharge and temperature, ALR level, Jordan River inputs (discharge, temperature, and sediment) to predict selected conditions within the areas of interest. The COCIRM model also is capable of computing sediment properties (suspended sediment concentrations, deposition and erosion) and was used to simulate larval drift patterns.

3.4 Study Area

The spatial boundaries of the 3D model include the White Sturgeon spawning and egg deposition/incubation area (from the Columbia River upstream of the confluence with the Jordan River to Big Eddy) and the early larval rearing area (from Big Eddy downstream to just downstream of the Highway 1 Bridge (Figure 2). This represents a 2.7 km by 3.7 km rectangular model domain that encompasses the approximate 5 km length of the river that was modelled.



LEGEND

EXTENT OF 3D MODEL

WHITE STURGEON EGG DEPOSITION / INCUBATION

WHITE STURGEON EARLY LARVAL REARING

425 212.5 0 425 850 1,275 Metres

SCALE 1:25,000

REFERENCE

TRIM MAPS PROVIDED BY BC HYDRO
BING MAPS FOR ARCGIS
PROJECTION: UTM ZONE 11 N DATUM: NAD 83

PROJECT

MIDDLE COLUMBIA RIVER
WHITE STURGEON HABITAT ASSESSMENT

TITLE

WHITE STURGEON
SPAWNING AND EARLY REARING AREA
AND EXTENT OF 3D MODEL

Golder Associates

PROJECT NO. 09-1480-0506			SCALE AS SHOWN	REV. 0
DESIGN	DF	11 Jun. 2014		
GIS	JG	5 Sept. 2014	Figure 2	
CHECK	DF			
REVIEW				

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The upper boundary of the study was selected based on the furthest upstream collection of White Sturgeon eggs. The lower boundary, located approximately 1 km downstream of the Highway 1 Bridge, was selected based on the likely downstream limit of free embryo or larval drift. Areas used for spawning/egg incubation and for early rearing likely overlap as some early rearing may occur in the immediate vicinity of where the free embryos hatch. This assumes that suitable hiding habitat is available in the area of hatching and extensive downstream drift by post-hatch larvae to locate suitable early incubation habitat is not required. The lower study area boundary was situated downstream from the constriction of the channel at the highway and railway bridge areas, which results in noticeable flow in this area at high Revelstoke Dam discharges even during high ALR levels. This flow maintains areas of clean gravel downstream from the bridge crossings and if clean gravel represents suitable early rearing/hiding habitat as indicated by recent lab research (pers. comm. S. McAdam, BC MOE, Vancouver, BC and B. Kynard, Emeritus PI, Conte AFRC USGS, Turners Falls, MA USA, 2009), then this area has the potential for early rearing use. The river downstream of this area is heavily influenced by ALR levels and transitions rapidly into finer substrates although gravels and cobbles are present in the thalweg areas of the seasonally active river channels.

The backwatering effect caused by high ALR levels adds to the complexity of flow effects in the White Sturgeon spawning area. The effect is greatest from June to August when ALR is near or at full pool level and can extend upstream into the white sturgeon spawning/early rearing habitats below Revelstoke Dam. White sturgeon spawning habitat in the middle Columbia River can, therefore, be substantially affected by both discharge from the Revelstoke Dam and ALR water surface elevation. Further complexity within the study area is provided by the effects of Jordan River inputs (flow, sediment, and temperature), Big Eddy (a large dynamic hydraulic feature), recent bank protection works adjacent to the spawning area, and the construction of an experimental white sturgeon spawning bed (details in Crossman and Hildebrand 2012).

4.0 METHODS

To obtain the data needed to develop the 3D model, field measurement programs were conducted during Years 1 (2010) to 3 (2012) of the study program (Table 2). Details of the methods used to obtain the required data are provided below.

Prior to the present study, a HEC-RAS model had been developed by BC Hydro for the approximate 37 km section of the Columbia River downstream from Revelstoke Dam to compute water levels and calculate productive area habitats. Although the HEC-RAS model was not sufficiently sensitive to provide the information required to address the management questions for the present study, bathymetric data from the existing HEC-RAS transects (Figure 3) were used as preliminary inputs to the 3D model. As described in the following sections, the information collected for the subsequent development of the 3D model was collected from a select subset of the existing HEC-RAS transects. In this way, the updated and expanded information depth and velocity data collected for the 3D model was also used to update and expand the HEC-RAS model so it could be used to address other management questions that do not require the resolution of a 3D model.

Table 2: Chronology and descriptions of field programs undertaken to provide data for the development of the 3D model, 2010 to 2013.

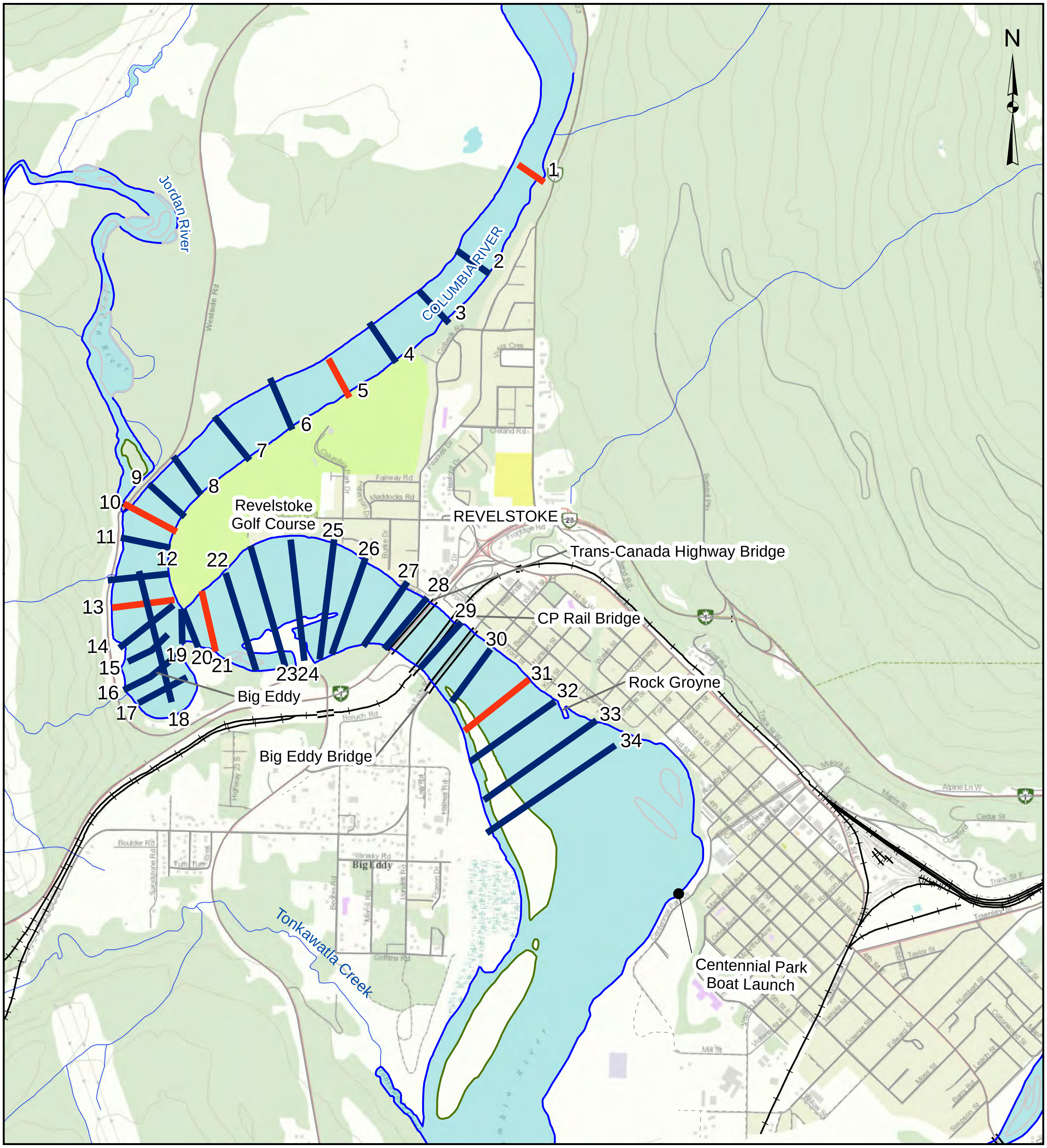
Data Collected	Collection Period(s)	Data Source	Comments
Depth and Velocity	June 2010, August 2010, October 2010, August 2011, August 2 & 3, 2012	ADCP surveys along 34 transects established in study area	
Substrate	September 10-13, 2010 October 19 - 22, 2010	Underwater video surveys along 34 transects	34 transects surveyed in total over two sessions
Jordan R. Water Temperature	15 November 2007 to 16 August 2012	Onset Tidbit™ thermisters	Middle Columbia River Productivity Study (CLBMON 15)
Jordan R. Discharge	August 7, 2010 to October 25, 2010	Instream measurements	Middle Columbia River Productivity Study (CLBMON 15)
Columbia R. Water Temperature	2010 to 2013	Thermisters	BCH Revelstoke Golf Course station
Columbia R. Discharge	At each depth and velocity measurement period (see above)	Revelstoke Dam: BC Hydro Power Records	
Arrow Lakes Reservoir Levels	At each depth and velocity measurement period (see above)	Gauge at Nakusp BC: BC Hydro Power Records	

A detailed description of the 3D model structure, input and output parameters, the various calibration, verification, and additional model runs, and the model results are provided a separate document (Lin and Fissel 2014) that has been included as Attachment A in this report. Various figures and summary tables have been extracted from the Lin and Fissel (2014) document and inserted in the present report to support the discussions and conclusions regarding how Revelstoke Dam and ALR operations influence the availability and suitability of white sturgeon spawning habitat in the middle Columbia River.

4.1 Velocity and Depth Measurements

An RD Instruments Rio Grande 1200 kHz Acoustic Doppler Current Profiler (ADCP) was used to obtain velocity and bathymetry data along each of 34 transects that were either previously established in the study area (i.e., HEC RAS transects) or were established in the present study to provide more detailed information on specific areas (Figure 3). The horizontal resolution of this instrument was 20 to 25 m along each transect, to accuracies of 5% or better of the measured velocities and vertical resolution of 0.5 m or better. A SOKKIA GSR2700 ISX Real Time Kinematic (RTK) Global Positioning System (GPS) was used to provide accurate 3D positions (accuracy of 2 cm). Transects were surveyed by maneuvering the boat slowly from bank to bank with the ADCP and RTK activated. ALR levels (metres above sea level - masl) during each survey were obtained from the BC Hydro gauging station at Nakusp.

Bathymetry and depth data were collected using an Ohmex Instrumentation SonarMite Echo Sounder (235 kHz transducer with a depth range of up to 75 m and an accuracy of 2.5 cm) coupled with the RTK to provide accurate 3D positions.



425 212.5 0 425 850 1,275
Metres

SCALE 1:25,000

LEGEND

- TRANSECT LOCATION
- TRANSECT LOCATION CHOOSEN FOR DETAILED SUBSTRATE ANALYSIS

REFERENCE

TRIM MAPS PROVIDED BY BC HYDRO
BING MAPS FOR ARCGIS
PROJECTION: UTM ZONE 11 N DATUM: NAD 83

PROJECT

MIDDLE COLUMBIA RIVER
WHITE STURGEON HABITAT ASSESSMENT

TITLE

SURVEYED TRANSECTS

Golder Associates

PROJECT NO. 09-1480-0506			SCALE AS SHOWN	REV. 0
DESIGN	DF	11 Jun. 2014		
GIS	JG	5 Sept. 2014		
CHECK	DF			
REVIEW				

Figure 3

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4.2 Substrate Surveys

The characteristics (e.g., size, composition, embeddedness) of substrate at sturgeon spawning grounds are considered important factors that influence white sturgeon egg and early rearing larval survival, but are presently poorly understood. Most riverbed substrate mapping techniques are limited to the identification of surficial characteristics, which may not be sufficient to assess suitability for rearing based on lab studies that suggests the underlying substrate conditions may be as or more important to larval survival (pers. comm., S. McAdam, BC MOE, Vancouver, BC,.2009).

In Year 1, substrate surveys were conducted at a sufficient level of detail to provide a general substrate size-class distribution in the study area. These surveys were conducted using videography along each of the 34 velocity transects (Figure 3) to provide the basic information necessary to map the size distribution of substrates, qualitatively assess substrate suitability, and provide inputs of surficial bottom sediment distributions to derive the bottom roughness coefficients needed to initialize the 3D model (see Attachment A, Section 8.2). The method also allowed the visual identification of finer scale differences in surficial substrate composition (e.g., small vs. large cobbles) and embeddedness.

Substrate surveys were conducted using an AquaView™ underwater video camera affixed to a 45 kg lead "fish" that was raised and lowered using a sounding reel. The lead fish was equipped with a scaling bar, positioned so it was visible at the bottom of the cameras viewing frame, to allow identification of substrate sizes (Figure 4).

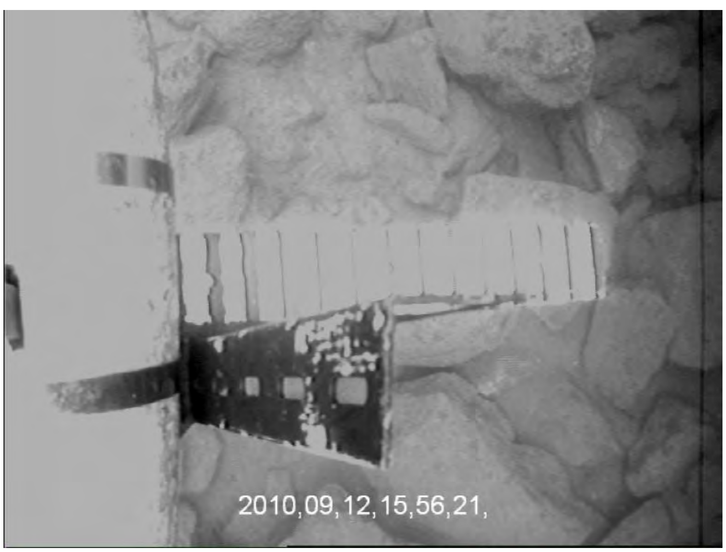


Figure 4: A typical video frame capture at transect 21. The object on the left is the lead fish and the bright object in the center of the frame is the scaling bar.

All footage during the substrate surveys was recorded on a laptop using Debut Video Capture Software™ (NCH Software). A differential GPS unit (Trimble) was used to provide positional data. During the surveys the camera was held stationary on the bottom at regular intervals (and at locations where the substrate conditions changed) along each transect to obtain better quality footage of the substrate and provide higher resolution GPS coordinates. On survey days, surface water turbidity (using an Orbeco- Hellige Model 966 portable turbidimeter accurate to 0.01 NTU in the lowest range) and Secchi depths (to the nearest cm, deployed on shaded side of the boat) were recorded in the general sample area. As a validation check for the substrate dataset, additional video samples were obtained at 50 randomly selected locations. These data points were located between transects and were used to check the validity of the interpolations of substrate types between transects as described below for the substrate mapping component. In addition, visual observations of the exposed portions of each transect were made and photographs taken during a period of low daytime flow (taken on each bank, as viewed from the water's edge to the exposed shore).

Surveys were conducted from September 10 to 13 and October 19 to 22, 2010. During the September sampling, hourly Revelstoke discharge (combined spill and generation flows) ranged from 0 m^3/s to 1295 m^3/s (mean ± SD of 387.6 ± 362.4 m^3/s), and elevation in Nakusp ranged from 435.49 to 435.69 masl. In October, hourly Revelstoke discharge (combined spill and generation flows) ranged from 8.7 m^3/s to 1580.9 m^3/s (mean ± SD of 676.4 ± 342.7 m^3/s), and elevation in Nakusp ranged from 433.76 to 433.83 masl.

Initial analysis of the video was conducted in March 2011; screen capture images from the substrate survey video footage were extracted from between 12 and 35 selected locations along six transects (Figure 3) and provided to ASL for incorporation into the 3D model. On March 18, 2010, in the early morning during low flows, five substrate samples were collected downstream of Big Eddy (Figure 5). Sieve analyses of these samples were conducted in the lab and the results were sent to ASL to assist in assigning bottom roughness coefficients for use in the 3D model (see Section 5.9).

4.2.1 Substrate Suitability Rating

Another objective of the present study was to characterize the substrate and near-bottom flow velocities within the study area in terms of size and availability of interstitial spaces as a means to assess potential suitability for sturgeon spawning and early rearing. The collected data are summarized in context of White Sturgeon spawning, egg incubation, and early larval stage requirements.

Still images were extracted from video footage at each sampling point using the software packages Greenshot and Debut Video Capture Software™ (NCH Software). Each image was examined and classified based on parameters of substrate size and embeddedness (a measure of the availability of interstitial spaces). Substrate composition at each sampling point was assigned a ranking (substrate rating) based on the size of the recorded substrate. Substrate ratings were categorized as 1 = low (fines [< 2 mm diameter] and bedrock), 2 = moderate (gravels [2 to 64 mm] and boulders [> 256 mm]), or 3 = high (cobbles [64 to 256 mm]); classification of substrate by size ranges was based on the Wentworth scale (Cummins 1962). These ratings were loosely based on observations of larval White Sturgeon in the Columbia River downstream of McNary Dam, where larvae were collected most commonly over cobble substrates, followed by gravels and boulders, and lastly, fines and bedrock (Parsley et al.1993) and are the same rankings used to assess substrate conditions downstream from the known White Sturgeon spawning/egg deposition areas near Waneta (Golder 2009) and the below the Arrow Lakes Hydro/Hugh L. Keenleyside Dam (ALH/HLK area: Golder 2013).

A rating of available interstitial space at each sampling point was assigned using the same classification values (1 = low, 2 = moderate, 3 = high). Low values were assigned to points with minimal or no interstitial spaces. Moderate values were assigned to sampling points where interstitial space was available, but partially filled by smaller substrates, or where interstitial spaces were too large to provide adequate cover for sturgeon yolk sac embryos. High values were assigned to sampling points where smaller interstitial spaces were abundant, and thereby provided what was considered the best cover for White Sturgeon early larval stages.

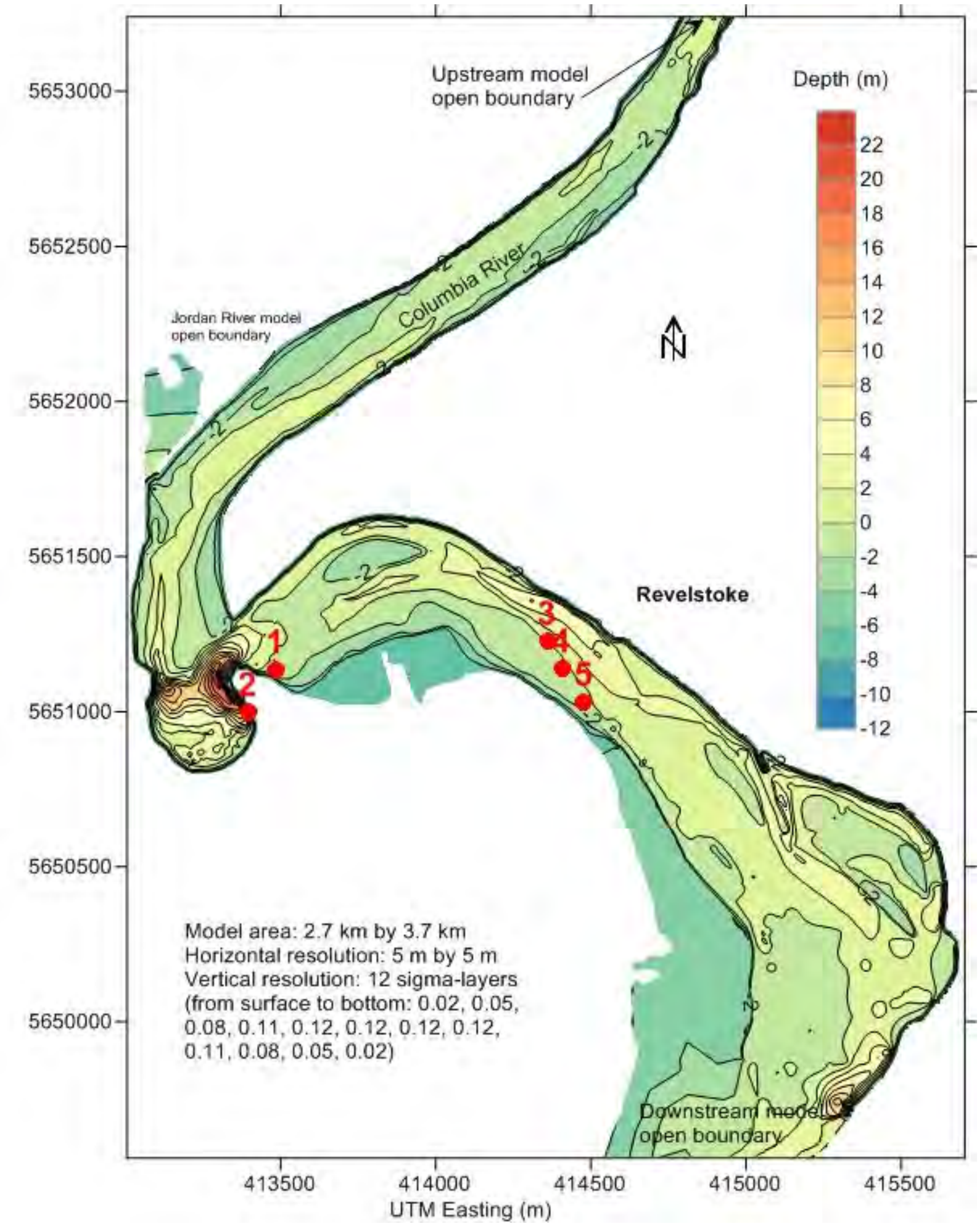


Figure 5: Map showing 3D model domain and bathymetry. Red dots represent sites where bottom sediment categories were quantified using sieve analysis. From Lin and Fissel (2014).

The substrate and interstitial space ratings were added together for each sampling point to provide a total suitability rating. This provided an overall indication of habitat quality for White Sturgeon spawning and early life stages within a range of 2 (lowest) to 6 (highest). Substrate, interstitial space, and total ratings for each sampling point were plotted on geo-referenced maps. Examples of classification of substrate, interstitial space, and total suitability are provided in Appendix A, Plates 1 to 6.

In addition to classification of substrate value and interstitial rating, five points per transect, equidistant along the transect line, were selected for quantitative measurement of substrate. Substrate size was measured along the longest axis of the selected particle using the ImageJ freeware. Two types of images were measured – underwater images, extracted from transect footage, and images taken using hand-held cameras during examination of exposed areas on each bank along the transect line. When analysing the underwater images, up to 20 substrate particles per image were measured (all particles were measured in images with less than 20 particles). For the exposed shoreline images, 20 objects per image were selected using a 5x4 grid overlain on the image, so that measured particles represented the entire photographed area. The measured particles were marked with a number on the image (Appendix A, Plates 7 and 8). A corresponding number was entered in a separate column in the dataset, for future reference. In both types of images, if larger objects (cobbles, boulders) were only partly visible, they were measured, and a separate column was used to indicate that the measurement was an underestimate of total object size. This was done to reduce measurement bias – if only fully-visible objects are measured, most large-size substrate would be omitted, therefore substantially reducing mean particle size estimates.

Plots of substrate, interstitial, and total ratings, their interpolations, and substrate sizes were performed using the statistical environment R v. 3.1.0 (R Development Core Team, 2013) and packages ggplot (Wickham 2009) and ggmap (Kahle and Wickham 2013).

4.3 Discharge and Water Temperature

Mean hourly discharge from Revelstoke Dam and Columbia River water temperatures at the Revelstoke golf course during the survey periods were obtained from BC Hydro Power Records. To determine the influence of the Jordan River on water temperatures in the adjacent Columbia River, Onset Tidbit^{TM} thermisters (accurate to ±0.2°C; set to record at hourly intervals) were deployed from August 7, 2010 to October 25, 2010 (Table 2). Two thermisters (one near each bank) were deployed in the Columbia River upstream of the Jordan River and one was deployed downstream of Big Eddy near the south bank.

The Jordan River enters the Columbia River just downstream of egg deposition area and immediately upstream of the early rearing area. At present, there is no active discharge gauging station on the Jordan River but BC Hydro maintains a water level gauge on the river and there are historical records available from Water Survey of Canada. To assess the possible effects of the Jordan River flows on habitat parameters in the sturgeon spawning/early rearing area, data on Jordan River discharge was estimated by first generating a correlation between the Illecillewaet and Jorden rivers using measured flows between 1963-1988. A second correlation was then developed between measured water levels (from the BC Hydro station on the Jordan River) and estimated Jorden flows using the first relationship. The estimated values were then compared to measured flows collected by BC Hydro and found to representative of the low flow range experienced during the sturgeon spawning period of July and August. Water temperatures in the Jordan River were recorded by an Onset TidbitTM thermister in the mouth of the Jordan River during the August 7 to October 25, 2010 period (Table 2).

4.4 Model Development, Calibration, and Verification

In June 2010, velocity survey data were obtained at low, intermediate, and high flows when ALR water surface elevation at Nakusp were below 437 masl, the level above which backwatering effects occur (Figure 6). In August 2010, surveys were conducted at intermediate flows when ALR levels were just above 437 masl. In October 2010, surveys were conducted at low, intermediate, and high flows and ALR levels over 3 m below the level at which the backwatering effect occurs.

On August 2 and 3, 2012, additional ADCP surveys were conducted as a component of a separate study commissioned by BC Hydro to examine the effects on the White Sturgeon spawning area of adding a sixth generation unit (REV6) at the Revelstoke Dam, which would increase the maximum Revelstoke Dam discharge (REVQ) at five units of generation (REV5Q = 2124 m^3/s) to six units (REV6Q = 2548 m^3/s). This data was collected at a higher discharge level than had been previously examined (i.e., previous maximum REVQ examined was 1699 m^3/s). The opportunity to collect this information came in early August 2012, when near record high flows in the upper Columbia Basin resulted in a combined spill and power plant REVQ discharge of 2124 m^3/s. The data collected for that study was incorporated into the present 3D model to expand the upper model bounds (see Attachment A: Table 1-2); the results and conclusions of the REV6 flow analysis are provided under separate cover (Hildebrand et al. 2013; Lin et al. 2012) but are discussed where appropriate in this report.

The velocity, depth, and substrate data collected from the 34 transects along with Columbia River discharges and the Arrow Lakes Reservoir levels were provided to ASL for input into the 3D ASL-CORCIRM model (Fissel and Jiang 2008; Jiang and Fissel 2011). The model also incorporated a Jordan River temperature of 11.0^{o}C (daily average for August), a Columbia River temperature of 11.6^{o}C (daily average for August) and a Jordon River discharge of 19 m^3/s (daily average for August). Details of the data used for the various model calibration, verification, and additional runs depicted in Figure 4 are provided in Attachment A (Section 1.2, Tables 1-1 and 1.2).

Results of the 3D modeling for the Waneta Expansion project showed that most White Sturgeon eggs were captured on egg collection mats that were situated in channel areas with near-bottom velocities of 1.0 to 2.0 m/s (WEPC 2007). This indicated that changes in near-bottom flow conditions would have the greatest influence on White Sturgeon spawning and early rearing habitats and as such, the subsequent analysis and discussion focusses on comparisons of near bottom flows at the various discharge and reservoir levels examined by the model runs.

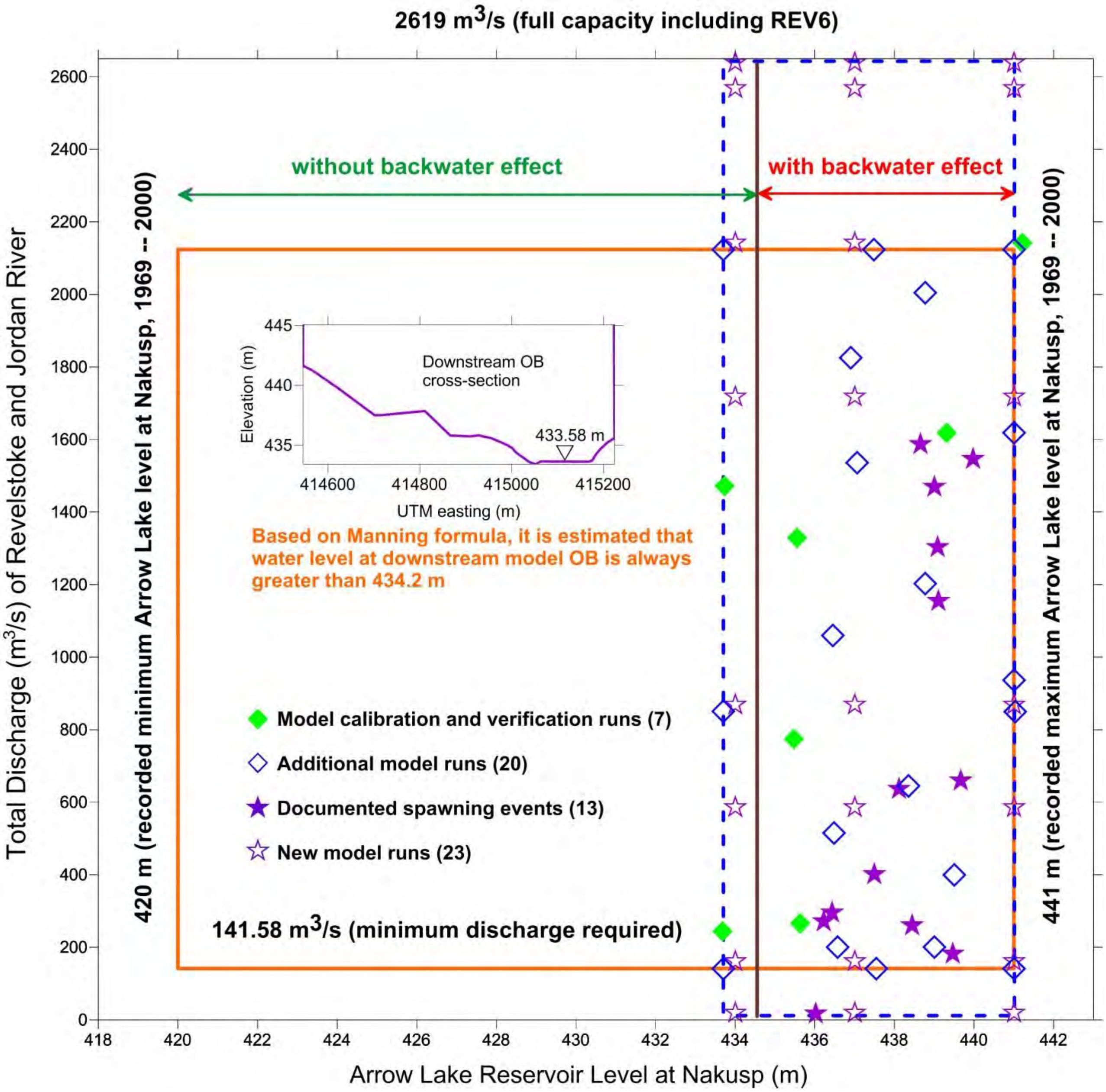


Figure 6: Summary of 3D model runs and associated Revelstoke Dam discharge and Arrow Lakes Reservoir level conditions. See Attachment A (Tables 1-1 and 1-2) for specific data on each model run. From Lin and Fissel (2014).

5.0 RESULTS

5.1 Discharge and Temperature

Discharge from Revelstoke Dam over the July and August periods of 2009, 2010, and 2011 exhibited substantial daily fluctuations typical of a facility that generates power based on daily market demand (Figure 7). The main differences between years was the stable discharge period in mid to late July 2010, which was caused by unit outages at Revelstoke Dam (only one unit was operational), the increase in the minimum discharge from 0 m^3/s in 2009 and 2010 to 142 m^3/s in 2012, and the increase in the maximum discharge from 1699 m^3/s in 2009 and 2010 to 2124 m^3/s in 2011. The latter two differences were the result of REV5 coming on-line in October, 2010.

When combined with the backwater effect due to high ALR levels, these hourly and daily discharge fluctuations can substantially alter water surface elevations in the study area. At low ALR levels, daily load shaping can result in water levels fluctuations up to 2.6 m in the spawning area as was the case in 2009 when the mean ALR level during the spawning period was 436.5 masl (Golder 2010). At higher mean ALR levels, such as the 439.0 masl observed during the 2011 spawning period, the magnitude of these fluctuations was reduced to ~1.5 m (Golder 2011).

Water temperatures in the Columbia River in the study area also are affected by the daily and hourly discharge regime and can fluctuate up to 6.6 ^{o}C within a 30 h period (Golder 2010; Figure 7). Large, rapid increases in water temperature occurred in all of the study years and although the reasons are not fully understood, are likely related to a combination of flow volume, the water temperature profile in Revelstoke Reservoir, and backwater effects from ALR. The top of the dam intakes are at approximately 36 m depth and typically pass cold hypolimnetic water from Revelstoke Reservoir; however, during periods of maximum reservoir stratification in July and August and periods of higher sustained dam discharge, warmer epilimnetic water from Revelstoke Reservoir is occasionally entrained through the intakes, which results in increased temperatures downstream. In all years, hourly water temperatures in the Revelstoke spawning area were typically below 12^{o}C, with maximum temperatures of 12.5^{o}C in 2009, 14.1^{o}C in 2010, and 16.1^{o}C in 2011 (Figure 7).

In 2010, Jordan River discharges were relatively low (below 20 m^3/s) throughout July and early August, with occasional short-term increases due to rain fall and high elevation snowpack melt (Figure 8). Two heavy rainfall events occurred in the latter part of August that resulted in short term increases in discharge up to 100 m^3/s before rapidly returning to base flow levels. In 2011, Jordan River discharges were initially high in July but steadily declined and dropped below 20 m^3/s in early August.

Temperatures in the Jordan River fluctuated on a daily basis, with increases over the day and decreases over the night (Figure 8), a reflection of the high altitude characteristics of the drainage basin. In both years, maximum and minimum temperatures ranged from approximately 6 ^{o}C to 14 ^{o}C.

Mean daily water temperatures in the Jordan River during the White Sturgeon spawning period in August over the 2009 to 2011 study period ranged between 8.3 ^{o}C to 13.7 ^{o}C although averaged values over the three years ranged from approximately 10 ^{o}C to 12 ^{o}C (Attachment A: Figure 2-1). Values of 12.5 ^{o}C and 9.0 ^{o}C were selected as the upper and lower temperature bounds in the 3D model to demonstrate effects on near-bottom water temperatures in the adjacent downstream early larval rearing area. Mean daily Columbia River temperatures in August were relatively stable around 11 ^{o}C.

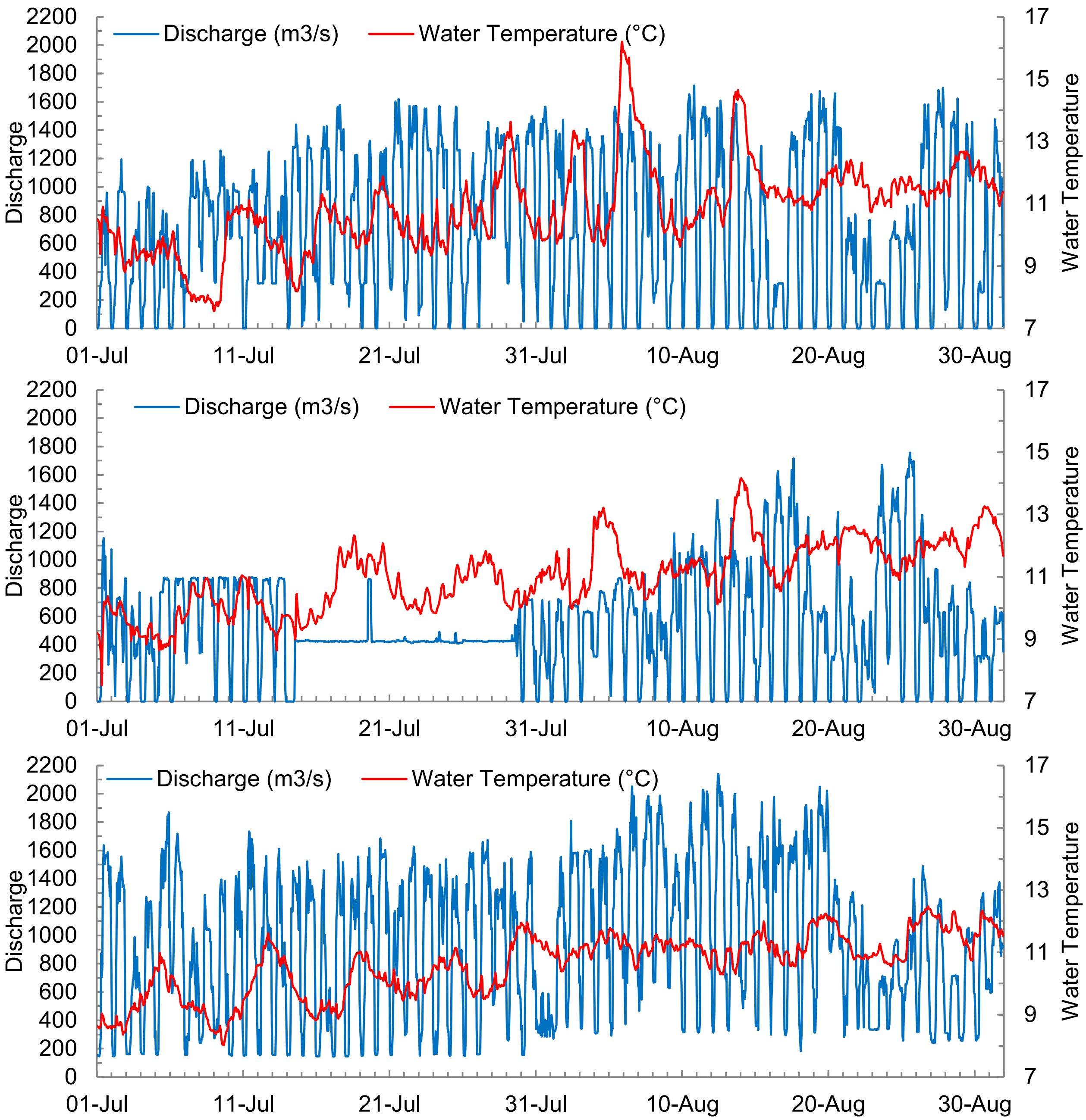
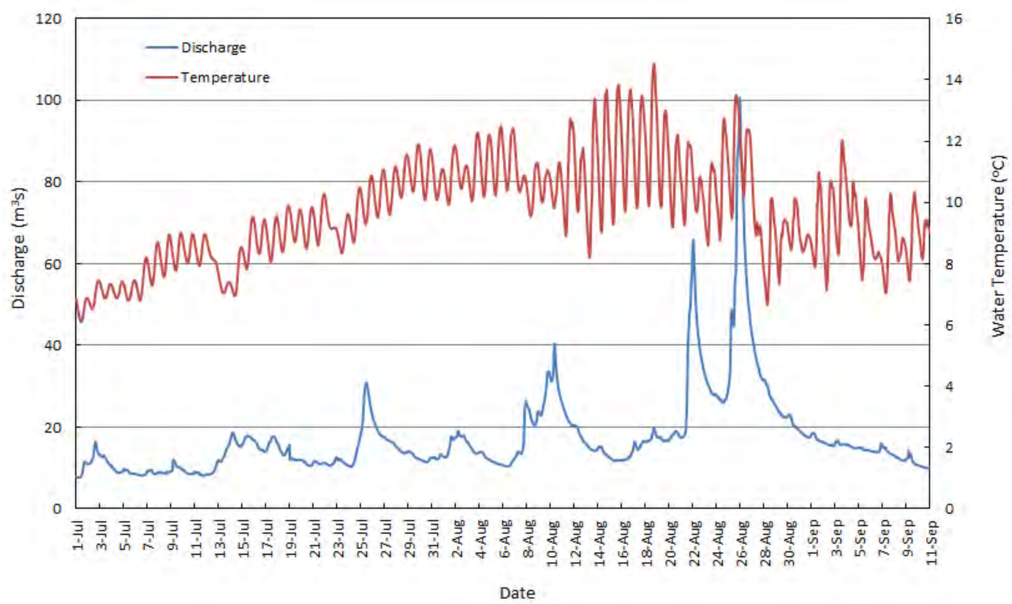


Figure 7: Hourly discharge from Revelstoke Dam and hourly water temperature at the Revelstoke spawning area during the July 1 to August 31White Sturgeon spawning periods in 2009 (top), 2010 (middle), and 2011(bottom). Vertical dashed bars represent estimated spawn timing; spawning was not recorded in 2010. From Golder (2010, 2011, 2012).



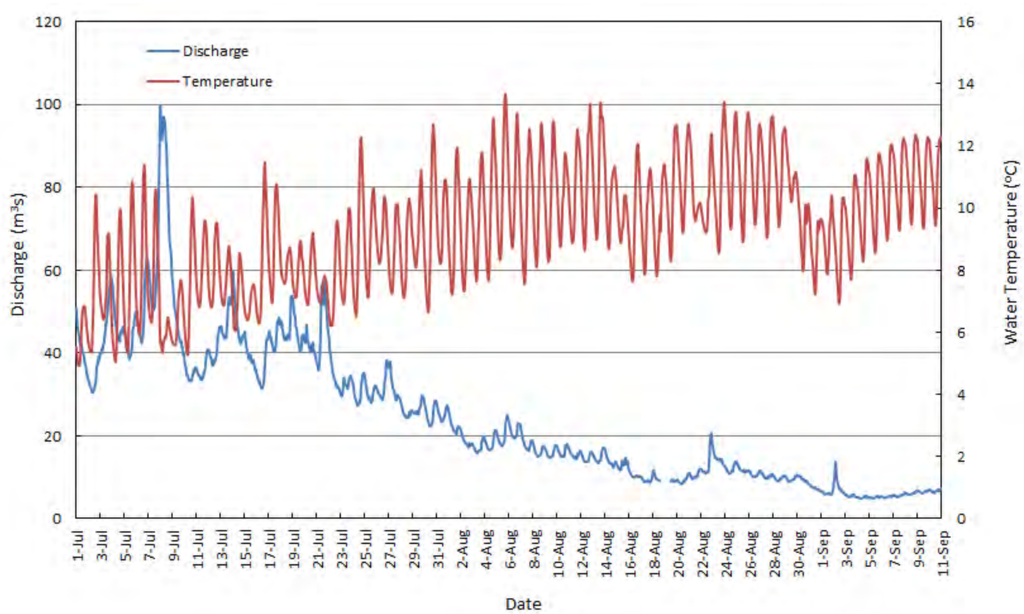


Figure 8: Jordan River Hourly discharge and temperature during the July 1 to August 31 White Sturgeon spawning periods in 2010 (top) and 2011 (bottom). Note: 2009 discharge data was unavailable.

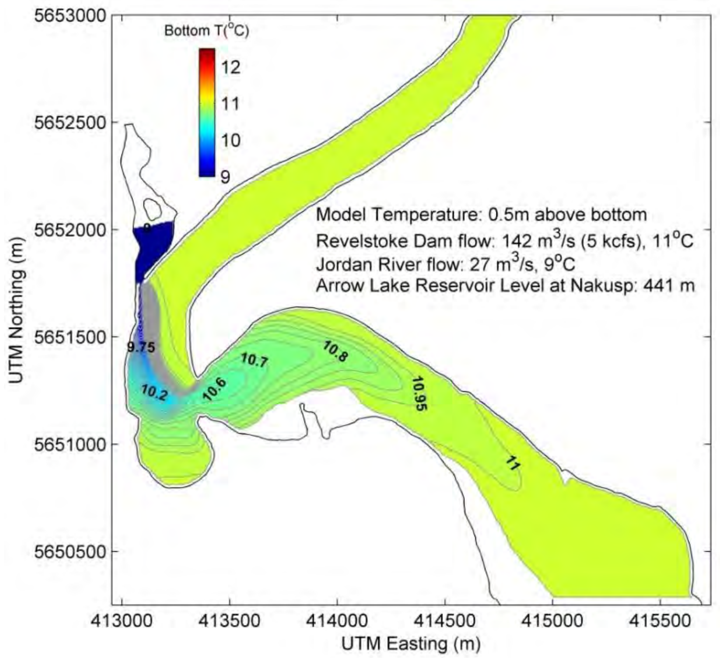
The effect of Jordan River inflows on water temperatures in the egg incubation and early larval rearing area was examined using 8 model runs (Attachment A: Section 2). Results indicated that for all the cases examined, the Jordan River had very minor effects on downstream water temperatures in the Columbia River. This is illustrated by the examples provided in Figure 9 that show that even at minimum Columbia River discharge and the maximum temperature differential of 2 °C between the two waterbodies, temperature changes in the downstream early larval rearing area were typically less than 1 °C. At high ALR levels, temperature effects quickly dissipated with downstream distance from the Jordan River mouth (Figure 9, upper panel). At low ALR levels, temperature effects persisted for greater distances downstream (Figure 9, lower panel).

The colder (9.0 ^{o}C) Jordan River water had a relatively larger influence on the near-bottom temperature of the Columbia River than the warmer (12.5 ^{o}C) Jordan River water, because of the higher density of the colder water relative to the Columbia River water temperature and density. There was no notable effect of the temperature difference on the magnitude or direction of the bottom flows in the study area.

5.2 Bathymetry

The river bathymetry within the 3D model domain transitions from a deeper, singular U-shaped channel in the upper section to a more braided channel form in the lower section (Figure 10). In the upper section, the single thalweg shifts from the north to the south shore, just upstream from where he majority of White Sturgeon eggs have been captured at egg mat sites set within the thalweg area adjacent to the south bank.

The Jordan River enters just upstream of Big Eddy, a large counter-clockwise gyre that exhibits the greatest depths (up to 30 m) within the study area. Downstream from Big Eddy, the river channel widens and becomes shallower with multiple channels and instream gravel bars. This change in morphometry of the downstream section reflects a combination of reduced bedrock control and the influence of high ALR levels during the summer period that create delta like conditions in this area.



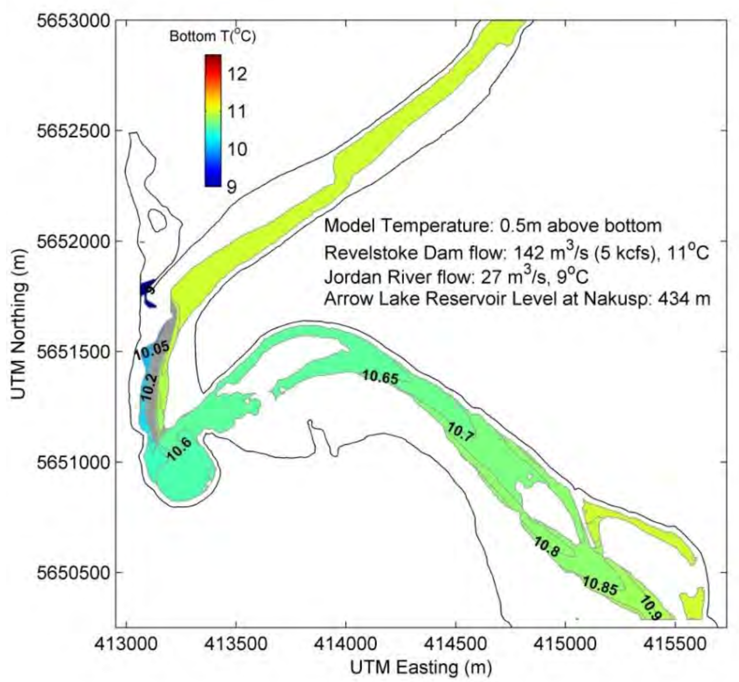


Figure 9: Effects of Jordan River flows on near bottom water temperatures in the White Sturgeon early larval rearing area at minimum Revelstoke Dam discharge and high (upper panel) and low (lower panel) ALR elevations. From Lin and Fissel (2014).

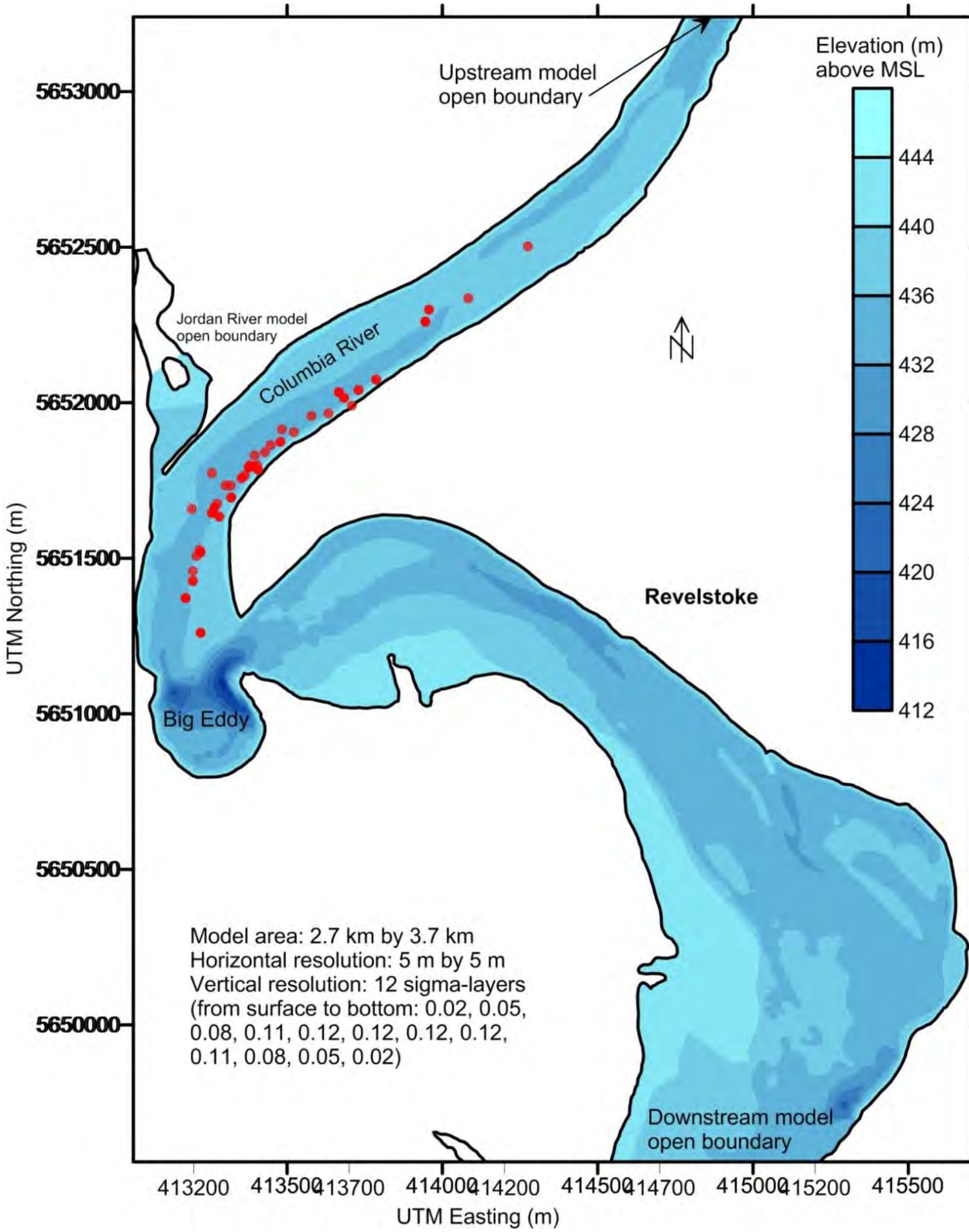


Figure 10: Study area boundaries and bathymetry (metres above mean sea level) as represented in the 3D model. The red dots represent sites where White Sturgeon eggs were captured on egg mats. Adapted from Lin and Fissel (2014).

5.3 Near-Bottom Velocities During Spawning

The 3D model was used to determine the near-bottom flow conditions at locations where White Sturgeon eggs were captured (Figure 10) and at the time that spawning occurred as determined by the back-calculation of developmental stages of captured eggs (Attachment A, Section 3, Figures 3.1 to 3.13). Discharge, water level, and water temperature conditions at the time of the 13 estimated spawning events were highly variable (Attachment A, Section 3, Table 3-3). Revelstoke Dam discharge and temperature ranged between 0 and 1520 m^3/s (mean = 730.9 ± 578.39 m^3/s) and 8.8 °C and 12.2 °C (mean = 10.8 °C ± 1.32 SD), respectively; Jordan River discharge and temperature ranged between 14.4 and 26.6 m^3/s (mean = 21.3 m^3/s ± 5.09 SD) and 9.4 °C and 11.4 °C (mean = 10.6 °C ± 1.12 SD), respectively; and ALR levels ranged between 436.0 and 440.0 masl (mean = 438.3 masl ± 1.36 SD). The Jordan River enters downstream from the White Sturgeon egg deposition and incubation area and consequently, does not affect flow and temperatures conditions in the spawning area regardless of ALR elevations or Revelstoke Dam discharge. The water temperatures in the egg deposition area were within, but at the lower end, of the reported spawning temperature range for White Sturgeon throughout the species geographic distribution (Hildebrand and Parsley 2013).

Of the 14 spawning events identified in the Revelstoke spawning area since 1999, seven were estimated to have occurred between midnight and 05:00h (Table 3). The occurrence of putative spawning events in the night during periods of very low or zero discharge from Revelstoke Dam is suspect, as White Sturgeon are known to select high velocity habitats for spawning (Hildebrand and Parsley 2013) and egg deposition in other known spawning areas in the Columbia River typically occurs in areas with near bottom velocities of >1.0 m/s (WEPC 2007; Golder 2013).

Table 3: Estimated timing of White Sturgeon spawning events based on the developmental stages of captured eggs and mean water temperatures in the Revelstoke spawning area (Golder unpublished data).

Spawning Event Number	Early Estimate		Mid-Estimate		Late Estimate	
	Date	Time	Date	Time	Date	Time
1	30/Jul/99	18:00	31/Jul/99	0:00	31/Jul/99	05:00
2	01/Aug/99	14:00	02/Aug/99	6:00	02/Aug/99	23:00
3	21/Aug/99	17:00	22/Aug/99	9:00	23/Aug/99	02:00
4	02/Aug/03	13:00	03/Aug/03	0:00	03/Aug/03	16:00
5	13/Aug/03	12:00	14/Aug/03	1:00	14/Aug/03	13:00
6[a]	ND	ND	ND	ND	ND	ND
7	31/Jul/08	11:00	31/Jul/08	16:00	31/Jul/08	22:00
8[b]	21/Aug/08	16:00	21/Aug/08	17:00	21/Aug/08	18:00
9	02/Aug/09	09:00	03/Aug/09	05:00	04/Aug/09	00:00
10	07/Aug/09	17:00	08/Aug/09	04:00	08/Aug/09	15:00
11	17/Aug/09	01:00	18/Aug/09	01:00	19/Aug/09	01:00
12[b]	30/Jul/11	01:00	30/Jul/11	03:00	30/Jul/11	05:00
13	20/Aug/11	07:30	20/Aug/11	10:30	20/Aug/11	13:30
14[c]	ND	ND	27/Aug/11	06:21	ND	ND

[a] Eggs damaged; stages could not be determined
[b] Based on the capture of recently fertilized eggs
[c] Based on the capture of one egg; range of estimates could not be determined

A possible explanation for this apparent anomaly is the highly variable hourly discharge regime combined with error in the estimator used to predict the exact hour that spawning (egg fertilization) occurred. Typically, egg mats were checked once per week and consequently, many of the eggs captured were in advanced stages of development and several developmental stages were identified (Golder 2011). This increased the potential for error when back-calculating spawn timing as is shown by the estimated uncertainty around the estimates in Table 3. For example, several of the spawning events were estimated to have occurred around midnight; discharge from Revelstoke Dam in August is typically reduced in late evening with lowest flows occurring between midnight and 06:00h. If these nighttime spawning events had occurred a few hours earlier, then discharges could have been substantially higher. A similar scenario applies to the several spawning events that were estimated to occur in the early morning between 03:00h and 05:00h. An example is spawning event #9 on August 2, 2009 that was estimated to have occurred at 05:00h (Figure 11, upper left panel). This was just a few hours before daily generation from Revelstoke Dam is typically increased in August and based on high level of uncertainty around the estimated time of this event, (± 19h; Table 3) it is assumed that it likely occurred when flows were higher.

The same explanation may not apply to event #12, estimated to have occurred on July 30, 2011 at 03:13h (see Attachment A, Section 3, Figure 3.11). The eggs from this event were recently fertilized with a low level of uncertainty (± 2h; Table 3). Although the 142 m^3/s REV5 minimum flow was in effect on that date, ALR levels were high (439.5 masl) and the modeled near-bottom velocities in the study area at that time were less than 0.4 m/s. The timing estimate for this event however, was based on two eggs and may not have represented the full range of developmental variability.

Based on the low (± 3h) estimated error bounds and the relatively high number of eggs (n = 27) used to estimate spawn timing for event #13 on August 20, 2011 at 10:26h (Table 3), the flow patterns depicted in Figure 11 (upper right panel) were considered as a reasonably accurate depiction of likely spawning conditions during this event. Event #8 on August 21, 2008 at 17:00h (Figure 11 , lower left panel), also was considered representative of likely spawning conditions during this spawning event. The 3 eggs collected from this event were recently fertilized and the estimated error bound around the timing was ± 1h (Table 3). However, as eggs were recorded in low numbers and at essentially the upper (1 egg from site 9) and lower (2 eggs from site 11) bounds of the egg deposition area, further inferences of spawning conditions during this spawning event are limited.

Even for spawning events estimated to have occurred during periods of higher Revelstoke Dam discharge (when sturgeon spawning would more typically be expected) some of the egg capture locations were in areas of low near-bottom velocity. This likely reflected the difficulty in maintaining egg collection mats in the thalweg. Typically, egg mats were deployed in or adjacent to the thalweg but due to high velocities and the relatively smooth armoured river bottom, the mats often shifted and when retrieved (i.e., when GPS locations were recorded), the mats has been pushed out of the thalweg and were located in calmer water near the bank. This is illustrated in Figure 11 (lower right panel), which shows the locations of three egg mats that captured eggs during the spawning event #1 on 31 July, 1999 at midnight. The modelled near-bottom velocities at these sites were: Site 3 = 0.23 m/s; Site 4 = 1.06 m/s; Site 5 = 1.55 m/s (Attachment A, Section 3, Table 3-4). All of these egg mats were initially deployed in higher velocity areas in the channel thalweg, at roughly equal distances from the bank; however, upon retrieval, Mats 3 and 4 had been pushed further inshore to lower velocity areas than Mat 5. As such, the location where the mat was retrieved may not have been the same location as where the eggs on the mat were captured.

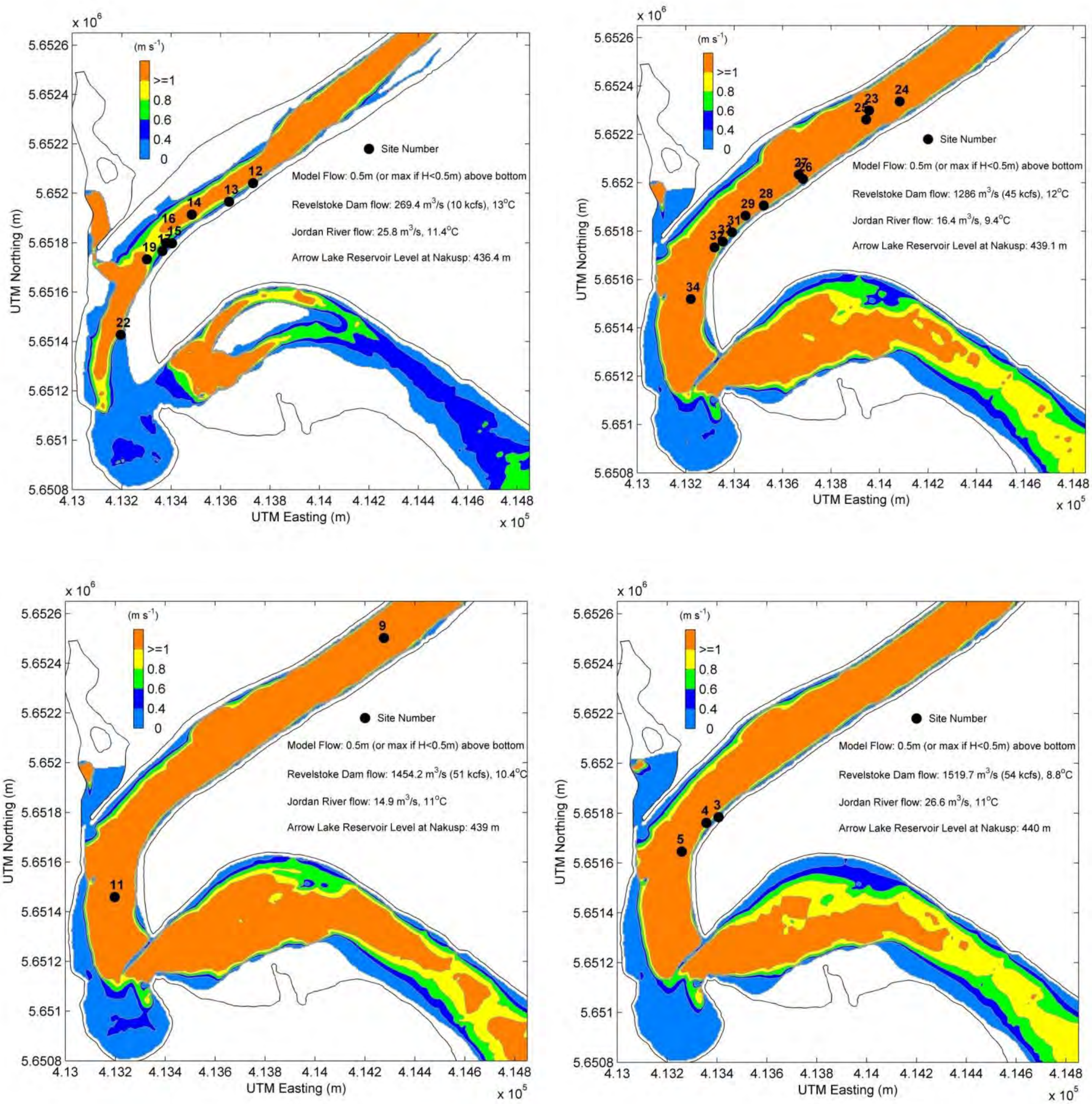


Figure 11: Near-bottom flow velocity plots of the Revelstoke White Sturgeon spawning and egg incubation area during Event #9 on August 3, 2009 at approximately 05:00h (upper left), Event #13 on August 20, 2011 at 10:26h (upper right), Event #8 on August 21, 2008 at 17:00h (lower left), and Event #1 on July 31, 1999 at 00:00h (lower right). The black dots are sites where eggs from each spawning event were captured. From Lin and Fissel (2014).

As a result of the potential confounding factors discussed above, many of the modelled near bottom flow velocities shown in Attachment A (Section 3, Figures 3-1 to 3-13), may not provide an accurate portrayal of near bottom flow conditions during each spawning event or at each actual egg collection location.

5.4 Near-Bottom Velocities During Egg Incubation

To examine the near-bottom velocity conditions experienced by incubating White Sturgeon eggs in the Revelstoke spawning area, the 3D model was used to calculate the hourly near bottom flow velocities at each of the egg capture sites for the 15 day period following each estimated spawning event (Figure 12). This period was selected based on data from Parsley et al (2011) that indicated the time for White Sturgeon eggs to hatch at 11°C, the average water temperature in the egg incubation area, was about 13 days post-fertilization.

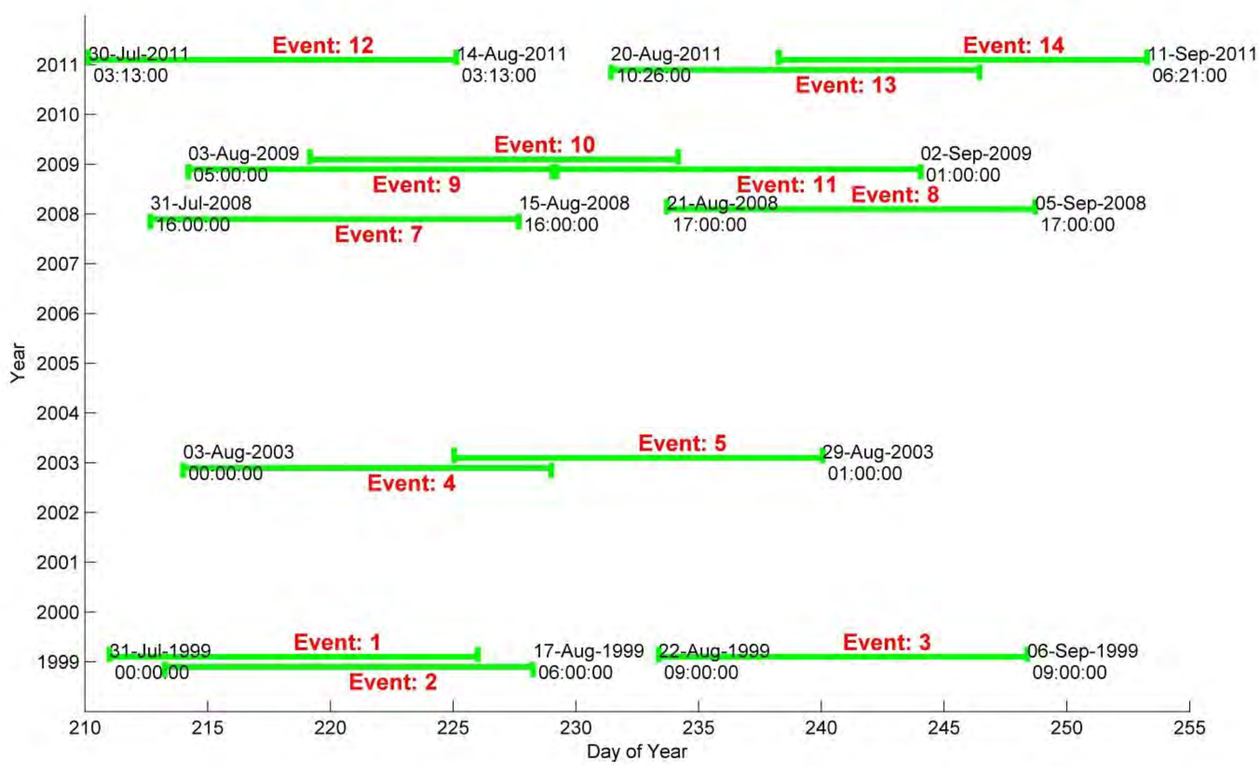


Figure 12: Estimated timing of documented White Sturgeon spawning events in the middle Columbia River and the subsequent 15 day egg incubation period after each spawning event. From Lin and Fissel (2014).

However, because of the long term study period, flow regimes were statistically estimated based on the empirical function derived from historical model results (Attachment A, Section 1, Tables 1-1 and 1-2, and Figure 1-5) for each selected egg mat site. The model cases were used to derive near-bottom velocity statistical relationships as a function of the total discharge of Revelstoke Dam and Jordan River, and Arrow Lake water level at Nakusp for the 34 selected egg mat sites that captured eggs from all the recorded spawning events. Derived empirical functions are provided in Attachment A (Appendix A); correlation coefficients (r^2 values) for these relationships ranged between 0.9469 and 0.9935, which indicated a high degree of correlation. The daily distributions of the near bottom flows at each of the 34 egg capture sites for the 15 day periods following each spawning event are provided in Attachment A (Appendix B).

The near bottom velocity distributions for over the 15 day egg incubation windows for each spawning event and at each egg capture site are provided in Attachment A (Appendix B) and summarized in Figure 13. There was considerable variability in cumulative distributions among years, which was a reflection of water availability and power demands. Years 1999, 2009, and 2011, had much higher proportions of hourly flows below the 1.0 m/s near bottom flow velocity threshold than 2003 and 2008 (Figure 13). In 2003, the greatest proportion of near bottom flow was in the 1.2 to 1.4 m/s flow bin and flows greater than 1.8 m/s were uncommon, whereas in other years, a range of all flow velocities was experienced by incubating eggs.

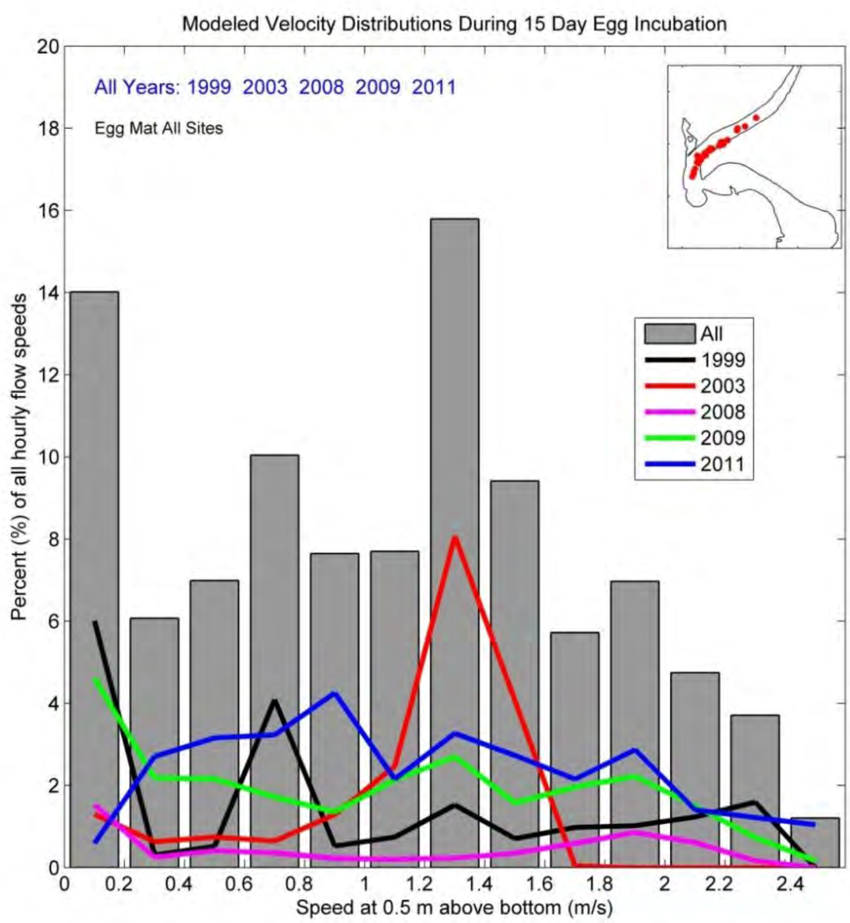


Figure 13: Near-bottom velocity distributions during the 15-day egg incubation window at each of the egg mat sites where White Sturgeon eggs were collected during all recorded spawning events. The grey bars are the cumulative values of the individual years. Map insert (top right) shows the locations of egg capture sites where the data in the figure were derived. From Lin and Fissel (2014).

For the reasons related to uncertainties in the estimation of spawn timing and the effects of altered egg mat locations between deployment and retrieval (as discussed in Section 5.3) caution should be used when interpreting the results of the near-bottom velocity distributions over the egg incubation periods.

5.6 Minimum REV5 Flow Effects

The effects of the 142 m^3/s (5000 cfs) REV5 minimum flow on near-bottom velocities were examined using the 3D model. Flow conditions were modelled for a range of High (H), Moderate (M), and Low (L) ALR levels and 0 m^3/s (the REV4 case of zero discharge from Revelstoke Dam but with seepage flows) and 142 m^3/s minimum flow (REV5 case) from Revelstoke Dam (Table 4). The areal extent of near-bottom flow velocity increments in the White Sturgeon egg deposition/incubation area (see Figure 2) and associated flow vectors are shown in Attachment A (Section 5, Figures 5-1 to 5-6) and are summarized in Table 4.

At high ALR levels, there was no difference in the areal extent of flow increments between the REV4 and REV5 minimum flow levels (Table 4). For the REV4 minimum flow case, at both Moderate ($M_{ALR}0_{REVQ}$) and Low ($L_{ALR}0_{REVQ}$) ALR levels, >94% of the study area experienced flows within the 0-0.5 m/s flow increment, a reflection of the low flow volume. For these cases, <6% of the total study area experienced flows greater than the 1.0 m/s velocity threshold for sturgeon spawning, with faster flows being restricted to the Jordan River confluence area and the upper portion of the early rearing area below Big Eddy (Figure 14).

Table 4: Model cases for the 0 m^3/s minimum flow (REV4) and the 142 m^3/s minimum flow (REV5) discharge (Q) showing the effects of the increased minimum flow on the areal extent of near-bottom flow velocity increments in the White Sturgeon spawning and early larval rearing areas. From Lin and Fissel (2014).

Model Run Designation	Revelstoke Dam Flow		Jordan River Flow (m^3/s) [a]	Arrow Lakes Reservoir Level at Nakusp (m)	Areal Extent (Percent of total area) of Flow Velocity Increments (m/s)					
	m^3/s	cfs			0-0.5	0.6-1.0	1.1-1.5	1.6-2.0	2.1-2.5	>2.5
$H_{ALR}0_{REVQ}$	0	0	19	441	100.00	0.00	0.00	0.00	0.00	0.00
$M_{ALR}0_{REVQ}$				437	97.03	1.11	0.77	0.51	0.58	0.00
$L_{ALR}0_{REVQ}$				434	94.78	1.38	0.96	0.97	1.70	0.22
$H_{ALR}5_{REVQ}$	142	5,000	19	441	100.00	0.00	0.00	0.00	0.00	0.00
$M_{ALR}5_{REVQ}$				437	37.23	41.36	20.24	0.83	0.34	0.00
$L_{ALR}5_{REVQ}$				434	28.38	38.64	25.28	6.55	1.07	0.07

[a] Daily average for August (range = 12.6 to 26.6 m^3/s).

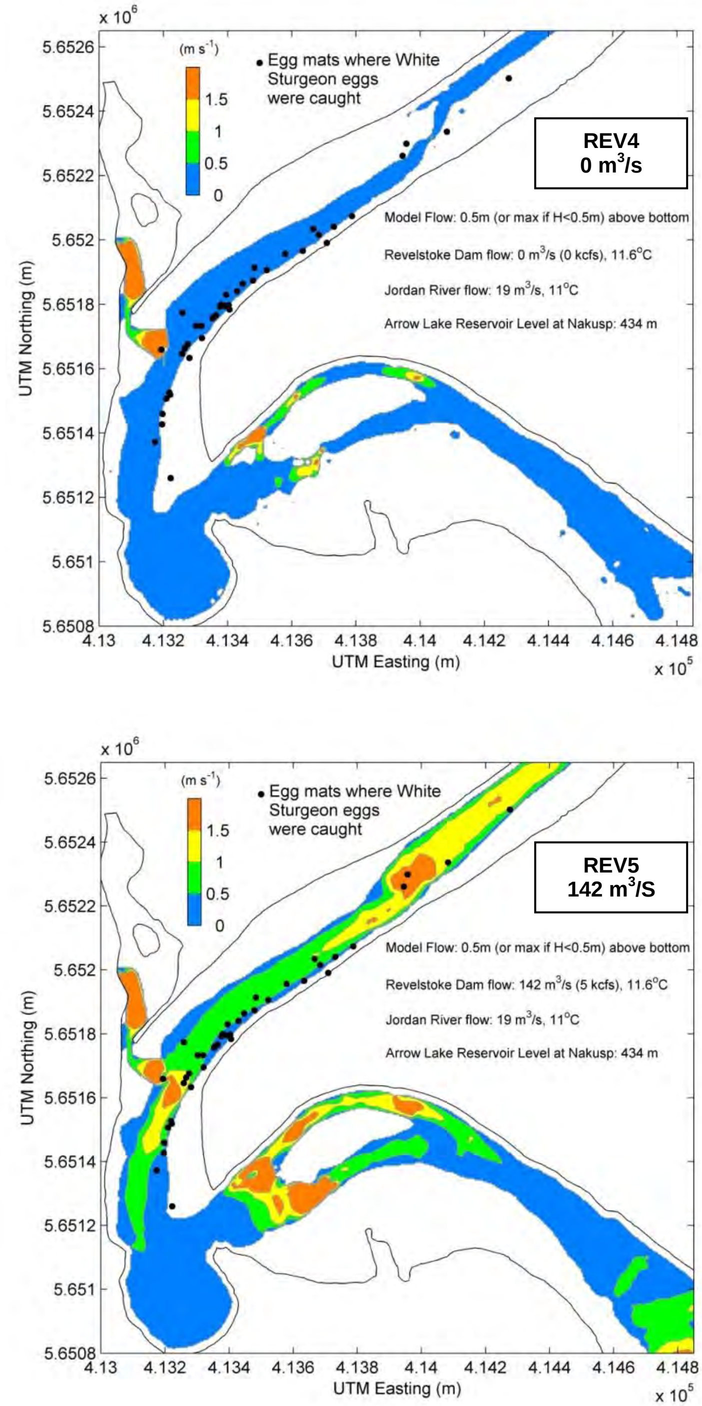


Figure 14: Near bottom flow velocities in the Revelstoke White Sturgeon spawning and early larval rearing areas at minimum Revelstoke Dam discharges of 0 m^3/s (REV4; upper panel) and 142 m^3/s (REV5; lower panel) and a Low Arrow Lakes Reservoir level. From Lin and Fissel (2014).

For the REV5 minimum flow case, there was a substantial increase in the areal extent of near bottom flows in the 0.6-1.0 m/s flow increment at both Moderate ($M_{ALR}5_{REVQ}$) and Low ($L_{ALR}5_{REVQ}$) ALR levels, as compared to the REV4 scenarios. The greatest increase in the proportion of the study area with flows >1.0 m/s occurred for the Low ($L_{ALR}5_{REVQ}$) ALR case where ~34% of the study area exhibited flows greater than this threshold (Table 4). Most of the increases in suitable spawning flows were recorded in the upper portions of the known spawning and early rearing areas (Figure 14).

5.7 PRE VS POST REV5 Flows

The effects of the incremental 424 m^3/s (15,000 cfs) increase in the maximum generation discharge capacity from REV4 [1699 m^3/s (60,000 cfs)] to REV5 [2124 m^3/s (75,000 cfs)] on near-bottom velocities in the spawning and early larval rearing areas were examined. Flow conditions were modelled for a range of High (H), Moderate (M), and Low (L) ALR levels and for the REV4 and REV5 discharges (Table 5). The areal extent of near-bottom flow velocity increments in the White Sturgeon egg deposition/incubation area (see Figure 2) and associated flow vectors are provided in Attachment A (Section 6, Figures 6-1 to 6-6) and summarized in Table 5.

Table 5: Model cases for the 1699 m^3/s (REV4) and 2124 m^3/s (REV5) cases showing the effects of the incremental 425 m^3/s increase in maximum Revelstoke Dam discharge capacity on the areal extent of near-bottom flow velocity increments in the White Sturgeon spawning and early larval rearing areas. From Lin and Fissel (2014).

Model Run Designation	Revelstoke Dam Flow		Jordan River Flow (m^3/s) [a]	Arrow Lakes Reservoir Level (m)	Areal Extent (Percent of total area) of Flow Velocity Increments (m/s)					
	m^3/s	cfs			0-0.5	0.6-1.0	1.1-1.5	1.6-2.0	2.1-2.5	>2.5
$H_{ALR}60_{REVQ}$	1699	60,000	19	441	12.85	19.93	48.70	18.53	0.00	0.00
$M_{ALR}60_{REVQ}$				437	10.55	9.00	10.88	16.42	37.81	15.34
$L_{ALR}60_{REVQ}$				434	10.61	8.93	10.77	16.08	37.34	16.28
$H_{ALR}75_{REVQ}$	2124	75,000	19	441	11.29	14.14	26.83	44.62	3.12	0.00
$M_{ALR}75_{REVQ}$				434	8.64	7.22	9.87	14.01	28.48	31.77
$L_{ALR}75_{REVQ}$				437	8.62	7.17	9.91	13.87	28.20	32.23

[a] Daily average for August (range = 12.6-26.6 m^3/s).

The effects of the incremental increase between the REV4 and REV5 maximum discharge capacities were not as clear as the effects of the REV4 compared to REV5 minimum flow scenarios discussed in Section 5.6. The greatest changes occurred between the High ALR cases for the two flow scenarios, where the areal extent of flows <1 m/s decreased about 7% from REV4 to REV5 (Table 5). However, differences in areal extents of flow velocity increments >1.0 m/s were not proportional to changes in either flow level or ALR level. For example, comparisons of the areal extents of the >1 m/s velocity increments at High and Low ALR levels, indicated that for the REV5 versus REV4 cases, areas of the 1.1-1.5 m/s and 1.6-2.0 m/s bins were slightly lower for REV5, areal extent of the 2.1-2.5 m/s bin was considerably lower for REV5, and the area of the >2.5 m/s increment was substantially greater for REV5 (Figure 15).

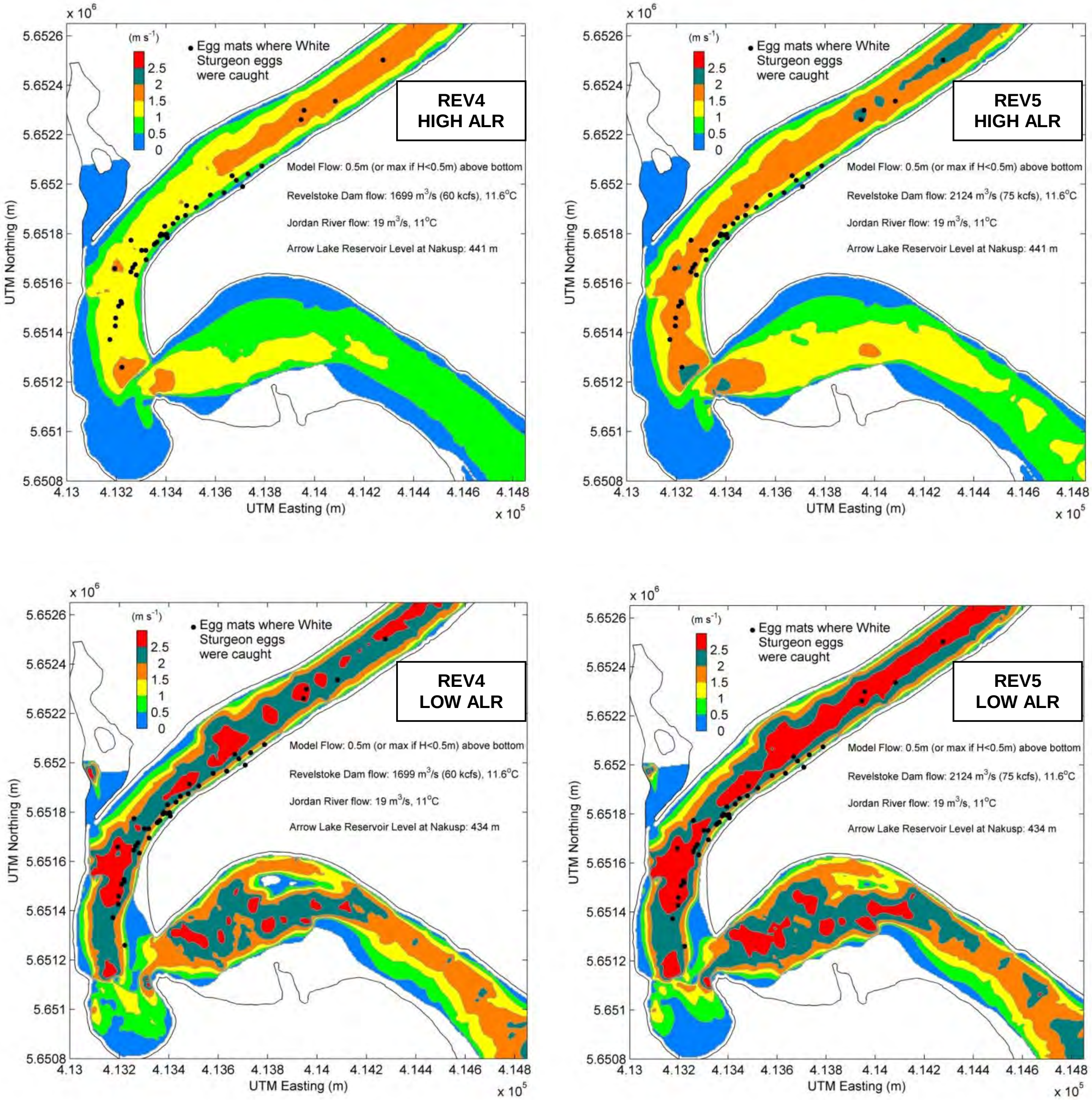


Figure 15: Differences in near bottom flow velocities in the Revelstoke White Sturgeon spawning and early larval rearing areas at High (top panel set) and Low (bottom panel set) ALR levels and maximum REV4 (left panel set) and REV5 (right panel set) discharges. From Lin and Fissel (2014).

The effects of the REV5 maximum discharge were most pronounced in the upper section of the egg deposition/incubation area during High ALR levels where there was a large increase in higher velocity area (Figure 15). During Low ALR levels, high velocities were prevalent throughout the study area and changes were more subtle and indicated more localized shifts in flow velocities.

5.8 Spawning Enhancement Flows

The effects of experimental flow releases from Revelstoke Dam proposed in the Columbia Water Use Plan Consultative Committee Report (2005) on near-bottom velocities in the White Sturgeon spawning and early larval rearing areas were examined for the 566 m^3/s (20,000 cfs) and 850 m^3/s (30,000 cfs) flow targets. Flow conditions were modelled for a range of High (H), Moderate (M), and Low (L) ALR levels and at 566 m^3/s and 850 m^3/s discharges from Revelstoke Dam (Table 6). The areal extent of near-bottom flow velocity increments in the White Sturgeon egg deposition/incubation area (see Figure 2) and associated flow vectors are shown in Attachment A (Section 7, Figures 7-1 to 7-6) and summarized in Table 6.

Table 6: Model cases for proposed 566 m^3/s and 850 m^3/s White Sturgeon spawning enhancement flows and the model results for areal extent of near-bottom flow velocity increments in the White Sturgeon egg deposition/incubation area. From Lin and Fissel (2014).

Model Run Designation	Revelstoke Dam Flow		Jordan River Flow (m^3/s) [a]	Arrow Lakes Reservoir Level (m)	Areal Extent (Percent of Total Area) of Flow Velocity Increments					
	m^3/s	cfs			0-0.5	0.6-1.0	1.1-1.5	1.6-2.0	2.1-2.5	>2.5
$H_{ALR}20_{REVQ}$	566	20,000	19	441	62.06	37.94	0.00	0.00	0.00	0.00
$M_{ALR}20_{REVQ}$				437	18.49	15.81	24.41	34.67	6.57	0.06
$L_{ALR}20_{REVQ}$				434	17.82	15.37	22.19	34.71	9.52	0.40
$H_{ALR}30_{REVQ}$	850	30,000	19	441	27.35	70.24	2.41	0.00	0.00	0.00
$M_{ALR}30_{REVQ}$				437	15.42	12.73	17.62	33.56	19.75	0.93
$L_{ALR}30_{REVQ}$				434	15.42	12.36	16.83	32.02	21.75	1.62

[a] Daily average for August (range = 12.6-26.6 m^3/s).

At High ALR levels, neither of the two proposed enhancement flows would provide an appreciable amount of sturgeon spawning habitat with near bottom velocities of >1.0 m/s (Table 6; Figure 16), although the 850 m^3/s flow provided a much larger areal extent of velocities in the 0.6-1.0 m/s increment. The greatest increases in areal extent of near bottom velocities >1.0 m/s for both scenarios would occur at Low ALR levels, with the largest increase provided by the 850 m^3/s enhancement flow.

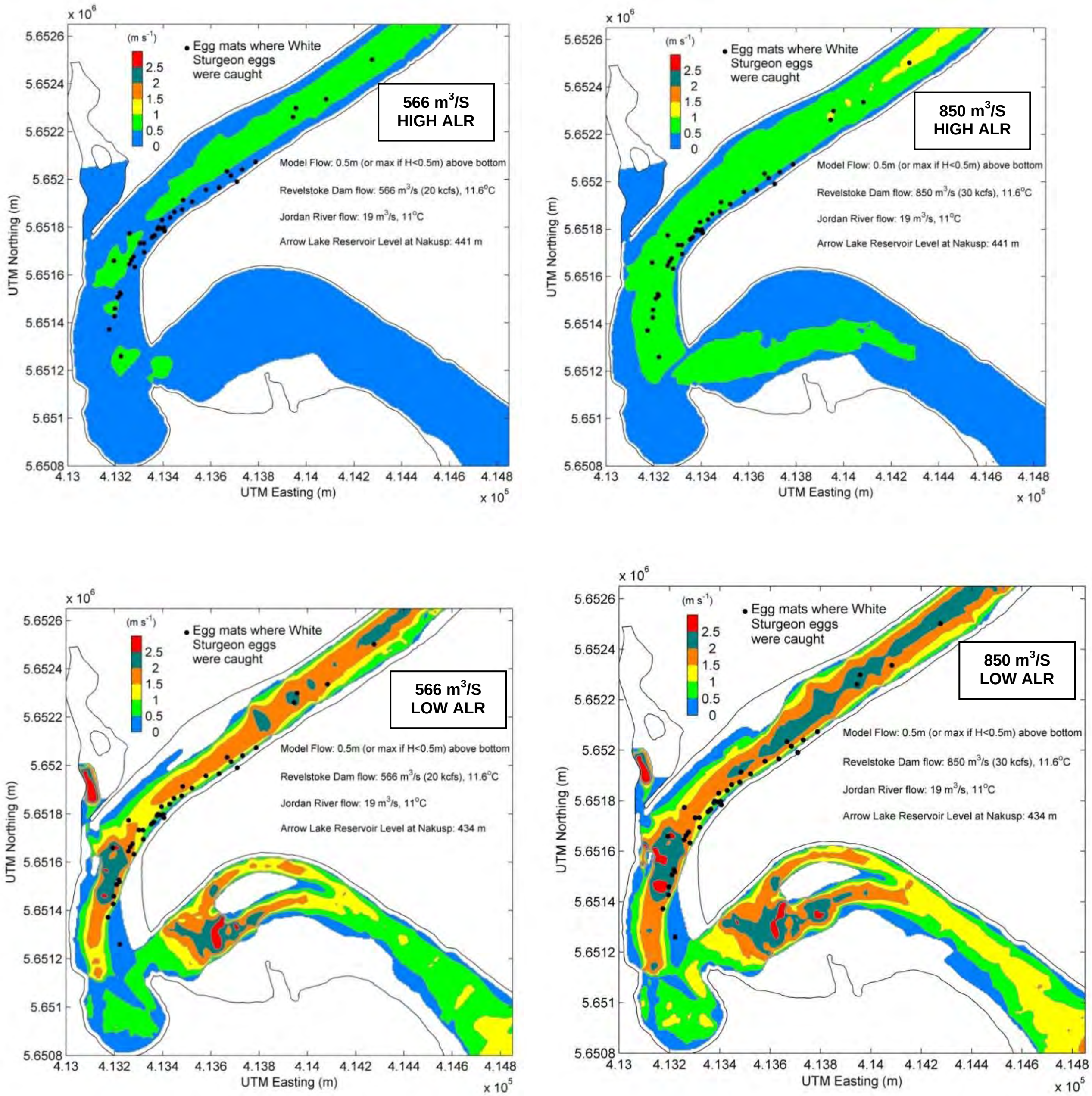


Figure 16: Differences in modeled near bottom flow velocities in the Revelstoke White Sturgeon spawning and early larval rearing areas at proposed White Sturgeon spawning enhancement flows of 566 m^3/s (left panel set) and 850 m^3/s (right panel set) and High (top panel set) and Low (bottom panel set) ALR levels. From Lin and Fissel (2014).

5.9 Effects of REV5 Discharges on Riverbed Substrates

The objective of this modeling component was to examine the effects of the full 2124 m^3/s (75,000 cfs) discharge capacity of Revelstoke Dam with the fifth generation unit (REV5) in operation on the substrate size composition and distribution in the White Sturgeon spawning and early larval rearing areas (Figure 3). Two model cases were conducted with the sediment transport module of the 3D model activated (Table 7). The cases selected were associated with PRE (1699 m^3/s) and POST (75,000 cfs) REV5 flow conditions and low ALR levels (434 m) to represent the highest flow velocity conditions with the greatest potential to alter substrate composition and distribution in the study area.

Table 7: Hydrodynamic conditions during the videography survey and the parameters that were used in the PRE and POST REV5 model runs. From Lin and Fissel (2014).

Model Run Designation	Revelstoke Dam Discharge		Arrow Lake Level at Nakusp (masl)	Jordan River Flow (m^3/s) [a]	Columbia River Temperature (°C)	Jordan River Temperature (°C)
	(m^3/s)	(cfs)				
Verification 2 Run[a]	1274	45,000	435.6	19.0	11.6	11.0
PRE REV5 Model Run	1699	60,000	434.0	19.0	11.6	11.0
POST REV5 Model Run	2124	75,000	434.0	19.0	11.6	11.0

[a] Conducted at similar conditions as the videography survey

Selected images from the 34 videography transects were examined to obtain the sediment distribution data needed for the modeling study on bottom substrate erosion and deposition. The analysis methods used to interpret the video imagery collected on September 11 to 13, 2010 and calibrate the image analysis process are described in Attachment A (Section 8). The primary bottom sediment size distribution as determined from the videography was compared with modeled near bottom velocities along the selected transects and with sieve analysis results from five sediment samples collected within the study area (Figure 5). The model near bottom flow results were from the Verification 2 run, which modeled hydrodynamic conditions similar to those in effect during the videography survey (Table 7).

Data derived from videography frames for areas where near bottom velocities were less than 1.8 m/s indicated the percentage of fine-grained sediment (coarse sand, fine sand, and silt and clay) was negatively correlated with the near bottom velocities with a proportionately larger percentage of gravel (Attachment A, Section 8, Figure 8-4). For the areas where near bottom flow was >1.8 m/s, the data exhibited a large amount of scatter, with no apparent relationship between the flow speed and sediment size distributions (not shown). These results indicated that the stronger the near bottom flow, the lower proportion of fine grained bottom sediment.

Although qualitative, the model results suggested the effects of the maximum 2124 m^3/s REV5 discharge on bottom erosion and deposition in the White Sturgeon spawning/egg incubation and early rearing area were relatively minor (Figure 17). As presented in Figure 17, bottom sediment was suspended in the blue areas, transported by the flow, and re-deposited in the yellow and red areas. For total sediment, erosion and deposition were less than 0.5 meters in most areas with most erosion upstream of Big Eddy and most deposition just before the water flows through the narrow channel downstream to the Big Eddy. Most suspended sediment was deposited along the east bank near the Golf Course in the following areas as shown in Figure 17:

A: upstream from the Jordan River confluence.

B: downstream from the Jordan River confluence and upstream from Big Eddy.

C: shallow areas in the wide channel downstream from Big Eddy.

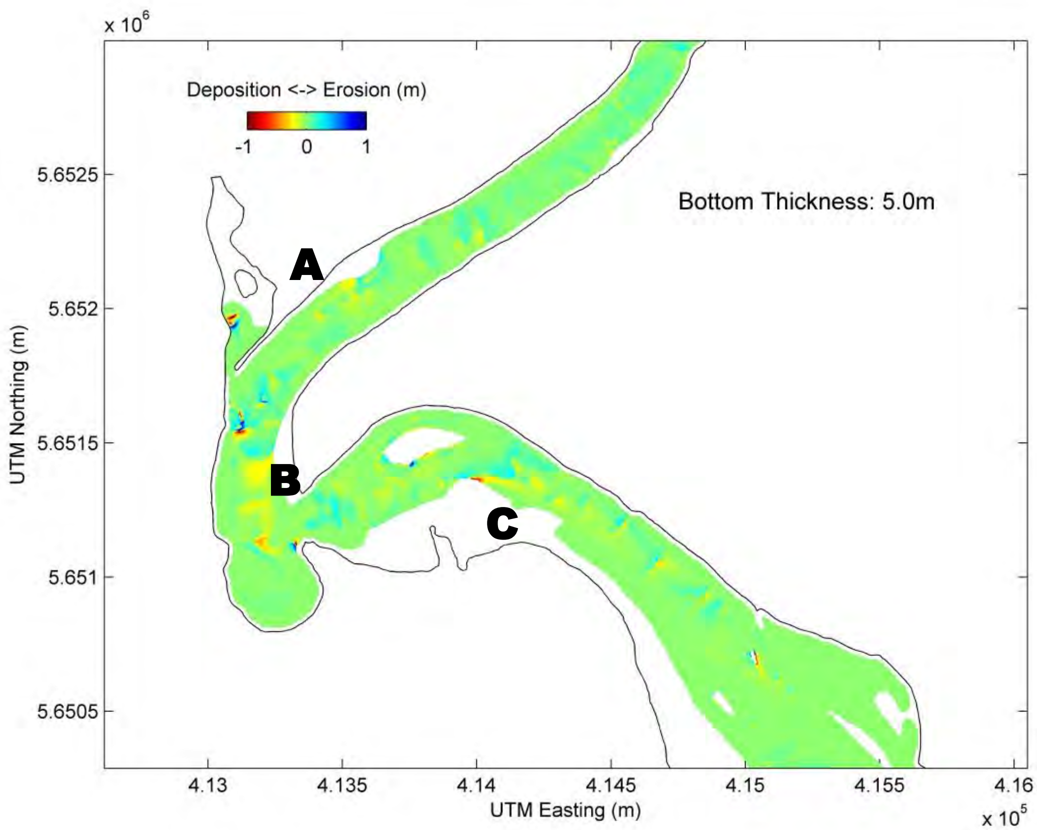


Figure 17: Difference between POST REV5 Model Run and PRE REV5 Model Run for total sediment. From Lin and Fissel (2014).

Differences in erosion and deposition between PRE and POST REV5 for fine-grained sediments (coarse sand, fine sand, and silt and clay) are provided in Attachment A (Section 8, Figures 8-8 to 8-10). The greatest effect of the POST REV5 flow was the erosion of fine sand upstream from the Jordan River confluence and the deposition of this material along the east bank near the Golf Course to the north of the Big Eddy (area B on Figure 17). The effect of the POST REV5 flow on larger substrates (gravels and cobbles) was negligible over the whole model domain (not shown).

5.10 Larval Dispersal Patterns

In total, 37 larvae have been captured in the study area since spawn monitoring began in 1999: 1 larva in 2003, 18 in 2009; 11 in 2007, and 7 in 2012 (Table 1). For the 18 white sturgeon free embryos captured in 2009, one was caught on August 13 and the other 17 were caught on August 20 (Golder 2010). Although in poor condition due to damage during capture, 16 larvae were estimated to be 0 to 1 days post-hatch (dph) and 2 larvae were 1 to 2 dph. The 11 larvae captured in 2011 were all caught on September 6 and of the larvae that could be staged, 7 were 1 dph, and 2 were 2 dph (Golder 2012).

In 2009, all the larvae were captured in D-ring sets just upstream from Big Eddy near Transect 13 (Figure 3). In 2011, nine larvae were captured from this same area but two were captured further upstream adjacent to the east shore near Transect 7. All larvae were free embryos that retained their yolk-sac. This life stage typically exhibits hiding behaviour in the substrate interstices until the yolk-sac is absorbed and the larvae enter the drift to seek suitable feeding habitats downstream of the spawning and early rearing area (Hildebrand and Parsley 2013). Their capture in the D-ring drift nets at early stages of development suggested they either were involuntarily displaced after hatch or volitionally entered the drift, possibly in search of more suitable hiding habitat

As discussed in Attachment A (Section 9), modeled results of particle tracking were used to demonstrate effects of various REV flows on dispersal patterns of feeding White Sturgeon larvae. Larval characteristics were simulated as a “particle” with a grain size of 13.38 +/- 0.299 mm, a neutral granular density, and a larval mass of 0.024 +/- 0.001 g (J. Crossman, BC Hydro, pers. comm., Sep. 2013). The larvae were “released” in the model at 0.5 m above the bottom at each of the 34 egg mat sites where eggs were captured (see Figure 10) to best simulate free embryos that either had absorbed their yolk sac and volitionally entered the drift as feeding larvae or were involuntarily displaced (i.e., due to high flows or unsuitable hiding habitat).

In total, 15 model runs (Table 8) with the particle tracking module activated were run at Columbia River discharges of 142 m^3/s (minimum REV5 flow), 566 m^3/s and 850 m^3/s (sturgeon spawning enhancement flows), 1699 m^3/s (REV4 maximum discharge), and 2124 m^3/s (REV5 maximum discharge). Each discharge was modeled at low, moderate, and high ALR levels and over 15, 30, 60, 90 and 180 min periods. The model assumed that the larvae remained in the drift within the lower 1 m depth interval over the entire time examined (i.e., larvae did not resettle on the bottom).

The simulated movement tracks of larvae “released” from each of the 34 egg mat locations where eggs where captured are presented by time-lapse snapshots in Attachment A (Appendix C). These tracks represent the start and end points of the drifting larvae for each run. For discussion purposes, the 34 release locations examined by the model were combined into six groups based on similarities of channel depth and location, and the features of the larval dispersal tracks (Table 9; Figure 18).

Table 8: Summary of model cases and conditions used to examine White Sturgeon larval dispersal patterns. From Lin and Fissel (2014).

Model Cases	Revelstoke Dam Flow		Jordan River Flow (m^3/s)	Arrow Lakes Reservoir Level at Nakusp (masl)
	m^3/s	cfs		
$H_{ALR}5_{REVQ}$	142	5,000	19	441
$M_{ALR}5_{REVQ}$	142	5,000	19	437
$L_{ALR}5_{REVQ}$	142	5,000	19	434
$H_{ALR}20_{REVQ}$	566	20,000	19	441
$M_{ALR}20_{REVQ}$	566	20,000	19	437
$L_{ALR}20_{REVQ}$	566	20,000	19	434
$H_{ALR}30_{REVQ}$	850	30,000	19	441
$M_{ALR}30_{REVQ}$	850	30,000	19	437
$L_{ALR}30_{REVQ}$	850	30,000	19	434
$H_{ALR}60_{REVQ}$	1699	60,000	19	441
$M_{ALR}60_{REVQ}$	1699	60,000	19	437
$L_{ALR}60_{REVQ}$	1699	60,000	19	434
$H_{ALR}75_{REVQ}$	2124	75,000	19	441
$M_{ALR}75_{REVQ}$	2124	75,000	19	437
$L_{ALR}75_{REVQ}$	2124	75,000	19	434

Table 9: Descriptions of the six groups used to examine White Sturgeon larval dispersal patterns.

Group#	Egg Collection Site#	Water Depth (m)	General Description of "Release" Area
1	9,23,24,25	2.8-3.0	Upper section of spawning area; Offshore
2	1,3,6,12,13,15,26,28	0.9-4.6	Upper section of spawning area: Nearshore
3	4,7,8,16,17,20,29,31,33	2.0-3.8	Middle section of spawning area: Nearshore
4	14,18,27,30	4.1-4.6	Middle section of spawning area: Offshore
5	5,10,19,32	3.2-3.5	Lower section of spawning area: Offshore
6	11,21,22,34	2.0-2.9	Lower section of spawning area: Midchannel

As expected, there was a strong relationship between the downstream distance travelled by the drifting larvae and the combination of Revelstoke Dam discharge and ALR levels. At high ALR levels and a minimum discharge of 142 m^3/s, even after 3.0h, larvae from the upper end of the spawning area (Group 1) only drifted as far as the river bend at Big Eddy, a distance of about 0.9 km (Figure 19, Panel 1). Larvae from the lower portion of the spawning/egg deposition area (Group 6) drifted around the corner at Big Eddy and into the upper section of the putative larval rearing area in the bottom half of the study area (Figure 19, Panel 2). Distance drifted at the high ALR level increased with higher Revelstoke Dam discharges. At 850 m^3/s and high ALR levels, most larvae from the upper portion of the spawning/egg deposition area (Group 1) had drifted into the early rearing area (Figure 19, Panel 3) and those from the lower area (Group 6) had drifted out of the study area (Figure 19, Panel 4). At the full REV5 discharge of 2124 m^3/s, most of the larvae from all locations had drifted out of the study area after 3.0h (Figure 19, Panels 5 and 6), although the model indicated some became entrained and trapped in small eddies along the north bank (see Attachment A, Appendix C, Part 4).

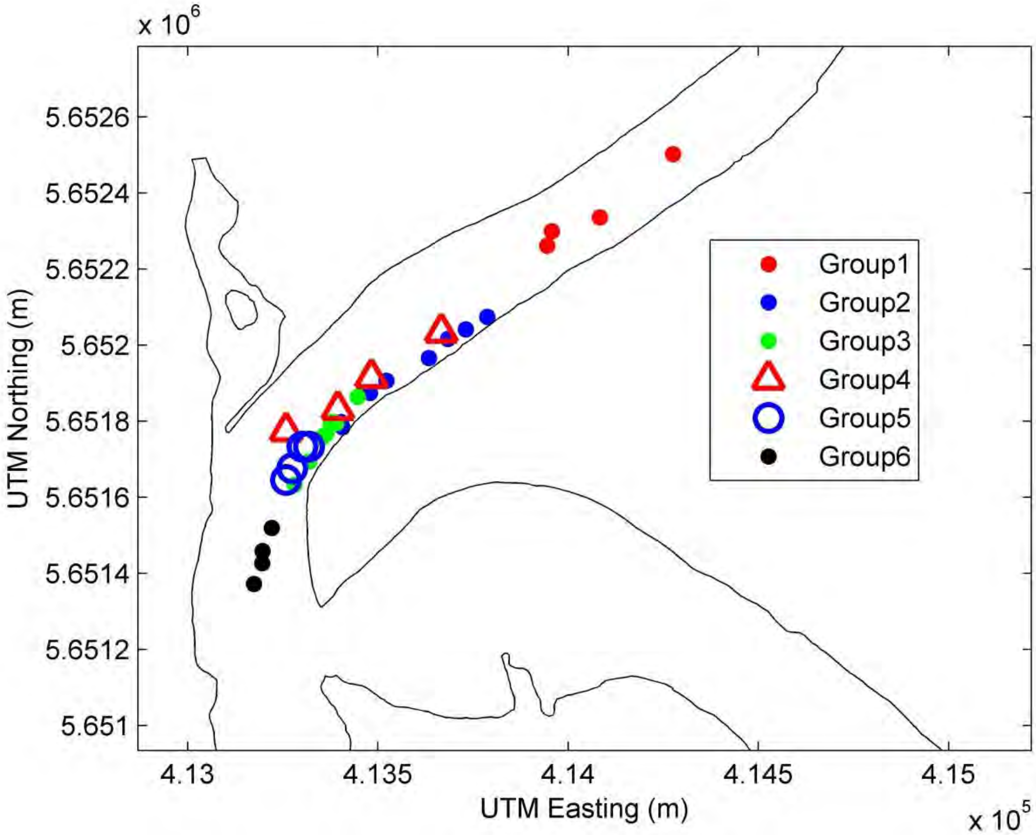


Figure 18: Locations of the six groups used to examine White Sturgeon larval dispersal patterns.

At low ALR levels and a minimum discharge of 142 m^3/s, after 3.0h none of the larvae from any location had drifted downstream past Big Eddy (Figure 20, Panel 1). For this scenario, Big Eddy expanded upstream and all the larvae from all of the groups became entrained in the eddy. At low ALR levels (i.e., without the backwater influence of ALR), one would expect larval drift distance would rapidly increase with increased discharge levels; however, this was not the case. At discharges of 566 m^3/s and 850 m^3/s, larvae from all locations did drift downstream but were then entrained into Big Eddy where according to the model, they remained trapped for the duration of the 3.0h model run (Figure 20, Panels 2 and 3).

At discharges of 1699 m^3/s and 2124 m^3/s, larvae drifted downstream out of the spawning/egg deposition area into the upper portion of Big Eddy but were then deflected and continued to drift downstream into the early rearing area (Figure 20, Panels 4 and 5). Most larvae drifted out of the study area, although similar to the high flow high ALR scenario discussed above, some became entrained and trapped in small eddies along the north bank.

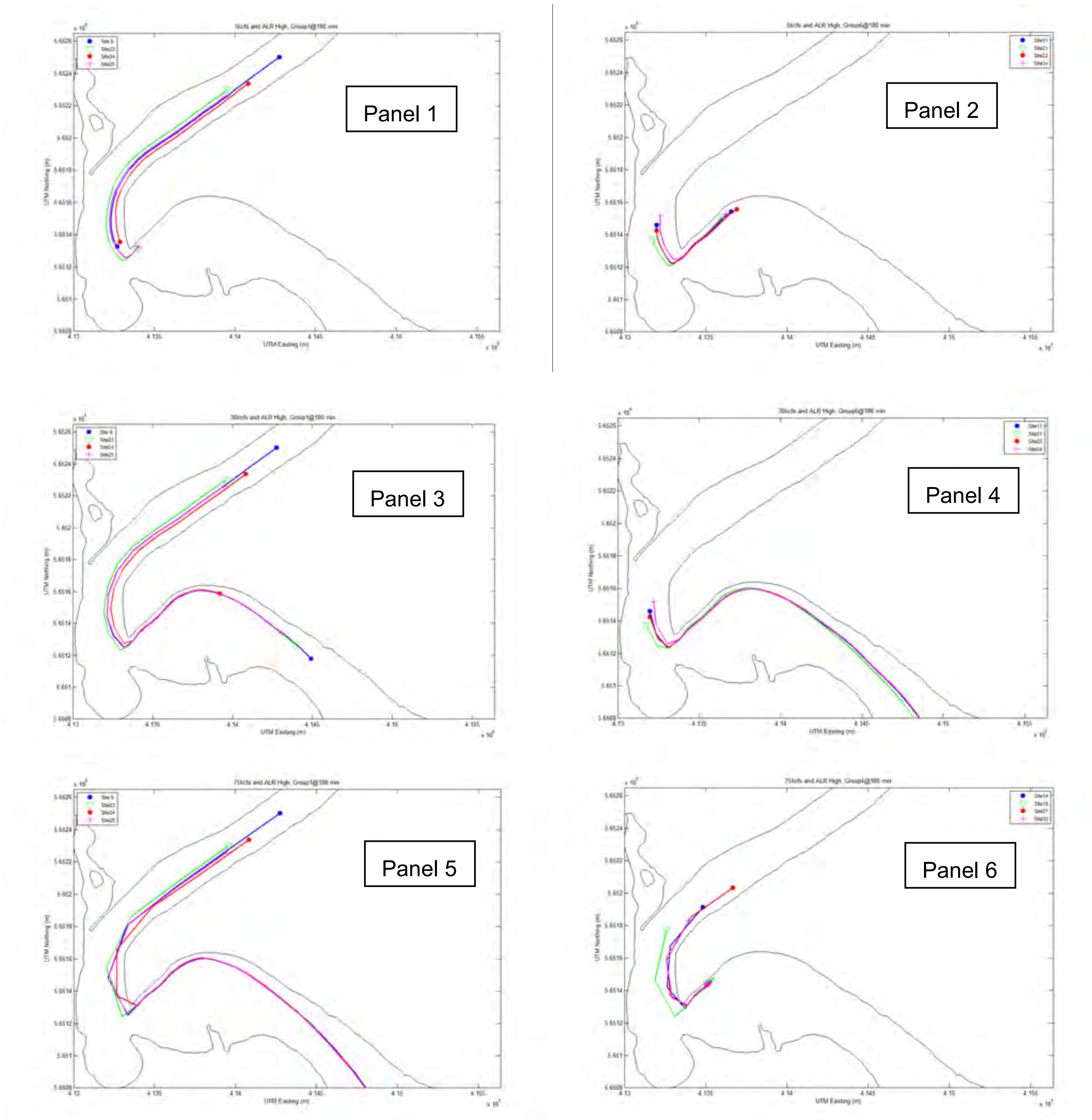


Figure 19: Examples of White Sturgeon larval drift patterns for release group 1 at different Revelstoke Dam discharges and high ALR levels. From Lin and Fissel (2014).

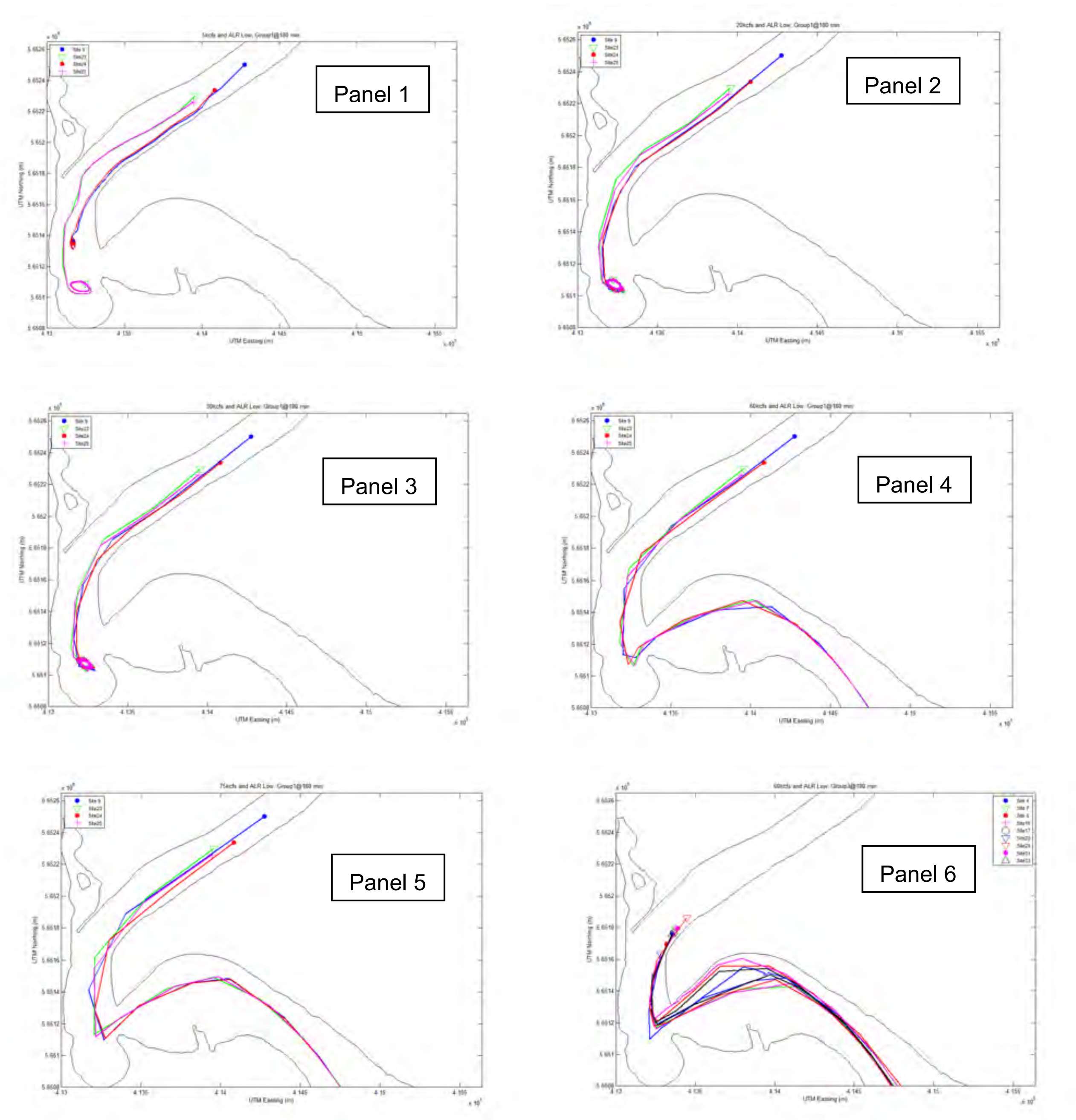


Figure 20: Examples of White Sturgeon larval drift patterns for various release groups at different Revelstoke Dam discharges and low ALR levels. From Lin and Fissel (2014).

There also was relationship between the rate of downstream larval drift and the combination of Revelstoke Dam discharge and ALR levels. These relationships were illustrated using animated GIF files to show the drift speeds of a larval sturgeon that emerged from the substrate at egg mat site #23 (i.e., within Group #1; see Figure 18) and then drifted either near bottom or near surface under a range of Revelstoke Dam discharges (142, 850, and 1699 m^3/s) at either High and Low ALR levels (Appendix B). The model was allowed to run for a maximum of 10 hours or until the larvae had drifted out of the study area. Brief descriptions of the larval drift pattern under each scenario are provided in (Table 10).

Table 10: Descriptions of White Sturgeon larval drift patterns modeled for a range of Revelstoke Dam discharges, at high and low Arrow Lakes Reservoir levels, and near the top and bottom of the water column.

Revelstoke Dam Discharge (m^3/s)	Arrow Lakes Level[a]	Location in Water Column[b]	Description of Larval Drift Pattern[c]
142	High	Bottom	Slow downstream drift in mid-channel and then around corner along north bank by 5 h and then very slow drift along north shore for 5 h
		Surface	Slow downstream drift in mid-channel and then towards west bank by 2.5 h and then stalled in upper portion of Big Eddy for remaining 3.5 h
	Low	Bottom	Moderate downstream drift in mid-channel and then at 1 h entrained into center of Big Eddy where it remained for the remaining 5 h
		Surface	Same pattern as for bottom drift but entrained in a small nearshore eddy in the upper northwestern corner of Big Eddy where it stayed for remainder of run
850	High	Bottom	Rapid downstream drift in mid-channel and to top edge of Big Eddy within 0.5 h; moved more slowly around corner and along north shore before increasing speed and exiting study area after about 3 h
		Surface	Rapid downstream drift in mid-channel and to top edge of Big Eddy within 0.3 h; then diverted towards west shore and entrained within Big Eddy where it remained for remainder of run
	Low	Bottom	Rapid downstream drift in mid-channel and into central portion of Big Eddy within 0.2 h where it remained for remainder of run
		Surface	Same pattern as seen for bottom drift but entrained into west side of Big Eddy where it remained for remainder of run
1699	High	Bottom	Rapid downstream drift in mid-channel and to top edge of Big Eddy within 0.3 h; moved more slowly around corner and along north shore before increasing speed and exiting the study area after about 2 h
		Surface	Rapid downstream drift in mid-channel and into central portion of Big Eddy within 0.3 h where it remained for remainder of run
	Low	Bottom	Very rapid downstream drift in mid-channel and to top edge of Big Eddy within 0.2 h; moved rapidly around the corner and along the north shore before exiting the study area after about 0.5 h
		Surface	Very rapid downstream drift in mid-channel and to top edge of Big Eddy within 0.2 h and into western edge of Big Eddy where it remained for remainder of run

[a] High Arrow Lakes Reservoir elevation (441 masl); Low Arrow Lakes Reservoir elevation (434 masl)
[b] Bottom = within 0.5 m of the river bed; Surface = within 0.5 m of the river surface
[c] Brief description based on the GIF files provided on the CD in Appendix B; most model runs were conducted over a 10 h duration

In general, drift rate increased with increased Revelstoke Dam discharge and at any given discharge, was faster at low ALR levels than at high levels. For the slowest scenario (142 m^3/s and High ALR), larvae that entered the drift near egg mat site #23 and drifted along the bottom were still situated within the lower third of the study area after 10 h (Table 10). Conversely, for the fastest scenario (flow of 1699 m^3/s and Low ALR), these same larvae could have drifted out of the study area in about 0.5 h. Although specific studies to determine the distribution of

White Sturgeon yolk sac larvae within the water column have not been done, White Sturgeon larval sampling programs elsewhere in the Columbia River have reported highest capture rates near the river bottom during the drift period, which suggests a benthic orientation (Parsley et al. 1993; Howell and McLellan 2008). In studies on other sturgeon species, results suggest drift can occur throughout the water column depending on river hydraulics (Caroffino et al. 2009).

For all three discharges examined in the present study, larvae that drifted near bottom (i.e., 0.5 m off-bottom) during periods of high ALR levels remained in the drift and were ultimately transported downstream into or through the putative early rearing area. At low ALR levels and discharges of 142 m^3/s and 850 m^3/s, the larvae were entrained into Big Eddy; however, at the 1699 m^3/s flow, larvae were transported downstream from the egg incubation area and into the upper part of Big Eddy but were then deflected and continued to drift downstream into the early rearing area.

Some larvae that initiate drift near the bottom may potentially be caught up in vertical eddies and non-volitionally transported to near the water surface. The model indicated that larvae that drifted near the surface were consistently entrained into Big Eddy at all the Revelstoke discharges and ALR levels examined (Table 10; Appendix B).

Drift tracks also varied with Revelstoke Dam discharge and ALR levels. At high ALR levels for all flow scenarios, the predominant drift track for all larval locations was typically along the left bank (as viewed facing downstream) as shown in Figure 19, Panels 4 and 5). This contrasts with the predominant mid-channel drift track for most of the discharge scenarios at the low ALR level, which often resulted in larvae being entrained into Big Eddy (Figure 20, Panels 1 to 3). There was also more diversity in drift tracks for the low ALR level runs; Figure 20, Panel 6 shows the drift patterns of Group 4 around a mid-channel bar at a low ALR and a discharge of 1699 m^3/s.

The reason for differences in drift patterns can be seen in the velocity vector plots in Attachment A (Section 6, Figures 6.1 to 6.3), which show that at high ALR levels, near-bottom flows through the spawning/egg deposition area are relatively uniform across the channel but as the river bed approaches Big Eddy, the flows are deflected northward towards the left bank and away from the eddy. Conversely, at moderate and low ALR levels, the higher near-bottom velocities through the spawning/egg deposition area are not deflected to the same degree by the eddy and as a result, some larvae are entrained while others are deflected and carried downstream in mid-channel where the strongest velocities occur.

6.0 SUBSTRATE SUITABILITY RATINGS

The 34 transects surveyed in the present study provided 1052 point sample photos that were visually analysed for substrate type (Appendix A, Table A1). The majority of substrate ratings (643 cases, 61%) were classified as “2 – moderate” (gravels [2 to 64 mm] and boulders [> 256 mm]; Figure 21, Figure 22), 354 cases (34%) were classified as “3 – high” (cobbles [64 to 256 mm]), and 55 (5%) were classified as “1 - low” (fines [< 2 mm diameter] and bedrock). Most sampling points with the highest substrate rating were located in the upper half of the study area (i.e., where White Sturgeon eggs were captured) and immediately downstream of Big Eddy. The lowest-score sampling points were found within Big Eddy and along the southern shoreline in the lower half of the study site.

Substrate ratings generally coincided with bottom velocity values during periods of high discharge from Revelstoke Dam and low ALR levels (Figure 15). At sites where near bottom velocity was highest (upper half of study area and thalweg areas of lower section), substrate ratings were intermediate (gravels [2 to 64 mm] and boulders [> 256 mm]) or high (cobbles [64 to 256 mm]). At sites with low velocity like Big Eddy and along the southern shoreline in the lower half of the study area, substrate ratings were typically lower, a reflection of the depositional character of these areas even under high discharge and low ALR conditions (Figure 15).

The majority of interstitial space ratings at the sampling points were classified as “3 – high” (668 cases, 63%), 322 points (31%) were classified as “2 – moderate”, and 55 points (6%) were classified as “1 – low”. Similar to the substrate rating, most of the points that scored highest for interstitial spaces were located within the upper half of the study area and along the thalweg downstream of Big Eddy (Figure 23, Figure 24). Interstitial space ratings were generally low within Big Eddy and along the southern shore of the lower half of the study area. At locations of egg/larval presence, the vast majority of substrate ratings were either “2 – moderate” or “3 - high”. That said, the early life stages captured at the downstream-most end of distribution of captured eggs/larvae (Figure 15) were in the area of “1 – low” and “2 – moderate” interstitial ratings.

Similar to substrate ratings, interstitial ratings also coincided with bottom velocity values during periods of high discharge from Revelstoke Dam and low ALR levels (Figure 15). At sites with high bottom velocity (upper half of study area and thalweg areas of lower section), interstitial ratings were high or intermediate. In Big Eddy and along the southern shoreline in the lower half of the study area, interstitial ratings were generally intermediate to low, since these areas are depositional even under high discharge and low ALR conditions (Figure 15).

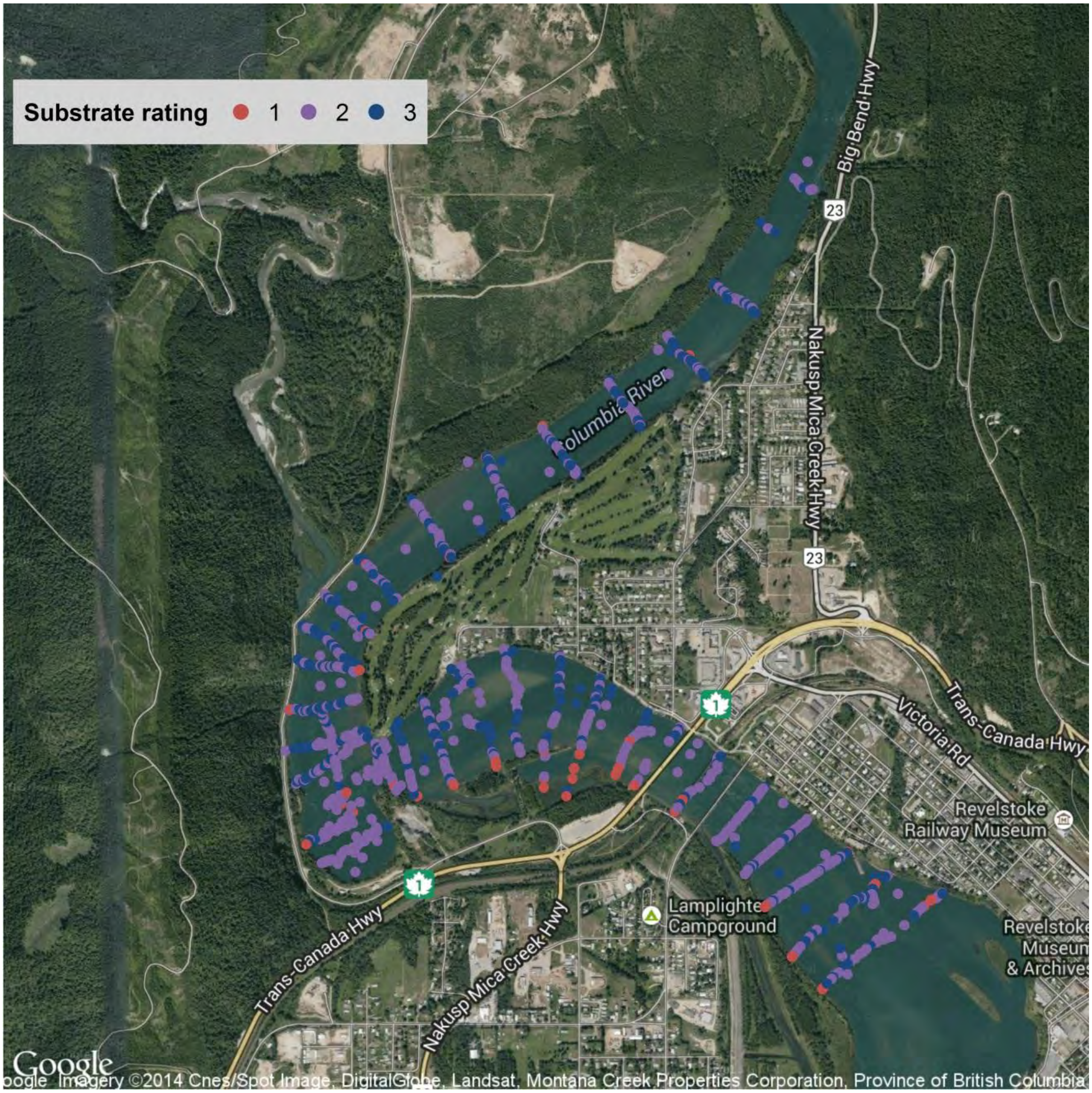


Figure 21: Substrate size suitability ratings (red is least suitable, blue most suitable) at each sampling point in the Revelstoke White Sturgeon spawning and early rearing area.

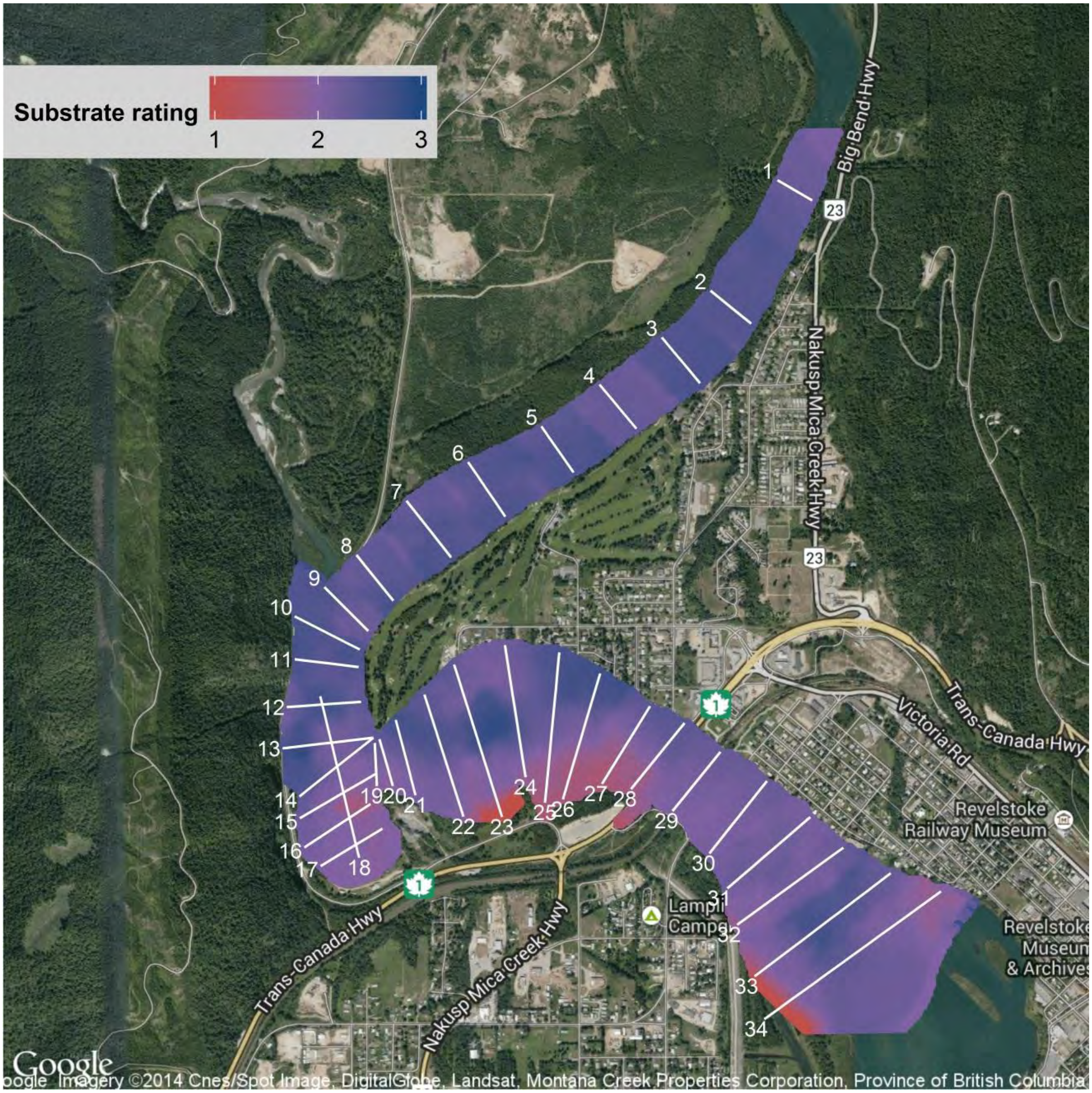


Figure 22: Interpolated substrate size suitability ratings (red is least suitable, blue most suitable) in the Revelstoke White Sturgeon spawning and early rearing area; white lines are transect locations.

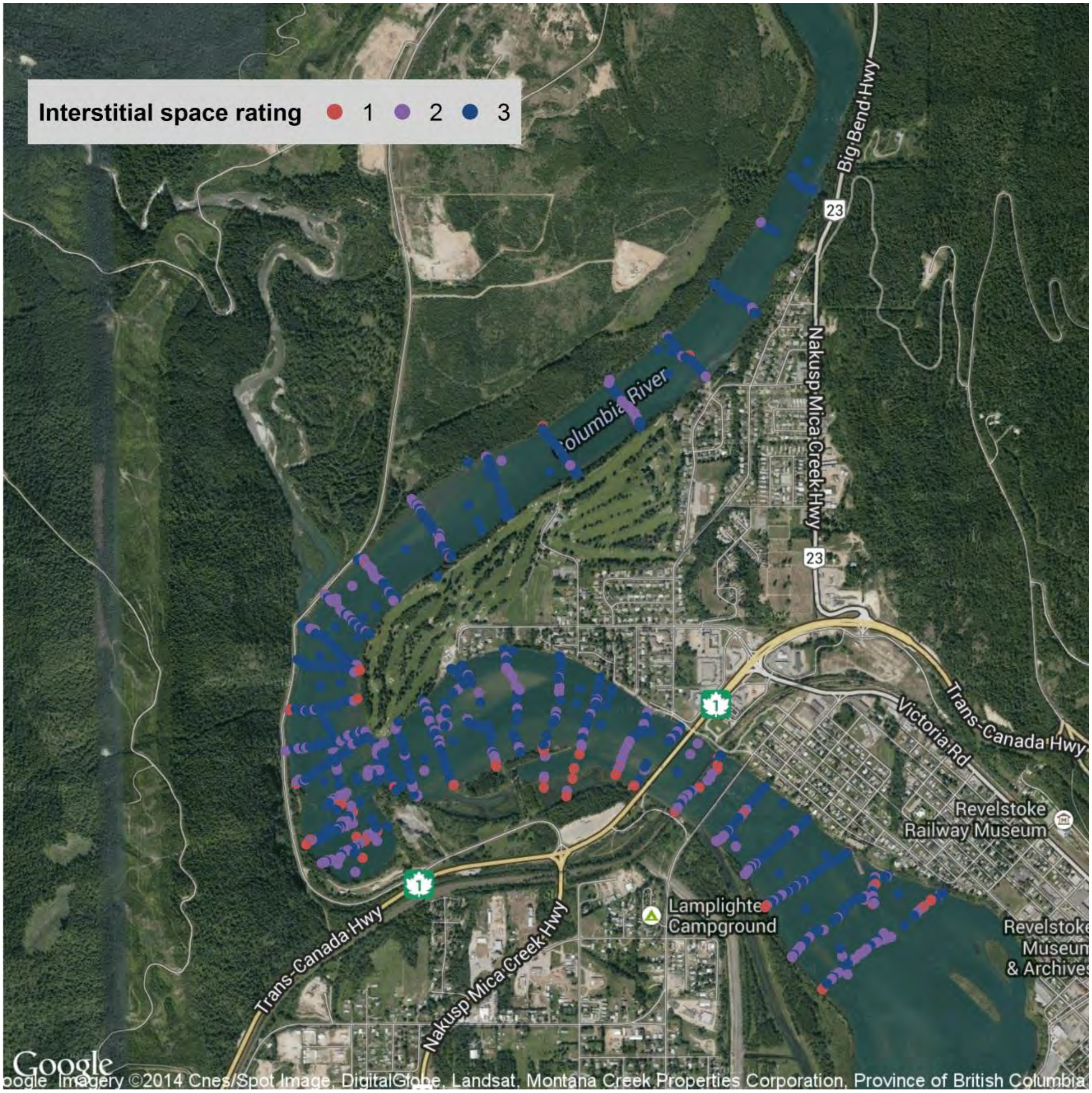


Figure 23: Substrate interstitial space suitability ratings (red is least suitable, blue most suitable) at each sampling point in the Revelstoke White Sturgeon spawning and early rearing area.

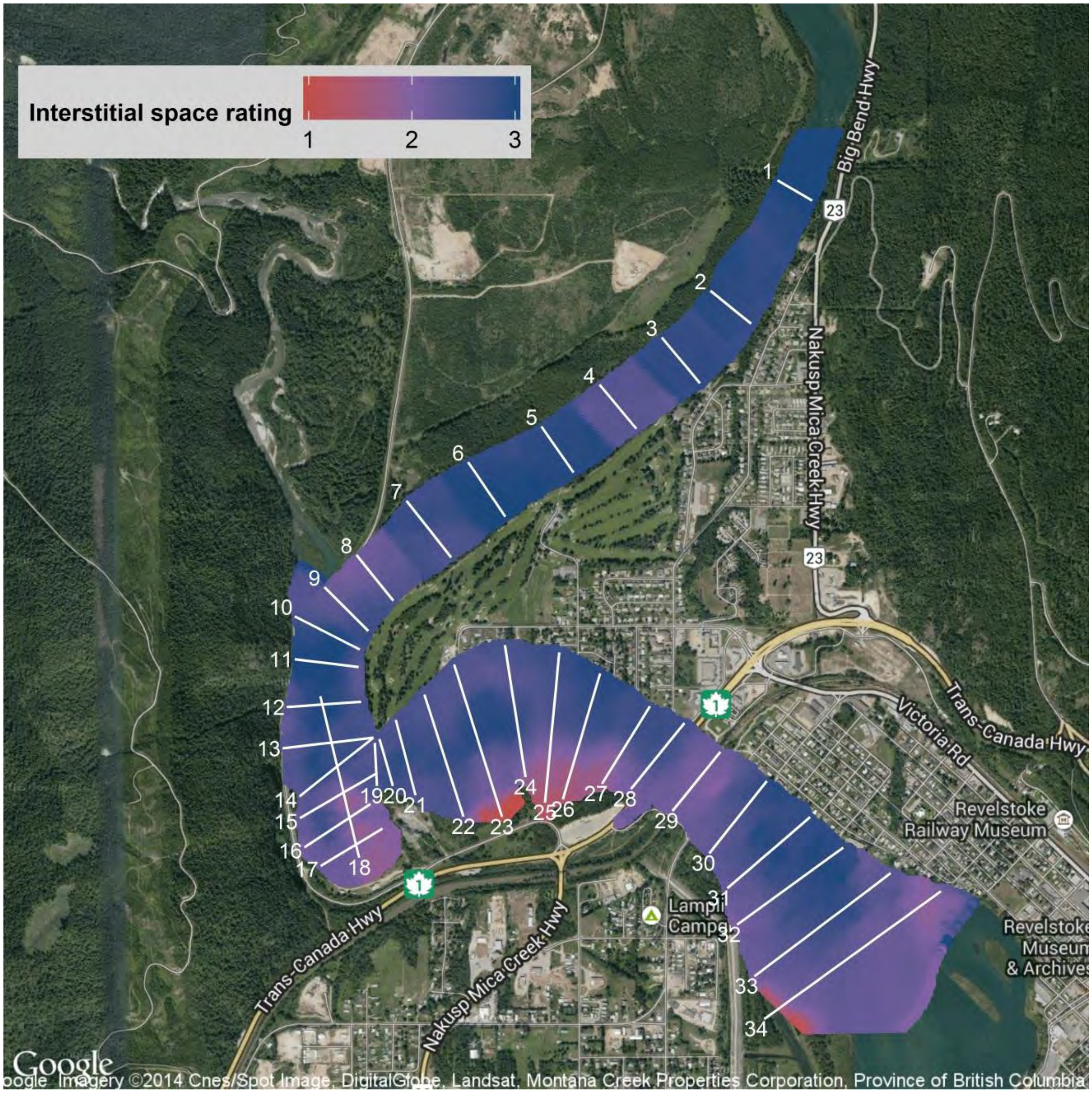


Figure 24: Interpolated substrate interstitial space suitability ratings (red is least suitable, blue most suitable) in the Revelstoke White Sturgeon spawning and early rearing area; white lines are transect locations.

The majority of total substrate ratings were classified as either “4” (237 cases; 23% of the examined cases), “5” (457 cases, 43%), or “6” (282 cases, 27%; Figure 25, Figure 26). Only 76 cases were classified as either “2” or “3” (7%) and these were mainly found within Big Eddy and along the southern shore of the lower half of the study area. Following the spatial distribution trend of interstitial space and substrate ratings, sampling points with higher total ratings (values of 5 to 6) were found throughout the study area. The highest-rated points were found along the right upstream bank of the upper half of the study area and along the right upstream bank and in the thalweg below Big Eddy. At locations of egg/larval presence (Figure 15), the vast majority of total ratings were either "4 – moderate", "5 – moderate-high", or "6 – high".

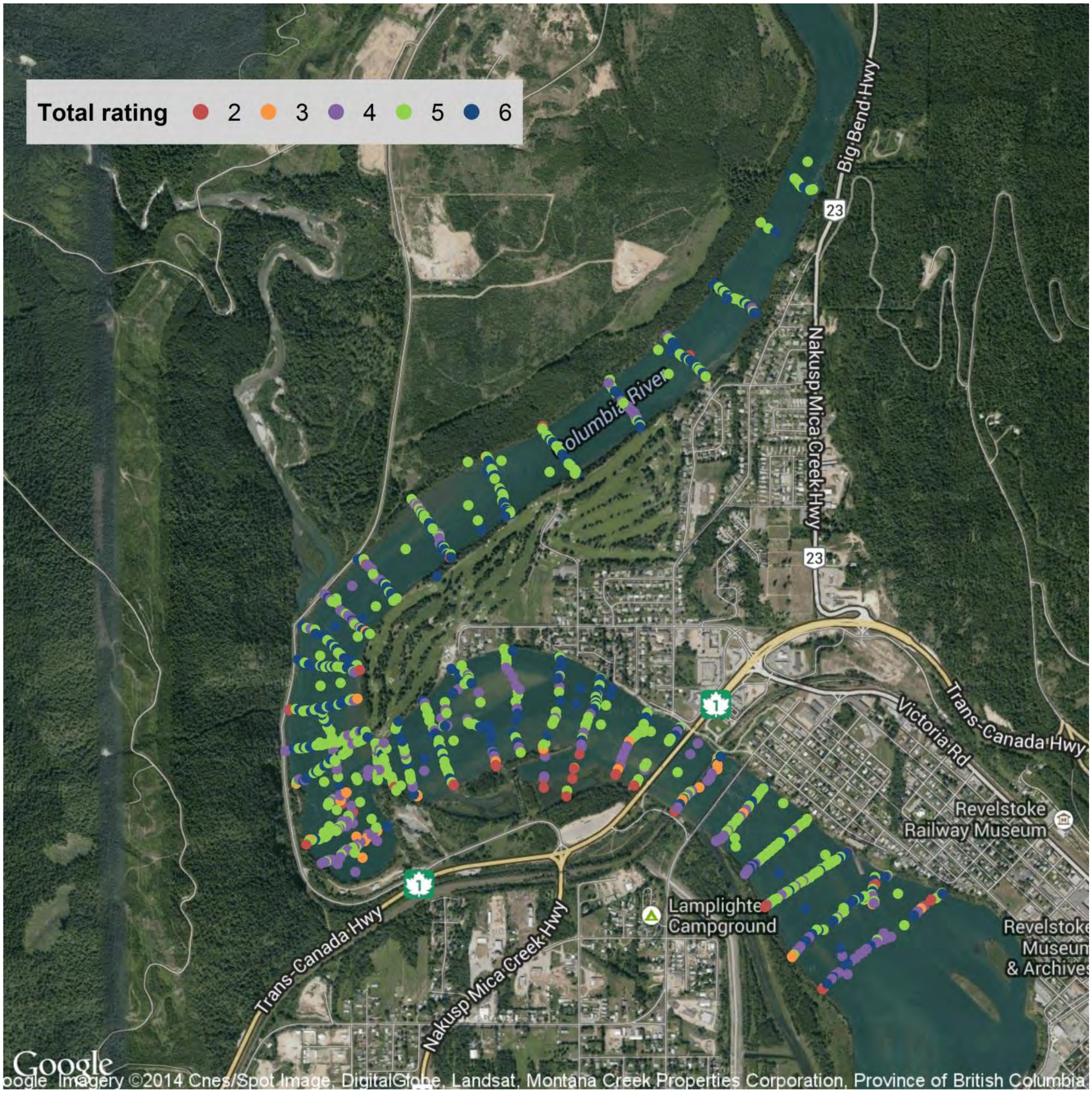


Figure 25: Total substrate suitability ratings (red is least suitable, blue most suitable) at each sampling point in the Revelstoke White Sturgeon spawning and early rearing area.

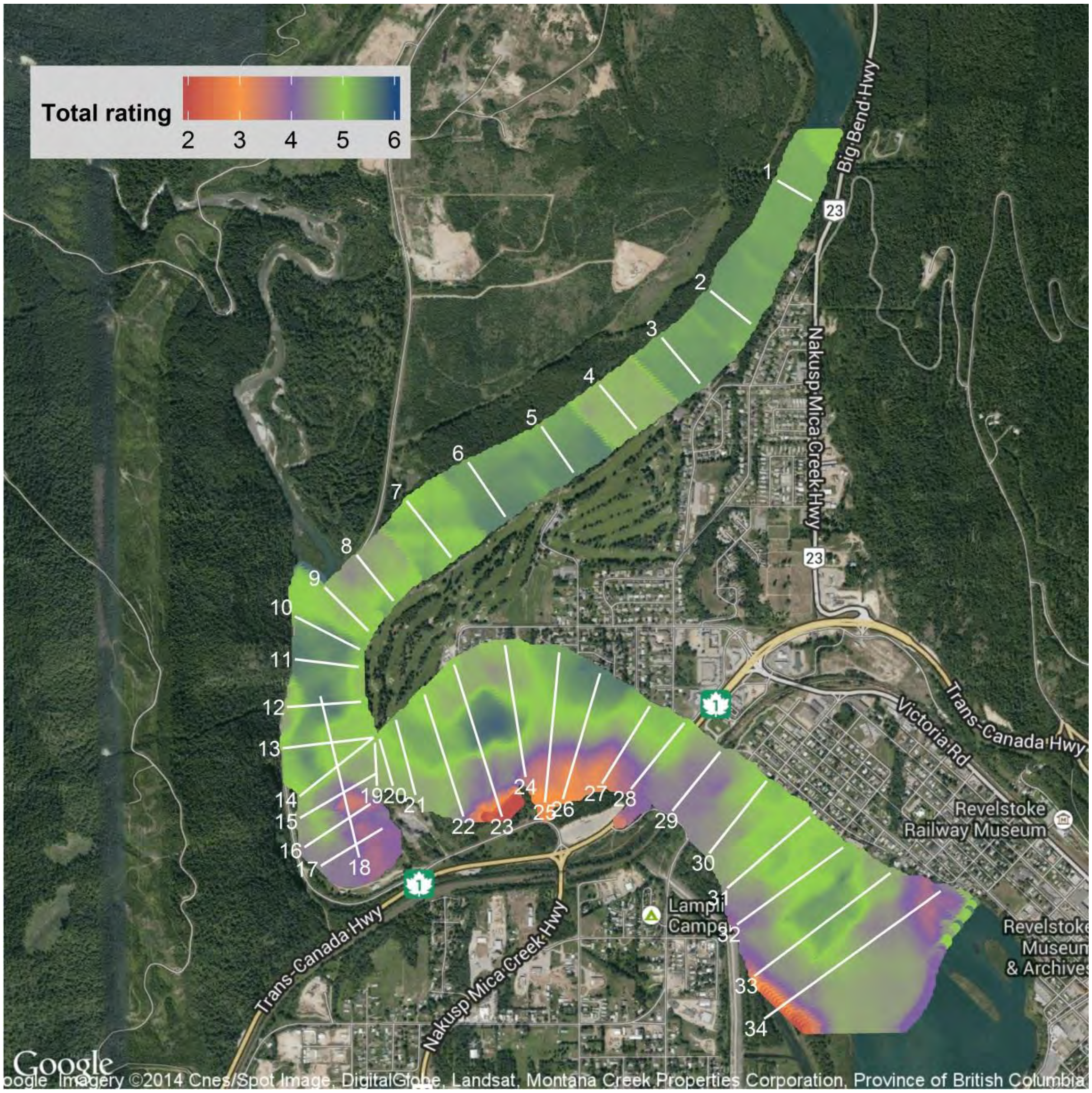


Figure 26: Interpolated total substrate suitability ratings (red is least suitable, blue most suitable); white lines are transect locations.

In the upper half of the study area, quantitative substrate analysis indicated the presence of larger substrate sizes (20-30 cm) and higher size variability (SD values of 10-30 cm) along the shores, and smaller (5-10 cm) substrates, with lower variability (SD values of 0-10 cm) in the channel (Figure 27). In Big Eddy (transects 15-18), substrate sizes were very low (1-5 cm), with low variability. Overall, there was a tendency for substrate size to decrease with downstream distance in the study area (Figure 28; Appendix A, Table A1).

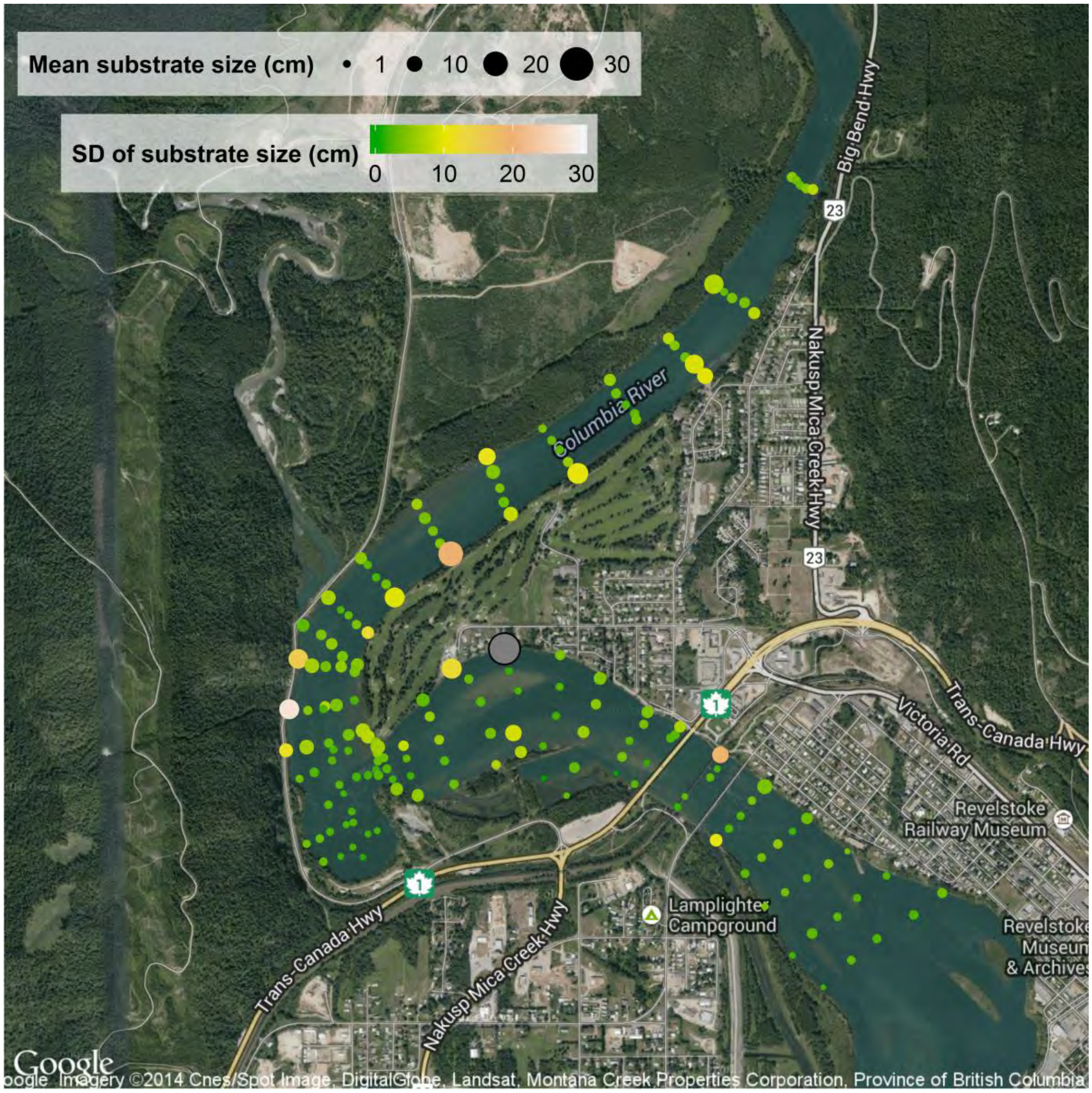


Figure 27: Substrate size measurements, plotted by particle size (dot size) and variability (standard deviation of measurements per image, dot colour). Points where only one measurement was available are plotted in grey.

In the lower half of the study area, substrate was generally smaller and more uniform in size than in the upper half (Figure 28; Appendix A, Table A1). Similar to the upper half, the larger, more variable substrates (10-30 cm mean size, SD values of 10-20 cm) were found along the shore (mainly the right upstream bank), while the smaller, more uniform substrates (mean size 1-10, variability of 0-5 cm) were found in the channel (Figure 27).

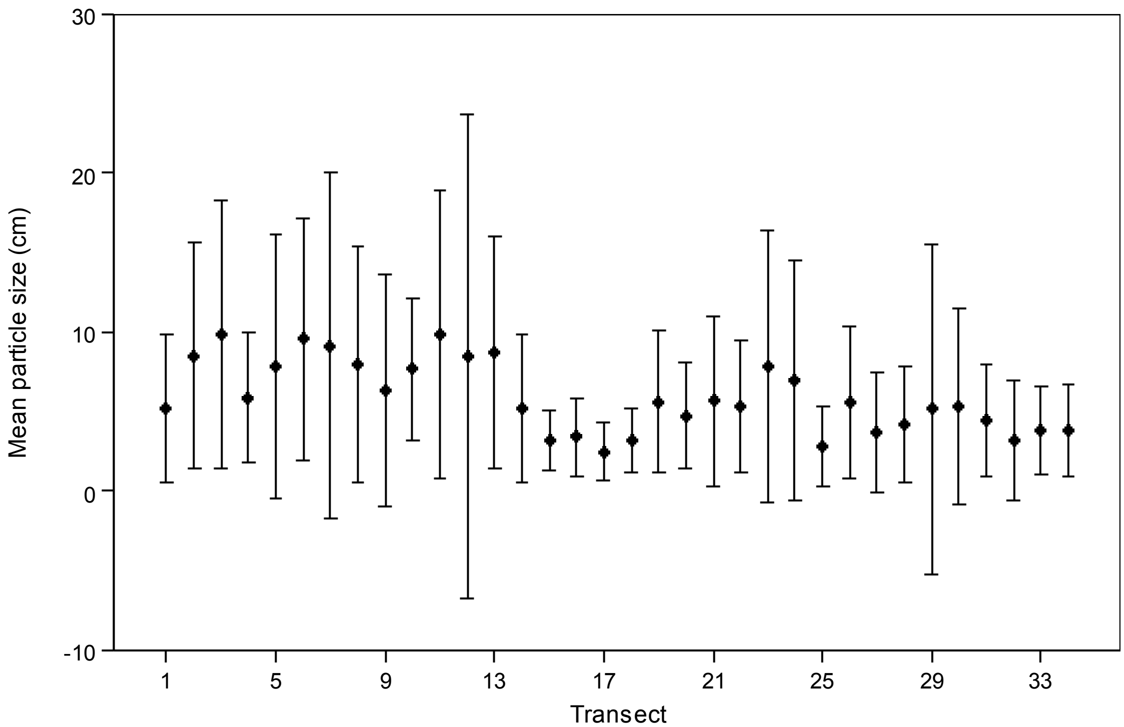


Figure 28: Mean particle size per transect, error bars are 1 SD value. This figure depicts the data provided in Appendix A, Table A1.

7.0 MANAGEMENT QUESTIONS

The primary White Sturgeon spawning/egg incubation sites in the Columbia River below Revelstoke Dam are located adjacent to the Revelstoke golf course just upstream from the Jordan River confluence (Figure 2). Spawning activity is low (maximum of three spawning events annually) and does not occur every year (8 of 12 years examined). However, sturgeon eggs have consistently been documented only in this relatively small area despite sampling in several years at other potentially suitable areas throughout the Columbia River between Revelstoke Dam and the Illecillewaet River. This indicates the physical habitat characteristics within this area are actively selected by sturgeon for spawning and egg incubation and suggests this area provides the most suitable habitat available within the flowing section of the Columbia River below Revelstoke Dam.

At present, there is still a high degree of uncertainty regarding the suitability of the spawning/egg incubation area and the immediate downstream section of the study area for larval hiding and feeding. The sample effort and number of larvae captured to date have been insufficient to determine early larval habitats or drift patterns and to assess early life stage use or suitability. In addition, flow requirements and physical characteristics of suitable early rearing habitats are still poorly understood for the species in general (Hildebrand and Parsley 2013).

The following discusses how the data obtained during the present study addresses the specific management questions related to each of the CLBMON-20 and CLBMON-54 study components. The first four management questions were the same for each of the two study components and are combined for the following discussions.

7.1 Management Question 1 (CLBMON-20 and CLBMON-54)

What are the depth, hydraulic properties (velocity/turbulence) and substrate conditions in the identified white sturgeon egg incubation and suspected early rearing habitat area(s) below Revelstoke Dam?

Successful White Sturgeon spawning and early life stage survival requires suitable substrate, water velocity, and depth conditions. Of these, substrate and velocity are widely considered the most important parameters and in general, spawning grounds across the species' range are reported to have water flow of 1 m/s or higher over gravel-to-boulder sized substrates (Parsley et al. 1993; Perrin et al. 2003; Hildebrand and Parsley 2013). Depths at spawning grounds range from 3 to 25 m but do not appear to be a critical factor influencing spawning site selection (Hildebrand and Parsley 2013).

In the White Sturgeon spawning/egg incubation and early rearing area below Revelstoke Dam, the highly regulated and variable daily discharge regime combined with the backwater influence from ALR do not allow the identification of typical depth and hydraulic parameters in this area. The results from the model runs conducted during this study do help illustrate how these parameters are influenced by operations of Revelstoke Dam and ALR and how these operations interact to influence habitat availability and suitability in the study area. The following discussion provides a general description of the depth, hydraulic properties, and substrate conditions in the study area and whether these conditions are generally suitable for White Sturgeon spawning and early life stage survival.

7.1.1 Depth

Maximum depth in the Revelstoke sturgeon spawning/egg incubation area during periods of maximum discharge from Revelstoke Dam typically ranges from 5 to 6 m in the channel thalweg although at the minimum 120 m^3/s Revelstoke Dam discharge, maximum depths can be reduced to 2 or 3 m. These values are within the reported depth range for spawning by this species at other locations. All sturgeon eggs recorded in the spawning area have been captured within the same relatively small area of the Columbia River and based on back-calculated estimates of spawn timing, have been spawned at various combinations of discharge and ALR levels that would have influenced depths within the spawning area. As such, depths in the study area appear sufficient to stimulate White Sturgeon spawning activity under all present flow regimes and ALR levels.

Depth requirements of early pre-exogenous feeding larvae are poorly understood but are assumed to be similar to those required for spawning and egg incubation, and likely not as important as substrate characteristics. Depth requirements for exogenous feeding larvae are unknown; in other areas of the Columbia River, this life stage has been recorded at a wide range of depths but more commonly in the thalweg areas of the channel near bottom (reference). However, these observations are based on captures of drifting larvae and may not represent actual depth selection of suitable rearing habitats. In the study area, thalweg depths in the downstream early rearing area were slightly shallower than in the spawning area, a reflection of the wider and more braided channel morphology as compared to the singular U-shaped channel in the spawning area. Based on this, depths in the study area are not considered as a major limitation to early life stage rearing.

7.1.2 Hydraulic Parameters

High water velocity is a key attribute of White Sturgeon spawning site selection. Mean water column velocities typically range from 0.5 to 2.5 m/s (Hildebrand and Parsley 2013) although lower velocities of 0.2 to 1.0 m/s have been reported for White Sturgeon spawning in the Kootenai River (Paragamian et al. 2001). Greater spawning success has been consistently observed in reaches and high-discharge years that provided higher velocities (Parsley et al. 1993). High water velocities may also improve suitability of early rearing habitats for yolk-sac larvae and help disperse feeding larvae. Habitat suitability criteria developed for U.S. populations of White Sturgeon identify a mean column velocity of 0.8 m/s as a minimum and 1.7 m/s or greater as optimum to stimulate spawning activity (Parsley et al. 1993; Parsley and Beckman 1994). Results of a 3D numerical model of the White Sturgeon spawning area at Waneta indicated most of the eggs were captured on egg mats situated in areas that exhibited near-bottom flow velocities >1.0 m/s over the entire egg incubation period (ASL et al. 2007; Hildebrand and Parsley 2013). This agrees with other researchers that indicate near-bottom velocities in egg deposition areas are typically >1 m/s (Parsley et al. 1993; Perrin et al. 2003; Golder 2013).

There is likely a higher threshold which near bottom velocity conditions start to negatively affect the suitability of White Sturgeon spawning/egg incubation and early rearing habitat (e.g., through substrate scouring or physical displacement of eggs and larvae), although this upper limit has not been determined. In the Waneta spawning area, velocity distributions were modeled for the combined set of spawning events (n = 44) from 2000 to 2005 (excluding 2001 which was a near record low flow year) over the following 8-day incubation periods (ASL et al. 2007). The velocity distributions at each egg mat location where eggs were captured were weighted by the egg catch-per-unit-effort to provide a more representative depiction of velocity conditions in areas with greatest concentrations of incubating eggs. The combined results of this analysis provided the following near bottom velocity distributions: <0.4 m/s = 2%; 0.5 to 0.8 m/s = 9%; 0.9 to 1.2 m/s = 23%; 1.3 to 1.6 m/s = 24%; 1.7 to 2.0 m/s = 34%; 2.1 to 2.4 m/s = 5%; > 2.5 m/s = 4%. These data suggests a strong selection by White Sturgeon for spawning in areas with near bottom velocities between 0.8 and 2.0 m/s, and may suggest an avoidance of areas outside of this range.

Based on the collection of fertilized eggs in the Revelstoke spawning area, suitable velocity conditions to stimulate spawning activity were present preceding each of the spawning events recorded. However, due to uncertainties in determining the exact hour that spawning occurred and the exact location in the channel where the mats captured the eggs, the velocity conditions at the time of spawning cannot be determined. Subsequent to the spawning act and over the course of the following 15 day egg incubation periods for each spawning event, suitable near bottom velocities of >1.0 m/s were provided during approximately 55% of the cumulative time for all events and years combined (Figure 13). Over approximately 20% of the combined incubation periods, near bottom velocities were less than 0.4 m/s, a reflection of the high frequency of zero flow events that were common prior to the implementation of the REV5 minimum flow in 2010 (see Section 7.5). Near bottom velocities exceeded 2.0 m/s for approximately 10% of the incubation period.

Turbulence has also been identified as an important characteristic of suitable sturgeon spawning habitat but the exact nature of the turbulence selected has not been quantified. In the Revelstoke spawning/egg deposition area, the flow conditions are typically laminar due to the uniform channel shape and the smooth armoured bottom. Big Eddy, a large counter-clockwise gyre, is a more complex hydraulic feature that is situated between the spawning/egg incubation and the putative early rearing area. As such, it has a low influence on spawning/egg incubation success but can strongly influence the pattern of larval drift (see Section 5.10).

The importance of velocity or turbulence in determining the suitability of early larval rearing habitat is poorly understood. High velocities are generally considered beneficial to maintain adequate substrate porosity needed for early larvae hiding refugia. Velocity and turbulence requirements of early feeding larvae are even less well understood but based on capture locations, this life stage appears to select low velocity areas with more laminar flows.

7.1.3 Substrate

The majority of substrates in the study area consisted of coarse materials (gravels, cobbles, or boulders), which encompasses the reported range of suitable White Sturgeon spawning substrates (Parsley et al. 1993; Perrin et al. 2003). Exceptions were Big Eddy and nearshore bars in the lower portion of the study area that contained areas with fine substrates. Substrate size, interstitial space, and combined substrate rankings within the study area were all rated as having a moderate-to-high suitability for spawning (Figure 26). Interstitial spaces are not required for spawning activity to occur, but are important for the survival of incubating eggs and early larval life stages. These ratings suggest suitable substrate conditions for White Sturgeon spawning and egg incubation are available in the Revelstoke area, despite the regulated flow regime that results in a moderate degree of riverbed armouring. Support for this assessment was provided by the capture of wild larval sturgeon, albeit in very low numbers.

Substrate quality ratings in the Revelstoke spawning area were similar to those recorded at the Waneta and HLK/ALH White Sturgeon spawning areas where the majority of sampling points were estimated to have intermediate-to-high substrate rating, interstitial space rating, and total rating (scores of 2-3, 2-3, and 4-6, respectively; Golder 2009, 2013). At the Waneta site, substrate survey results (Golder 2009) found that gravel with moderate interstitial space was most abundant (55% of samples, n=228), with high quality habitat (cobble-boulder with high interstitial space) only available at a small proportion of surveyed sites (3%). Though high quality habitat was marginally higher (12%, n=300) in abundance at an upstream spawning site used by a smaller number of breeders (ALH; Jay et al. 2014), habitat of moderate suitability was still the most abundant (32%; Golder 2013). Laboratory studies also suggest that the quality and abundance of early life stage habitat may negatively affect growth, development and survival of yolk-sac larvae (Boucher 2012; McAdam 2011). Field studies that indicate larval catch is dominated by young yolk-sac larvae (Golder 2009, Terraquatic 2011) also suggests that the quality of spawning habitat, while even of moderate suitability, influences the retention of yolk-sac larvae. Accordingly, spawning habitat restoration activities in the upper Columbia River are being developed based on early life history characteristics of the species.

Ontogenetic behaviour of White Sturgeon early life stages is largely associated with initial interstitial hiding and subsequent downstream dispersal. High proportions of gravel and cobble, and low proportions of fines and boulders have been reported at sites of White Sturgeon larval collections in the Columbia River (van der Leeuw et al. 2006). The size of the dominant substrate determines the amount of available interstitial space. Large substrates (boulders) create large interstitial spaces, which allow larvae to hide, but also enable predators to enter the hiding spaces. Smaller substrates (sand, fines) or embedded larger substrates may not provide larvae with interstitial spaces of sufficient size for hiding, which may increase predation or the energetic requirements to maintain position in the interstitial space. Intermediate interstitial spaces provide both suitable hiding habitat for larvae and protection from larger predators. This is supported by results of laboratory experiments that showed survival of larval White Sturgeon exposed to predation by sculpins was lowest over sand and embedded cobble and highest over gravel and cobble (McAdam 2011).

Studies of White Sturgeon free embryo and feeding larvae behaviour are challenging in large rivers, so most information on habitat requirements and drift behaviour for these early life stages are from laboratory studies. A variety of dispersal patterns ranging from immediate post-hatch hiding (McAdam 2011) to a 1-6 dph drift phase (Brannon et al. 1985; Deng et al. 2002; Kynard and Parker 2005; Kynard et al. 2010) have been reported. While population specific differences may be possible, more recent behavioural studies in the lab show a strong preference for small gravel at this life stage (Bennett et al. 2007), with drift occurring over sandy or bare substrates (McAdam 2011). The identification of immediate post-hatch hiding where suitable interstitial habitat is available (McAdam 2011), suggests that an initial drift (Brannon et al. 1985; Kynard and Parker 2005) or swim up (Deng et al. 2002) phase may be due to substrate limitations in prior laboratory studies. Support for this hypothesis was provided by results of a substrate modification experiment in the Revelstoke spawning area in 2010 (Crossman and Hildebrand 2012). Two day post-hatch free embryos were seeded over modified (loose angular gravels and cobbles) and control (existing natural cobbles and gravels) areas of the river. The modified site retained significantly greater numbers of larvae after release compared to the control site and larvae at the modified site were able to hide and remain in the substrate and initiated downstream drift after 15 days post-release. There was a significant effect of time after release and site on the total length of dispersing larvae, which suggested larvae at the control site expended more energy and had greater difficulty hiding. The capture of drifting larvae up to 26 days post-release below the control site indicated some larvae were able to hide and survive in the natural river bed substrates within the study area.

In addition to being able to hide from predators, rearing White Sturgeon larvae also require a source of food once their yolk sac is absorbed and external feeding commences. Locations of early larval feeding habitats in the middle Columbia River are unknown and the availability of suitable food is presently poorly understood.

7.2 Management Questions 2 and 3 (CLBMON-20 and CLBMON-54)

For ease of discussion, the responses to Management Questions 2 and 3 have been combined in the following section:

How does Revelstoke Dam (including the addition of Unit 5) and Arrow Lakes Reservoir operations affect hydraulic conditions in this/these area(s)?

How do these hydraulic conditions relate to incubation and early rearing habitat suitability (quality and quantity) for White Sturgeon?

The operations of Revelstoke Dam and ALR have both individual and synergistic effects on hydraulic conditions in the study area. When ALR level is stable, increased Revelstoke discharge produces a general increase in water depth and near bottom velocities throughout the study area. At a given Revelstoke discharge, increases in ALR levels generally produce increased depths and decreased near-bottom velocities throughout the study area but mostly in the lower section. During the White Sturgeon spawning period of July to August, ALR levels are generally stable and the greatest influences on hydraulic conditions in the study area are due to daily load shaping operations. However, the general level of ALR (low, moderate or high) during the spawning period can have a substantial influence on hydraulic conditions in the study area among years. Both Revelstoke discharges and ALR levels are also affected by the water year and operational considerations of the hydropower system in general, which introduces another source of variability into the hydraulic conditions that may be present in the spawning area in any given year and on any given day.

The greatest effects of the incremental increase between the REV4 and REV5 maximum discharge capacities on near-bottom flow velocities occurred at high ALR levels, where the areal extent of flows >1 m/s increased about 7% from REV4 to REV5 (Table 5). However, as discussed in Section 5.7, these differences were not proportional to either discharge or ALR level. The effects of the REV5 maximum discharge were most pronounced in the upper section of the egg deposition/incubation area during High ALR levels where there was a large increase in higher velocity areas >2.0 m/s (Figure 15). However, these increases were within the putative preferred range for sturgeon spawning/egg incubation and could therefore be viewed as favorable. During low ALR levels high velocities were prevalent throughout the study area for both discharge cases and although changes were more subtle with more localized shifts in flow velocities, there was an approximate 7% increase in the area of near bottom flows >2.0 m/s, which could be viewed as a negative effect. However, ALR levels during the sturgeon spawning season are rarely at low levels, which reduces the significance of this potential effect on White Sturgeon spawning success.

The REV5 minimum flow resulted in a substantial increase in the areal extent of near bottom flows in the 0.6-1.0 m/s flow increment at both moderate and low ALR levels, as compared to the REV4 minimum flow scenarios. At high ALR levels, there was no difference in the areal extent of flow increments between the REV4 and REV5 minimum flow levels (Table 4). The greatest increase in the proportion of the study area with suitable spawning flows of >1.0 m/s because of the minimum flow occurred during at the low ALR level (Table 4). Most of these increases occurred in the upper portions of the known spawning and early rearing areas (Figure 14) and represent improved habitat conditions in the spawning/egg incubation and early rearing areas compared to the REV4 minimum flows.

Load factoring operations of Revelstoke Dam have the potential to result in the stranding of White Sturgeon eggs (Golder 2010), though it has only been identified to occur once in the 9 years spawning has been documented. To date, the only documented stranding event occurred on August 7, 2009 (prior to the implementation of the REV5 minimum flow release) and involved the dewatering of seven eggs after Revelstoke Dam discharge was reduced to zero at midnight. Extrapolating the recorded density of 0.24 eggs/m^2 of dewatered substrate over the estimated 31 600 m^2 of dewatered river bed in the potential egg deposition area, resulted in an estimate of 7600 stranded eggs. The REV5 minimum flow release will reduce the likelihood that sturgeon eggs or early larvae will be dewatered during periods of minimum flow, although depending on where in the channel egg deposition occurs, some stranding is possible under operational scenarios and should be monitored in years where spawning is documented. Additional surveys of the egg deposition area, following reductions to post-REV5 minimum flow when incubating eggs are known to be present, would be required to definitively address this potential impact.

The influence of the backwatering effect on white sturgeon spawning in the middle Columbia River remains unknown. There is some evidence to suggest the location of White Sturgeon spawning in the Revelstoke area may be influenced by the ALR levels. In 2008, ALR levels during the July to August White Sturgeon spawning period were between approximately 439 and 440 masl, the highest levels recorded in all years spawning activity has been monitored. These levels resulted in a pronounced backwater effect that reduced current velocities throughout the spawning area. White Sturgeon eggs were captured further upstream in 2008 than in any previous or past studies since (see Figure 11, Site 9, lower left panel). This may reflect an upstream shift in spawning location to an area of the channel where near bottom velocities were greater and potentially more suitable. Conversely, the ALR water level in 2009 (mean = 436.5 masl) was the lowest recorded during the annual spawning surveys conducted and resulted in no backwatering effect for the majority of the spawning period. The higher current velocities that resulted may have contributed to the relatively high number of eggs captured and the capture of free embryos in 2009. Additional study is required to further define the effects of ALR levels on sturgeon spawning site selection.

Based on the model results, the greatest effect of the REV5 flow on riverbed substrates was the erosion of fine sand from the spawning/egg incubation area upstream from the Jordan River confluence and the deposition of this material along the east bank near the Golf Course to the north of the Big Eddy (Attachment A). This would likely have resulted in a slight increase in substrate interstitial space and a decrease in embeddedness. However, the benefits of this change on sturgeon spawning success are expected to be of limited duration and are not expected to result in increased sturgeon recruitment. The effect of the REV5 flow on larger substrates (gravels and cobbles) was negligible over the study area, as the river bed surface in 2010 (when the substrate was analysed) was a reflection of the scour and deposition that occurred during the previous spill event in 1991 that resulted in a combined spillway and powerplant discharge of 3341 m^3/s, much higher than the maximum REV5 discharge of 2124 m^3/s. A spill event in 2012 produced a peak combined discharge from Revelstoke Dam of 2573 m^3/s and would have also have redistributed fine substrates in the study area, although modelling the effects of that event were not conducted as part of this study.

As discussed in Section 7.1, locations of early larval rearing and feeding habitats in the middle Columbia River are unknown. As such, addressing the management questions related to effects of Revelstoke Dam and ALR operations on hydraulic conditions on these habitats has been based on the assumption that the early rearing area is located within the model domain. Although this assumption has not been verified, it is considered highly likely that early rearing and feeding habitats are situated downstream of the study area.

For the three discharges examined in the larval drift scenarios, larvae that initiated and maintained a near bottom drift at high ALR levels remained in the drift and were ultimately transported downstream into or through the putative early rearing area (Table 10; Appendix B). However, for the two lower discharge cases (142 m^3/s and 850 m^3/s) at low ALR levels, the larvae were entrained into Big Eddy but at higher flows (1699 m^3/s), were transported into the upper part of Big Eddy but were then deflected downstream into the early rearing area. This suggests that at low ALR levels, there is a flow threshold between 850 and 1699 m^3/s that when not met, results in larvae being entrained into the Big Eddy, an area rated as having a low substrate suitability for early larvae. This threshold was not determined in this study since ALR levels during the sturgeon spawning and early larval rearing periods are typically in the moderate to high range and therefore, this scenario has a low probability of occurrence. Larvae that initiated drift near the bottom but either volitionally or non-volitionally entered the drift near the water surface were consistently entrained into Big Eddy at all discharge and ALR levels examined (Table 10; Appendix B). These differences are related to the complex patterns of surface and sub-surface flows that develop within the eddy, which determine whether larvae are entrained into or deflected out of the eddy.

7.3 Management Question 4 (CLBMON-20 and CLBMON-54)

Can proposed minimum flows and spawning flow modifications to the operations of Revelstoke Dam protect or enhance middle Columbia River white sturgeon incubation and early rearing habitat?

The REV5 minimum flow resulted in a substantial increase in the areal extent of near bottom flows in the 0.6-1.0 m/s flow increment at both moderate and low ALR levels, as compared to the REV4 minimum flow. The greatest increase in the proportion of the study area with flows >1.0 m/s occurred for the REV5 and low ALR case where ~34% of the study area exhibited flows greater than this threshold (Table 4). Most of the increases in suitable spawning flows were recorded in the upper portions of the known spawning and early rearing areas (Figure 14). This represents a substantial increase in the areal extent of potentially suitable sturgeon spawning habitat in the middle Columbia River.

The implementation of the REV5 minimum flow also will provide a greater wetted area than was provided by the previous REV4 minimum flow; this will reduce the occurrence and severity of egg and larval stranding during minimum flow periods. In addition, the increased REV5 minimum flow will provide a greater volume of oxygenated water than was previously provided, which should improve conditions for incubating eggs and hiding larvae.

The uncertainty in estimates of spawn timing, the highly variable discharge, velocity, and temperature fluctuations, combined with the small sample size of spawning events and numbers of eggs captured, continues to create difficulties in determining White Sturgeon spawning cues or developing optimal spawning flows in the Revelstoke spawning area. Physical conditions below Revelstoke Dam have differed substantially among years when spawning assessments have been conducted but to date no discernable relationships have been established between operational factors (discharge, water temperature, ALR elevations, and the frequency of zero flow events) and years when spawning has occurred or the number of spawning events recorded in a given spawning year. As a result, addressing the management question as to whether proposed spawning flow modifications could protect or enhance middle Columbia River white sturgeon incubation habitat is problematic.

Two proposed augmentation flows were examined in this study: 566 m^3/s (20,000 cfs) and 850 m^3/s (30,000 cfs). These flows were suggested by the UCWSRI Technical Working Group as having the potential to improve White Sturgeon spawning conditions in the Revelstoke spawning area without incurring large costs in forgone generation revenue. At high ALR levels, neither of the two proposed augmentation flows would provide an appreciable amount of suitable sturgeon spawning habitat with near bottom velocities between 1.0 to 2.0 m/s (see Section 7.1.2) although the 850 m^3/s flow provided a much larger areal extent of velocities in the 0.6-1.0 m/s increment (Table 6; Figure 16). The greatest areal extent of suitable near bottom velocities would be provided by the 566 m^3/s flow for both low (57%) and moderate (59%) ALR levels. During the sturgeon spawning period, ALR levels are typically range between moderate to high levels so the potential benefits from this flow would only be achieved in some years assuming typical summer operation of ALR does not change.

The two augmentation flows were modeled as flow scenarios for the larval drift model. Results indicated that at both these flows and at high ALR levels, larvae were transported downstream into the putative rearing area; at low ALR levels, larvae were entrained into Big Eddy. Larval drift patterns were not modeled at moderate ALR levels in this study so the augmentation flow that would promote the best larval drift patterns at moderate ALR levels is unknown.

7.4 Management Question 5 (CLBMON-20)

Can modifications be made to operations of Revelstoke Dam and Arrow Lakes Reservoir to protect or enhance White Sturgeon incubation habitat?

Based on the results of this study and the numerous years of research that has been conducted over the past decade on White Sturgeon spawning activities in the Revelstoke spawning area, there is still considerable uncertainty as to what additional actions can or should be implemented that would protect or further enhance White Sturgeon incubation habitat. Spawning has occurred over a wide range of Revelstoke Dam discharges and ALR levels since the completion of the dam in 1984 and recent studies have shown that eggs are successfully fertilized and a portion of the wild spawn hatches and survives to at least the 2-day old larval stage (Golder 2012). The absence of any detectable recruitment over this 30 year time frame may suggest that effects of discharge or ALR levels on spawning/egg incubation habitat are not the primary factors preventing successful recruitment of White Sturgeon in the middle Columbia River.

The location of early rearing or feeding habitats and their availability and suitability in the study area are still unknown. Experimental introductions of 1-day post-hatch larvae into modified (loose angular rock) and control (embedded native gravels, cobbles, and boulders) portions of the Revelstoke spawning area in 2010 indicated larvae were able to hide and survive for up to 13 days in the control area and up to 25 days in the modified area (Crossman and Hildebrand 2012). Larvae from the modified area initiated volitional dispersal after 15 days and were significantly larger than larvae from the control area. This experiment supported findings from other studies that indicate modifications to embedded substrates at known sturgeon spawning sites can enhance conditions required for early larval hiding. Larval hiding has been identified as an important life history characteristic for White Sturgeon and is thought to be critical for early growth, development, and survival. The ability for larval sturgeon to hide and grow rather than expending energy searching for suitable habitat or trying to maintain position in unsuitable habitat is important, as recruitment failure in the study area is thought to occur primarily in the early life stages (Gregory and Long 2008).

8.0 CLOSURE

We trust that this report meets your current requirements. If you have any further questions, please do not hesitate to contact the undersigned.

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APPENDIX A

Substrate Classification

Plate 1 Total rating = 2; substrate rating low (1), interstitial space rating low (1)

Plate 2 Total rating = 3; substrate rating moderate (2), interstitial space rating low (1)

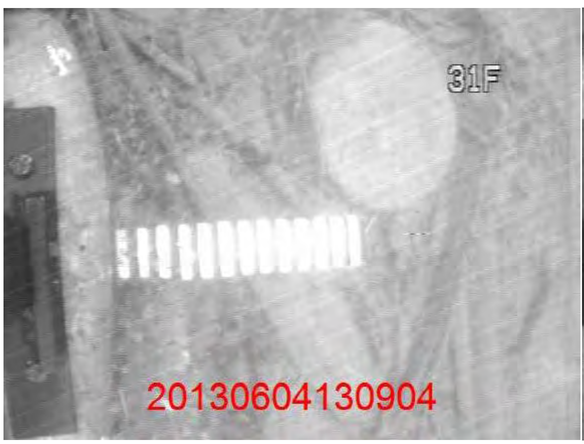

Plate 3 Total rating = 3; substrate rating low (1), interstitial space rating moderate (2)

Plate 4 Total rating = 4; substrate rating moderate (2), interstitial space rating moderate (2)

Plate 5 Total rating = 5; substrate rating high (3), interstitial space rating moderate (2)

Plate 6 Total rating = 6; substrate rating high (3), interstitial space rating high (3)

Plate 7: Screen capture from the underwater videography survey showing the substrate particles selected for measurement.

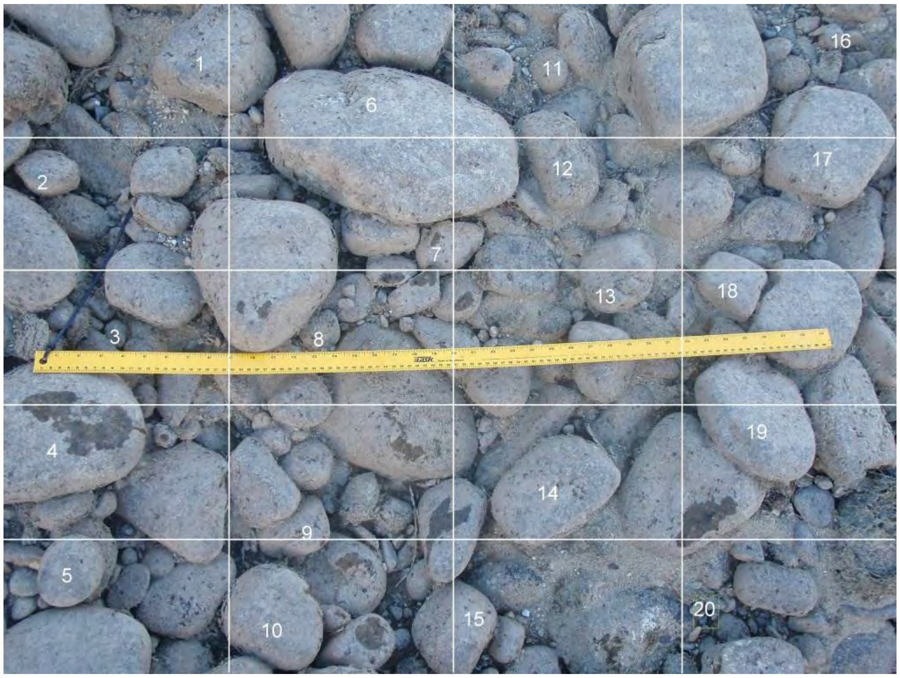

Plate 7: Image from the exposed shoreline photographs showing the substrate particles selected for measurement.

Table A1: Summary statistics of quantitative substrate analysis.

Transect	Mean particle size (cm)	Standard Deviation (cm)	Were all particles fully visible?	N points / transect
T1	5.19	4.67	No	5
T2	8.48	7.09	No	5
T3	9.86	8.4	No	5
T4	5.86	4.05	No	5
T5	7.8	8.3	No	5
T6	9.57	7.59	No	5
T7	9.15	10.85	No	5
T8	7.95	7.43	No	5
T9	6.35	7.3	No	5
T10	7.66	4.42	No	5
T11	9.82	9.07	No	5
T12	8.47	15.18	No	5
T13	8.72	7.26	No	5
T14	5.18	4.64	No	5
T15	3.19	1.87	No	5
T16	3.38	2.44	Yes	5
T17	2.44	1.83	Yes	5
T18	3.15	1.99	No	5
T19	5.63	4.47	No	5
T20	4.73	3.36	No	5
T21	5.66	5.34	No	5
T22	5.31	4.1	No	5
T23	7.83	8.53	No	5
T24	6.97	7.52	No	5
T25	2.81	2.56	Yes	5
T26	5.59	4.78	No	5
T27	3.7	3.76	No	5
T28	4.16	3.65	No	5
T29	5.15	10.36	No	5
T30	5.33	6.2	No	5
T31	4.39	3.51	No	5
T32	3.14	3.78	No	5
T33	3.82	2.79	Yes	5
T34	3.84	2.86	No	5

APPENDIX B

Larval Drift Patterns

GIF Files on DVD

ATTACHMENT A

Three-Dimensional Numerical Modeling of White Sturgeon Habitats in the Middle Columbia River Downstream of Revelstoke Dam (Lin and Fissel 2014)

Three-Dimensional Numerical Modeling of White Sturgeon Habitats in the Middle Columbia River Downstream of Revelstoke Dam

2012-2013 Final Report

Prepared for

BC Hydro

Through
Golder Associates Ltd.
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ASL File: PR705
18 July 2014

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1. Introduction

1.1 Background

A component of BC Hydro's Columbia Water Use Plan involved a research program to study White Sturgeon spawning, incubation, and early rearing habitats in the Columbia River downstream of Revelstoke Dam. In support of this program, a high resolution numerical modeling study of physical environmental parameters, including river velocities, temperatures and sediments, was conducted. The three-dimensional, finite difference numerical model COCIRM-SED was setup using the new bathymetric survey data by Golder Associates Ltd. in 2010, and followed by model calibrations in 2011 and 2012 (e.g. Jiang and Fissel, 2011). In the model, river bed roughness heights at each grid, used to calculate bottom drag, were derived using bottom substrate video survey data collected by Golder Associates Ltd. in 2011 (Figure 1-1).

The modeled river section is situated in the middle Columbia River near the Town of Revelstoke, BC and includes the White Sturgeon spawning and egg deposition area just upstream of the Town of Revelstoke and the suspected early life stage (larval) rearing area in the wider portion of the river downstream of Big Eddy to the Highway 1 bridge crossing (Figures 1-2, 3).

The high resolution COCIRM model provides near-bottom velocities and sediment properties on horizontal scales of 5 m. These parameters are of interest since near-bottom velocities influence predation of sturgeon eggs and sediment influence egg incubation success and early larval survival.

1.2 COCIRM-SED Implementation for White Sturgeon Habitat Modeling

The 3D numerical model COCIRM-SED used in this study represents a computational fluid dynamics, sediment transport, and water quality modeling approach for river, estuarine, and coastal applications (Jiang and Fissel, 2012, Fissel and Jiang, 2008, Jiang, et al., 2008, Jiang, et al., 2003). COCIRM-SED is a highly-integrated model, consisting of six sub-modules, including circulation, wave, multi-size sediment transport, morphodynamics, particle tracking and water quality (Figure 1-4). The model can be operated on either an integrated or an individual module basis. In running the model for circulation and sediment transport, inputs are required for the bathymetry, open boundary conditions, sediment grain size and percentage fraction for each sediment category, with total categories typically ranging from 5 to 20.

The COCIRM-SED model for the White Sturgeon habitat study downstream of Revelstoke Dam operates on a domain of size 2.7 km by 3.7 km. The model area is resolved using a horizontal grid size of 5 m by 5 m, and 12 sigma-layers in the vertical with higher resolution near the surface and bottom (Figure 1-2).

The model involves three open boundaries: (1) the upstream Columbia River, (2) the upstream Jordan River, and (3) the Columbia River downstream open boundary (Figure 1-2). The boundary conditions at the upstream Columbia River and Jordan River are specified by discharges. At the Columbia River downstream open boundary, a radiation open boundary condition is applied. Normally, water temperatures of the Columbia River and the Jordan River differ by a few degrees.

Consequently, the water in the model area will be partially stratified, which in turn, will influence flow patterns in the model area. Therefore, the model directly involves the simulation of water temperature and its associated baroclinic (depth varying) effects.

Initially, the velocities in the entire model domain are set to zero, and the water levels are the same as the uniform water levels at the Columbia River downstream open boundary. The stable model results at the 4^{th} hour are saved for post-processing and analysis unless otherwise specified.

Model calibration, verification, and additional cases are listed in Table 1-1. A new verification model run was conducted on August 2-3, 2012, which involved collecting ADCP flow transect survey data at a Revelstoke Dam discharge of 2124 m^3/s (75 kcfs) and Arrow Lake Reservoir level (at Nakusp) of 441 m. The model results were in very good agreement with the ADCP data (Lin et al., 2012).

New model cases conducted in 2013 are summarized in Table 1-2. These model runs were selected to provide sufficient coverage of the potential range of possible flow regimes and reservoir levels of interest to this study. The scenarios are bounded by (1) maximum Revelstoke Dam full capacity discharge of 2,619 m^3/s, including Revelstoke Unit 6 (REV6), (2) the minimum Revelstoke Dam discharge of 142 m^3/s implemented in 2010 as a component of the Revelstoke Unit 5 (REV5) regulatory approvals process, (3) the recorded maximum Arrow Lakes Reservoir (ALR) level of 441 m, and (4) the estimated minimum ALR level of about 434 m with backwater effect (Figure 1-5).

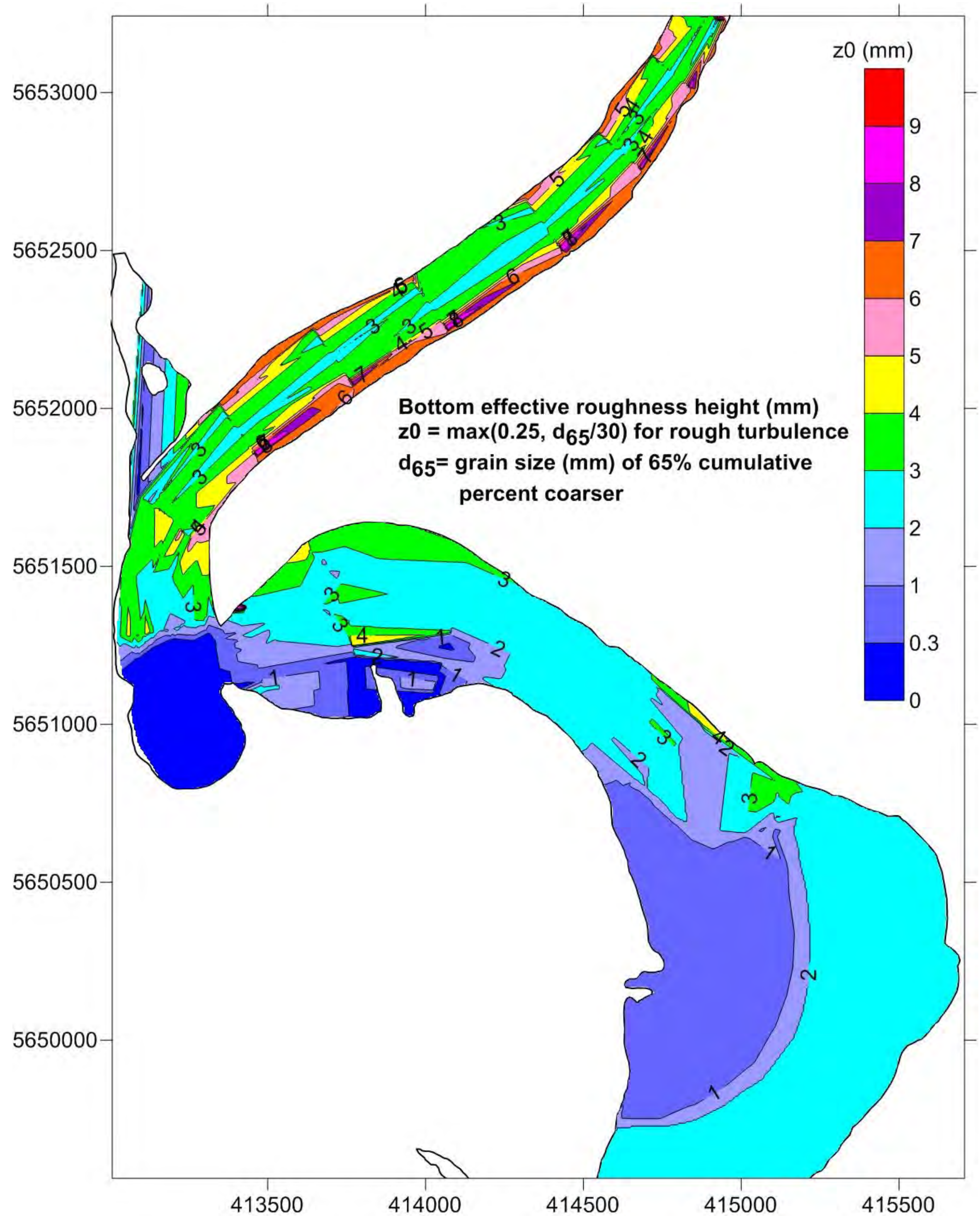


Figure 1-1: Bottom effective roughness height as represented in the COCIRM-SED numerical model.

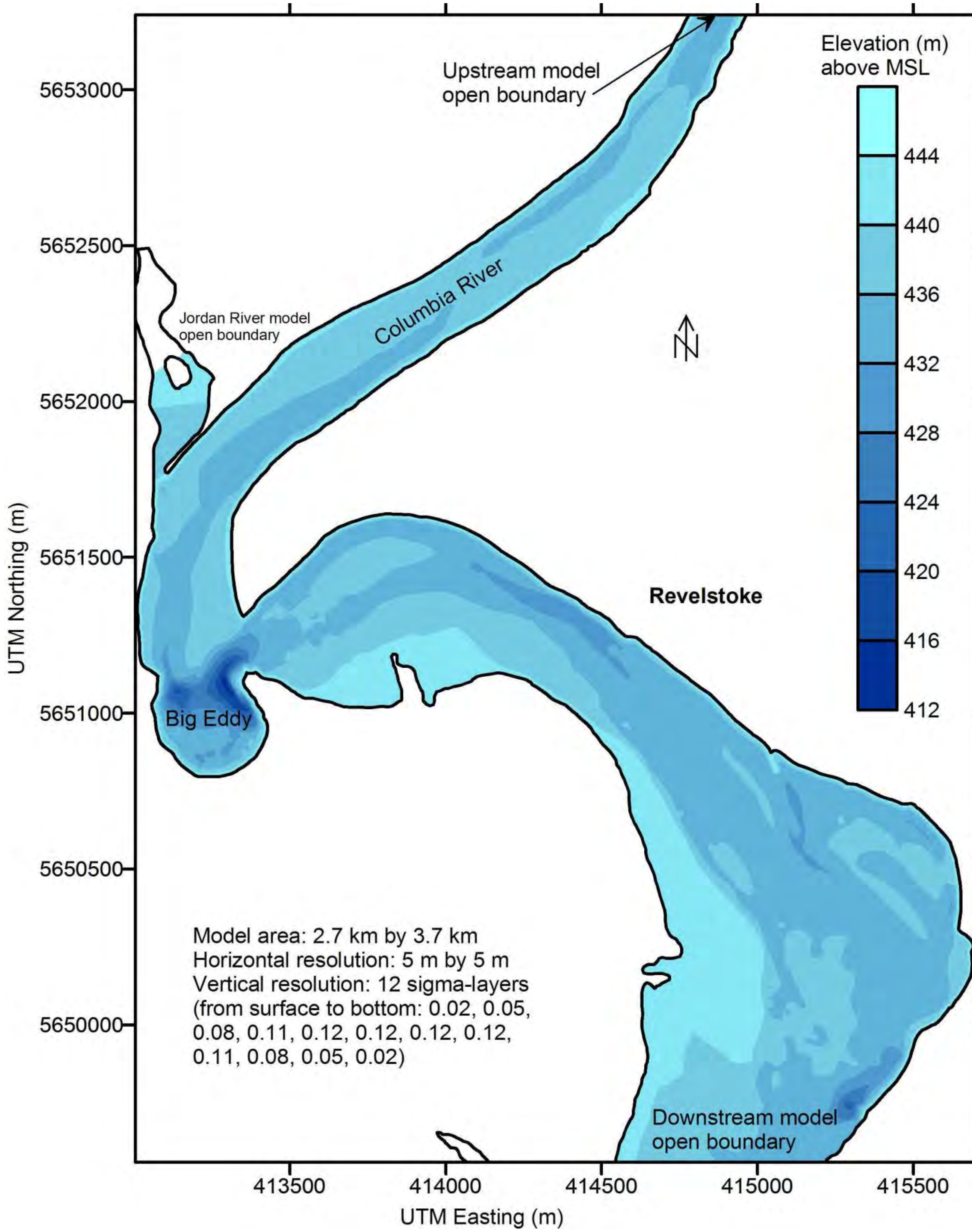


Figure 1-2: Map showing study area and bathymetry as represented in the COCIRM-SED numerical model.

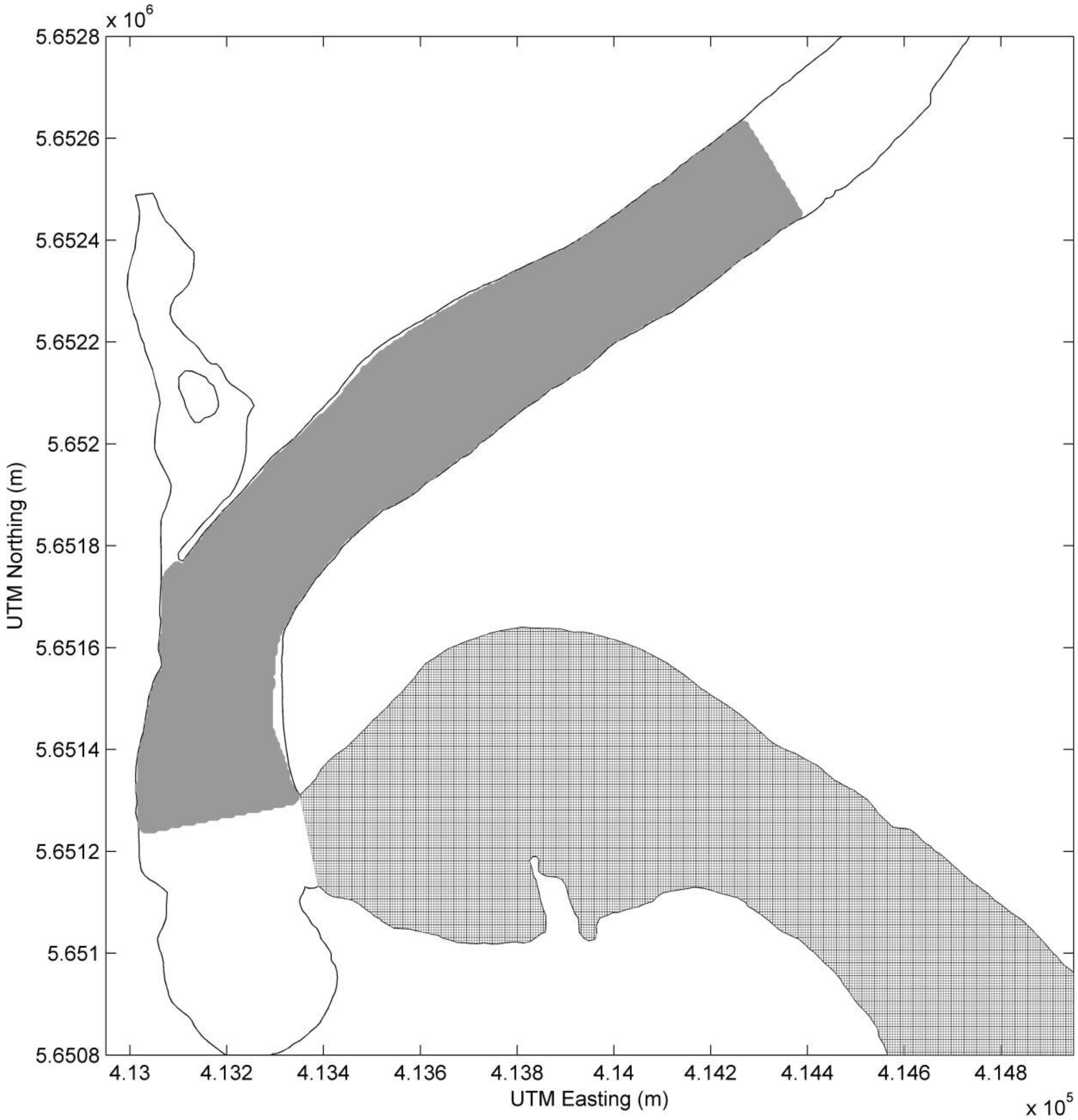


Figure 1-3: Known White Sturgeon spawning and egg deposition/incubation area (dark shading) and suspected early larval rearing habitat (cross-hatching).

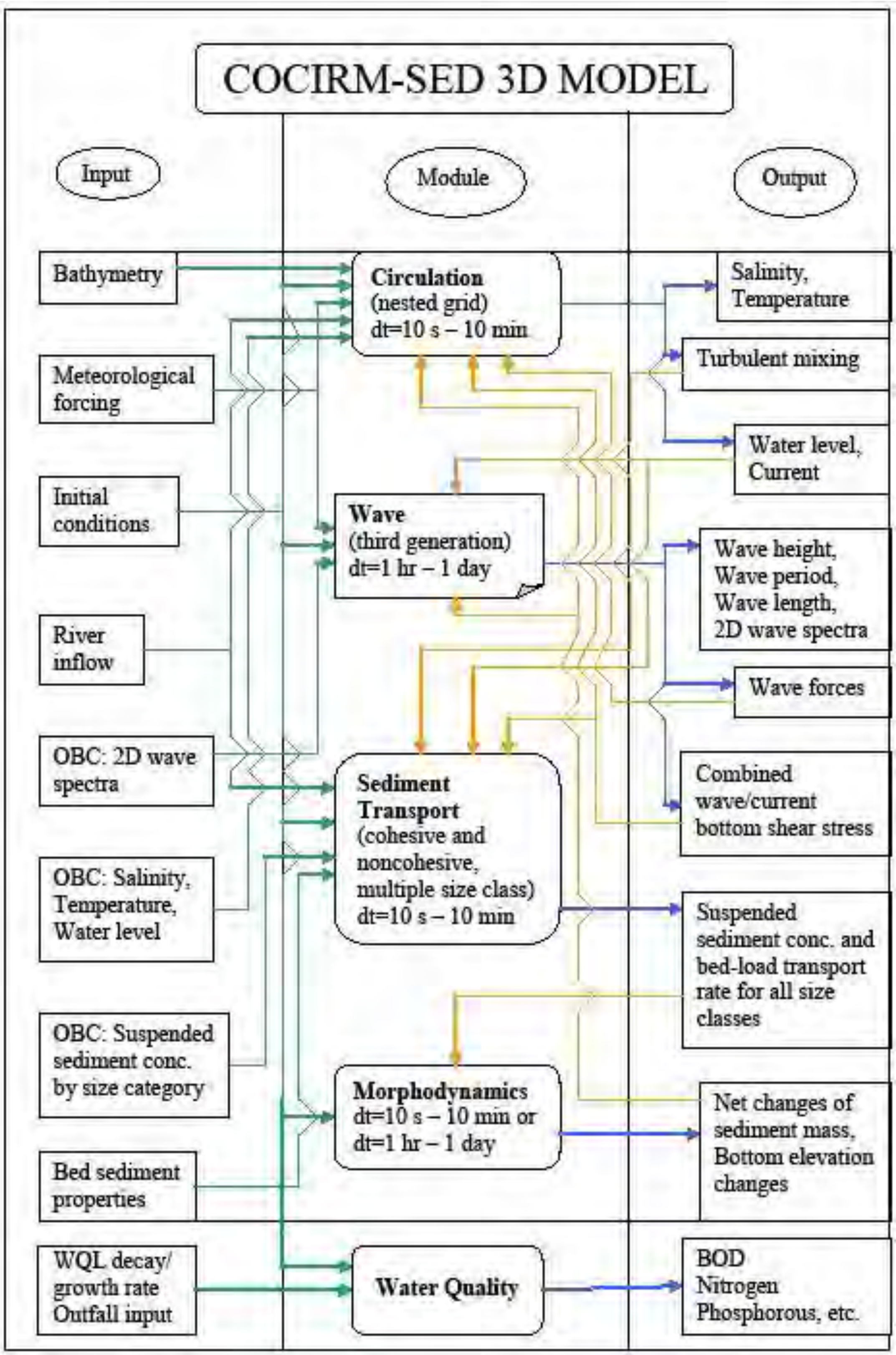


Figure 1-4: Schematic diagram of the COCIRM-SED numerical model.

Table 1-1: Summary of model calibration, verification, and additional cases.

Model Cases	**Flow/water level condition**	**Revelstoke Dam flow**		**Jordan River flow (m3/s)**	**Arrow Lake level at Nakusp (m)**	**Revelstoke Dam flow T (°C)**	**Jordan River T (°C)**	**Survey Date**
		m3/s	**kcfs**					
Calibration	Interm/Interm	720	25.4	55	435.5	7.29	5.63	Jun. 7, 2010
Verification 1	High/Low	1465	51.7	7	433.7	10.98	9.61	Oct. 25, 2010
Verification 2	High/Interm	1274	45.0	55	435.6	7.37	5.87	Jun. 8, 2010
Verification 3	Low/Interm	212	7.5	55	435.6	8.47	5.52	Jun. 9, 2010
Verification 4	Low/Low	235	8.3	9	433.7	11.31	9.94	Oct. 24, 2010
Verification 5	High/High	1587	56.0	31.15	439.3	7.37	5.87	Aug. 3, 2011
Verification 6 ($H_{ALR}75_{REVQ}$)	High/High	2124	75.0	19	441	11.6	11.0	Aug. 3, 2012
Additional 01	Interm/High	907	32.0	30	441	7.37	5.87	
Additional 02	High/High	2094	73.9	30	441	7.37	5.87	
Additional 03	Low/High	111.6	3.9	30	441	7.37	5.87	
Additional 04	High/High	1173	41.4	30	438.8	7.37	5.87	
Additional 05	High/High	1588	56.1	30	441	7.37	5.87	
Additional 06	Interm/High	615	21.7	30	438.4	7.37	5.87	
Additional 07	High/Interm	2094	73.9	30	437.5	7.37	5.87	
Additional 08	High/Low	2094	73.9	30	433.7	7.37	5.87	
Additional 09	High/Interm	1795	63.4	30	436.9	7.37	5.87	
Additional 10	Low/Interm	111.6	3.9	30	437.5	7.37	5.87	
Additional 11	Interm/Low	821	29.0	30	433.7	7.37	5.87	
Additional 12	Low/Low	111.6	3.9	30	433.7	7.37	5.87	
Additional 13	High/High	1975	69.7	30	438.5	7.37	5.87	
Additional 14	Low/Interm	370	13.1	30	439.5	7.37	5.87	
Additional 15	Low/Interm	485	17.1	30	436.5	7.37	5.87	
Additional 16	High/Interm	1030	36.4	30	436.5	7.37	5.87	
Additional 17	High/Interm	1506	53.2	30	437.1	7.37	5.87	
Additional 18	Low/Interm	170	6.0	30	436.6	7.37	5.87	
Additional 19	Low/High	170	6.0	30	439.0	7.37	5.87	
Additional 20	Interm/High	820	29.0	30	441.0	7.37	5.87	

Table 1-2: Summary of new model cases in 2013.

Model Cases	Revelstoke Dam flow		Jordan River flow (m^3/s)	Arrow Lake level at Nakusp (m)	Revelstoke Dam flow temperature (°C)	Jordan River flow temperature (°C)
	(m^3/s)	(kcfs)				
$H_{ALR}0_{REVQ}$	0	0	19	441	11.6	11.0
$M_{ALR}0_{REVQ}$	0	0	19	437	11.6	11.0
$L_{ALR}0_{REVQ}$	0	0	19	434	11.6	11.0
$H_{ALR}5_{REVQ}$	142	5	19	441	11.6	11.0
$M_{ALR}5_{REVQ}$	142	5	19	437	11.6	11.0
$L_{ALR}5_{REVQ}$	142	5	19	434	11.6	11.0
$H_{ALR}20_{REVQ}$	566	20	19	441	11.6	11.0
$M_{ALR}20_{REVQ}$	566	20	19	437	11.6	11.0
$L_{ALR}20_{REVQ}$	566	20	19	434	11.6	11.0
$H_{ALR}30_{REVQ}$	850	30	19	441	11.6	11.0
$M_{ALR}30_{REVQ}$	850	30	19	437	11.6	11.0
$L_{ALR}30_{REVQ}$	850	30	19	434	11.6	11.0
$H_{ALR}60_{REVQ}$	1699	60	19	441	11.6	11.0
$M_{ALR}60_{REVQ}$	1699	60	19	437	11.6	11.0
$L_{ALR}60_{REVQ}$	1699	60	19	434	11.6	11.0
$M_{ALR}75_{REVQ}$	2124	75	19	437	11.6	11.0
$L_{ALR}75_{REVQ}$	2124	75	19	434	11.6	11.0
$H_{ALR}90_{REVQ}$	2549	90	19	441	11.6	11.0
$M_{ALR}90_{REVQ}$	2549	90	19	437	11.6	11.0
$L_{ALR}90_{REVQ}$	2549	90	19	434	11.6	11.0
$H_{ALR}92.5_{REVQ}$	2619	92.5	19	441	11.6	11.0
$M_{ALR}92.5_{REVQ}$	2619	92.5	19	437	11.6	11.0
$L_{ALR}92.5_{REVQ}$	2619	92.5	19	434	11.6	11.0
Spawning Event1	1520	53.7	26.6	440.0	8.8	11.0
Spawning Event2	633	22.4	26.5	439.7	9.4	11.0
Spawning Event3	1573	55.5	14.4	438.7	10.2	11.0
Spawning Event4	611	21.6	25.8	438.1	9.7	11.0
Spawning Event5	381	13.5	19.0	437.5	10.5	11.0
Spawning Event7	1127	39.8	26.6	439.1	9.4	11.0
Spawning Event8	1454	51.4	14.9	439.0	10.4	11.0
Spawning Event9	269	9.5	25.8	436.4	13.0	11.4
Spawning Event10	249	8.8	21.4	436.2	12.1	11.0
Spawning Event11	0	0.0	16.7	436.0	11.1	11.4
Spawning Event12	156	5.5	26.6	439.5	11.9	7.4
Spawning Event13	1286	45.4	16.4	439.1	12.0	9.4
Spawning Event14	243	8.6	16.8	438.4	12.2	9.7

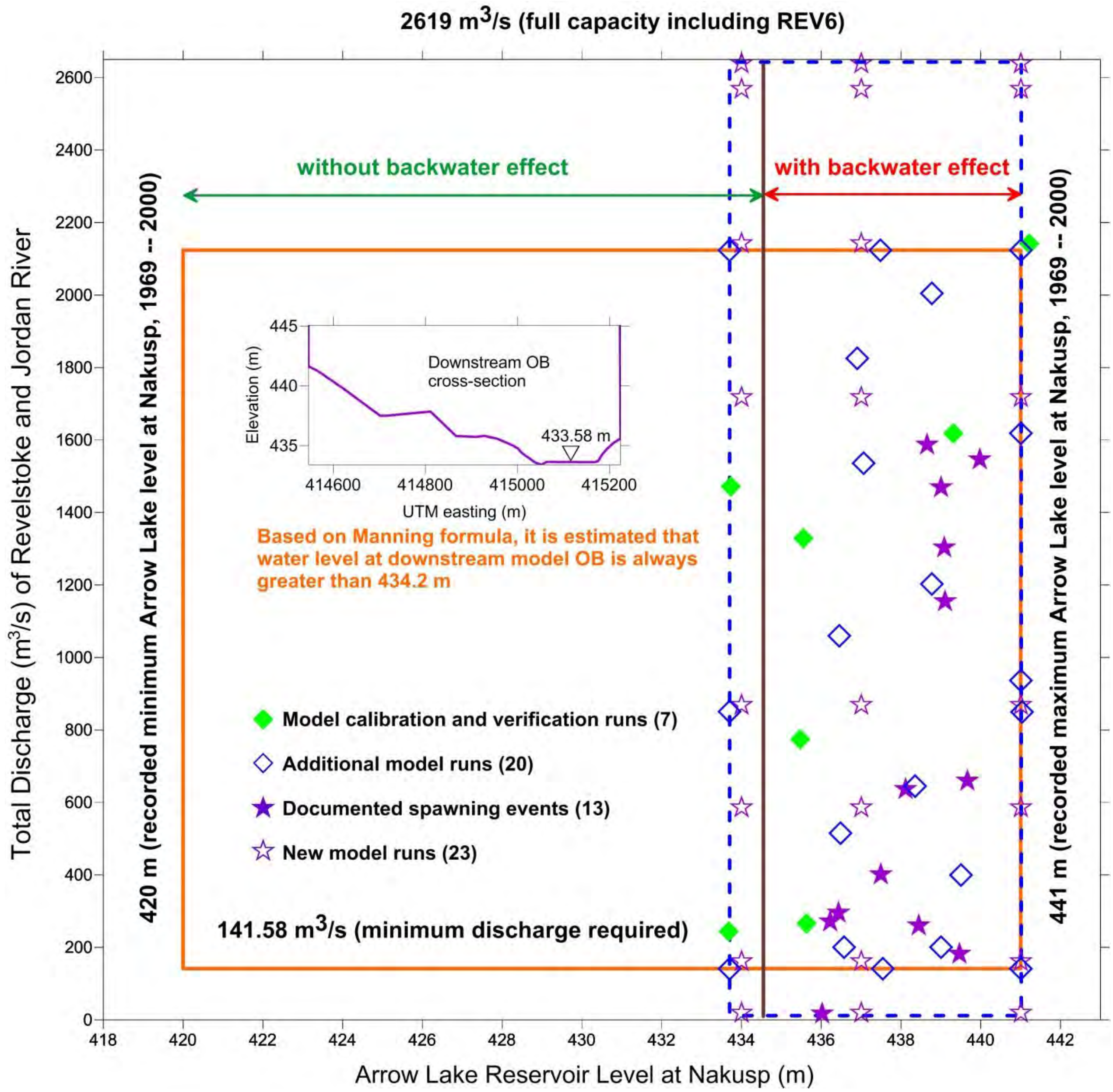


Figure 1-5. Revelstoke Dam discharge and Arrow Lakes Reservoir level conditions for all model runs in Table 1-1 and 1-2.

2. Effect of Jordan River Temperatures

Effects of Jordan River inflows on water temperatures in the egg incubation and early larval rearing areas were studied using 8 model runs shown in Table 2-1. Revelstoke Dam discharges of 142 m^3/s (5 kcfs) and 1699 m^3/s (60 kcfs) are examined with ALR levels of 411 m and 434 m separately. Jordan River discharges were set at 27 m^3/s based on historical measurements (maximum of multiyear mean daily averages from August 1 to August 31 in years 1964-1988).

Daily averaged Jordan River temperatures for August in the years 2009-2011 are shown in Figure 2-1. The values of 12.5^{o}C and 9.0^{o}C were selected to demonstrate their effect on the flow regimes. Columbia River temperatures in August were found to be varying with a small range around 11^{o}C.

The model results of near bottom temperature distribution are shown in Figure 2-2. The model results well demonstrated the influence of the temperature difference between the Jordan River and the Columbia River associated with different Columbia River discharges and downstream water levels.

Table 2-1: Summary of model cases to examine the effect of Jordan River water temperatures on White Sturgeon egg incubation and early larval rearing habitat.

Model Cases	Revelstoke Dam flow		Jordan River flow (m3/s)	Arrow Lake level at Nakusp (m)	Revelstoke Dam flow temperature (°C)	Jordan River flow temperature (°C)
	(m3/s)	(kcfs)				
$H_{Jordan}H_{ALR}5_{REVQ}$	142	5	27	441	11.0	12.5
$C_{Jordan}H_{ALR}5_{REVQ}$	142	5	27	441	11.0	9.0
$H_{Jordan}L_{ALR}5_{REVQ}$	142	5	27	434	11.0	12.5
$C_{Jordan}L_{ALR}5_{REVQ}$	142	5	27	434	11.0	9.0
$H_{Jordan}H_{ALR}60_{REVQ}$	1700	60	27	441	11.0	12.5
$C_{Jordan}H_{ALR}60_{REVQ}$	1700	60	27	441	11.0	9.0
$H_{Jordan}L_{ALR}60_{REVQ}$	1700	60	27	434	11.0	12.5
$C_{Jordan}L_{ALR}60_{REVQ}$	1700	60	27	434	11.0	9.0

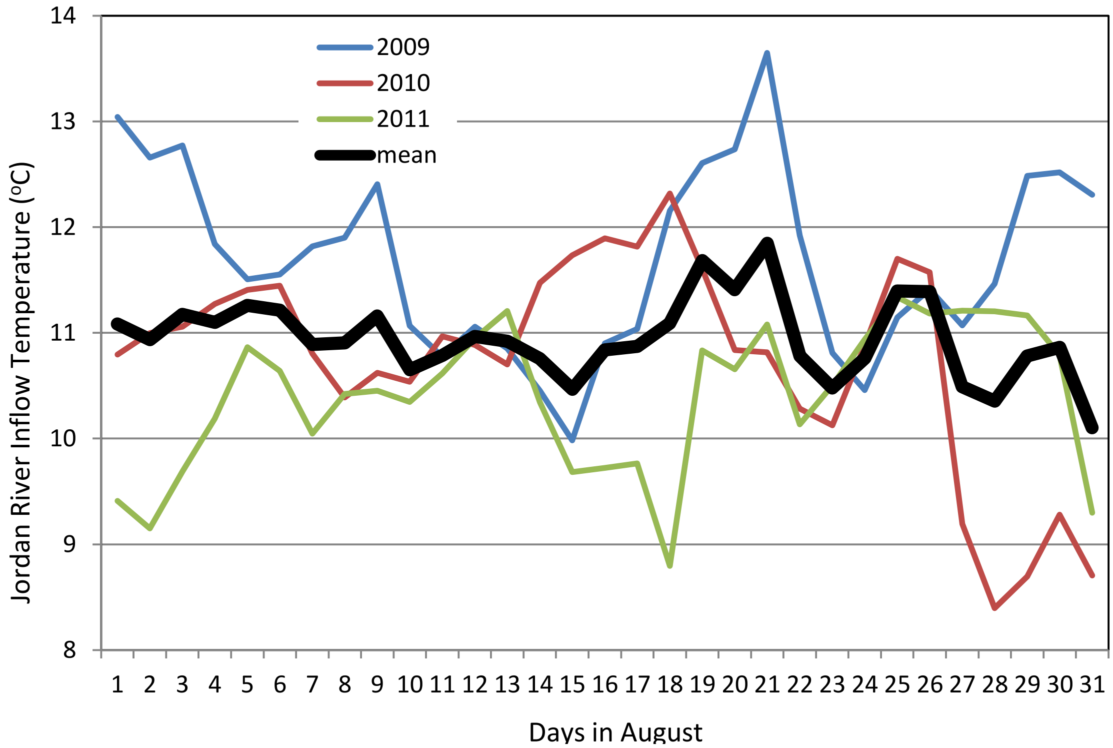


Figure 2-1: Jordan River temperatures (daily average) in August, 2009, 2010, and 2011.

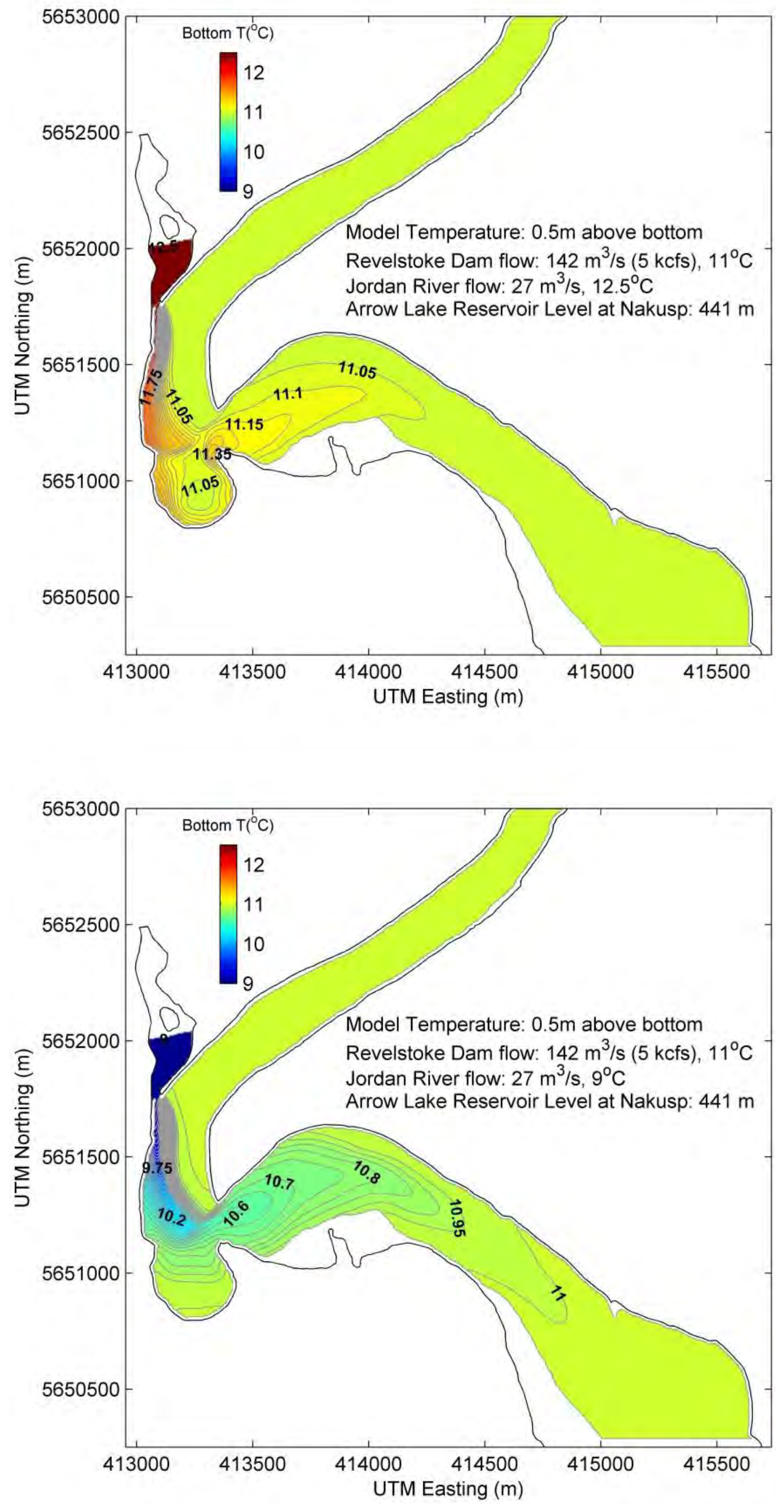
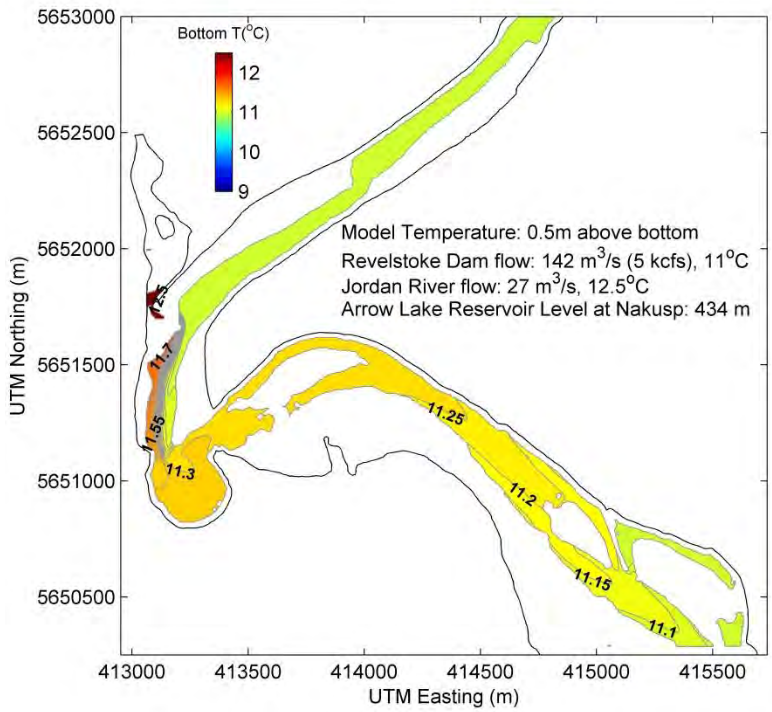


Figure 2-2: Model near bottom temperature for Jordan River temperatures of 12.5 °C (upper panel) and 9.0 °C (lower panel).



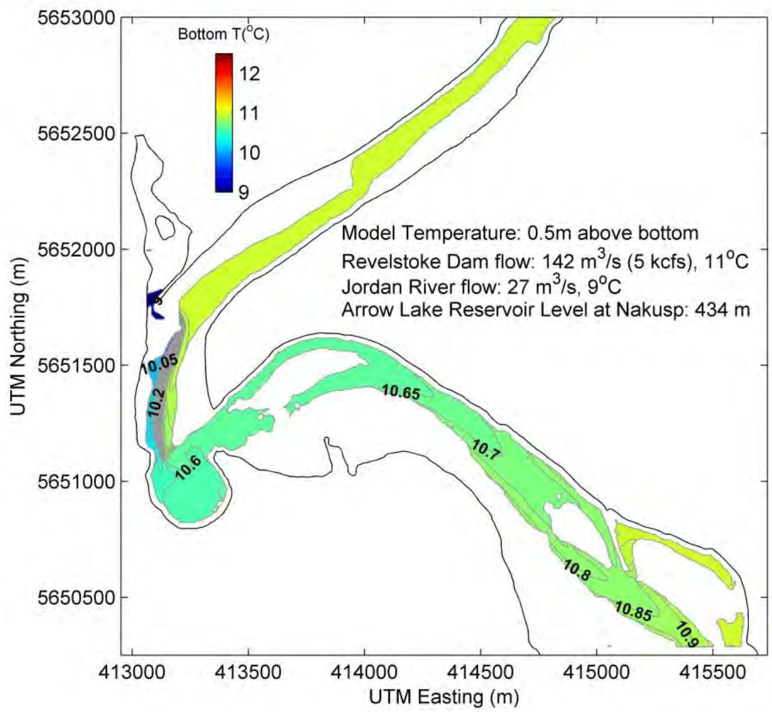
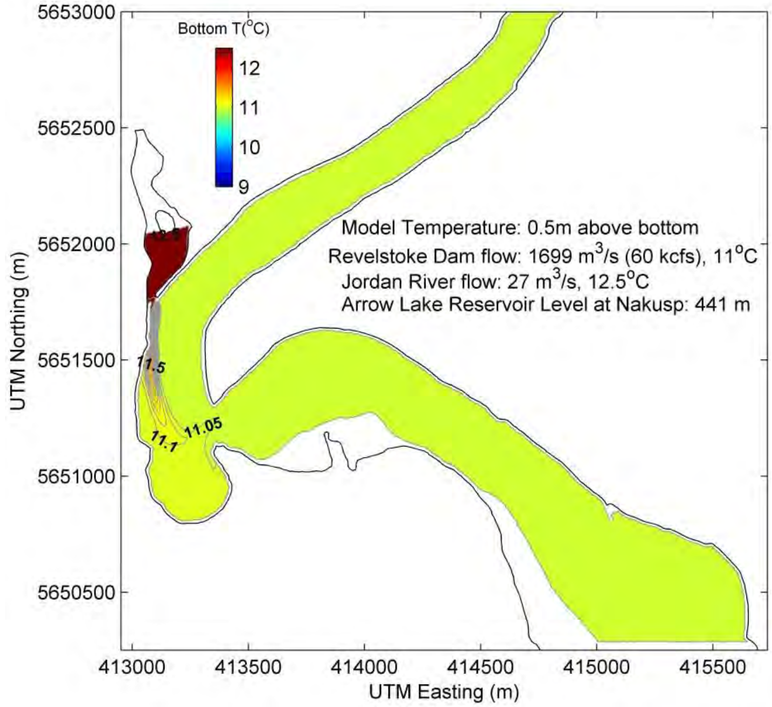


Figure 2-2: Continued.



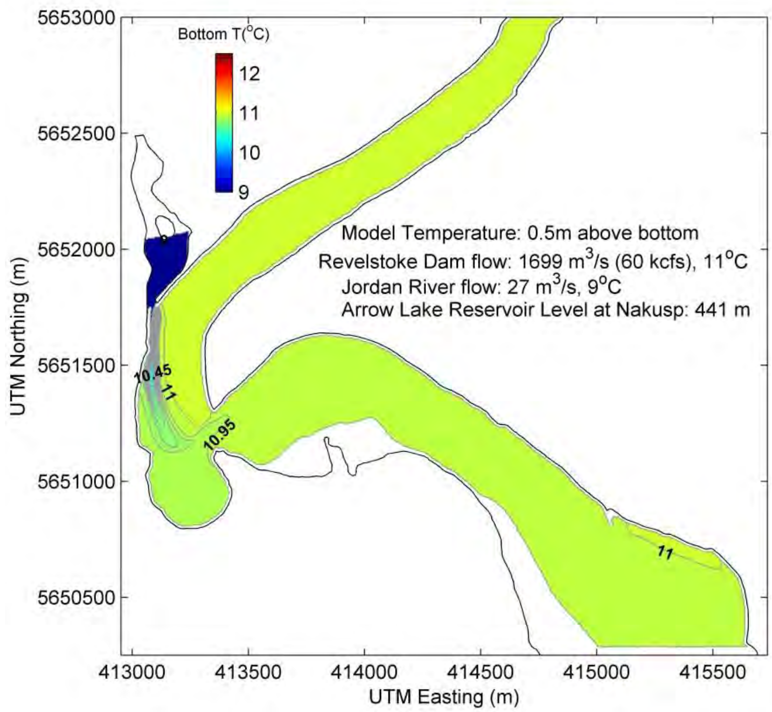
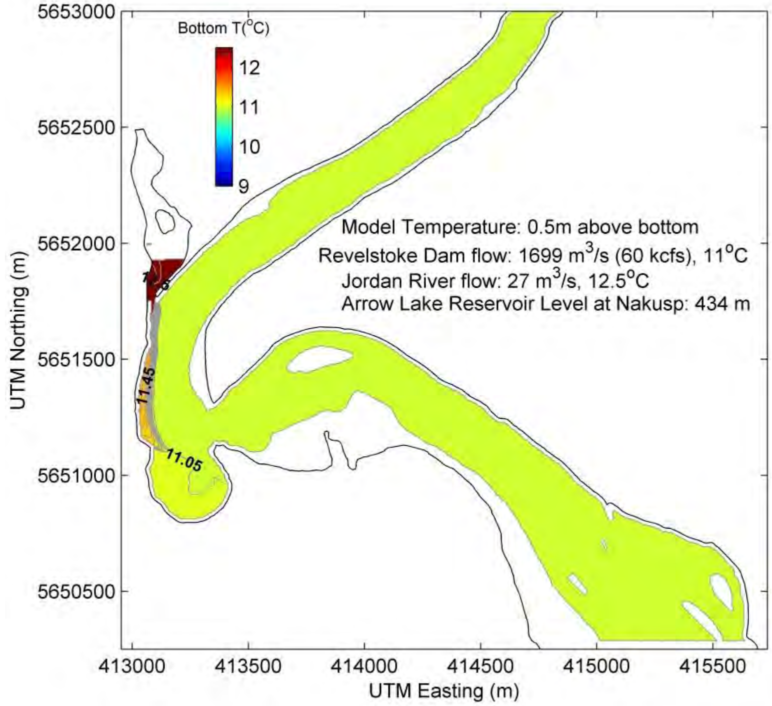


Figure 2-2: Continued.



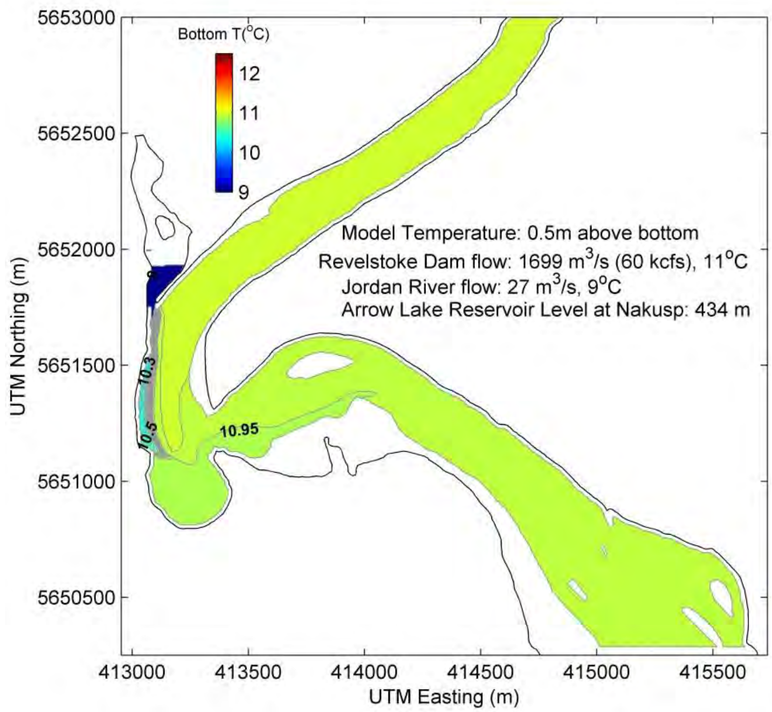


Figure 2-2: Continued.

3. Actual Near Bottom Flows during Spawning

In this section, near bottom flow conditions were examined at locations and estimated time of White Sturgeon spawning as determined by the back-calculation of developmental stages of captured eggs. There are 13 spawning events studied out of the 14 documented spawning events (information for Event #6 is missing, see Table 3-1). The coordinates of the 34 selected egg mat sites are listed in Table 3-2.

Discharge, water level, and water temperature conditions for the 13 spawning event model runs are summarized in Table 3-3. Hourly Columbia River discharges, temperatures, and ALR levels were obtained from BC Hydro records at the estimated time of each spawning event. Hourly measurements of Jordan River discharges and temperatures were not available for most spawning events; missing values were estimated by interpolation based on available data.

Modeled near bottom flow velocities in the Revelstoke White Sturgeon spawning and egg incubation area (speed and flow vectors) for each spawning event are shown in Figures 3-1 to 3-13. Modelled near bottom flow velocities for each of the 13 spawning events and at each egg mat site where eggs from that event were captured were summarized in Table 3-4.

Table 3-1: Estimated frequency and timing of White Sturgeon spawning events.

Event #	Date	Time (24h)	Site #
1	31-Jul-99	0:00	3, 4, 5
2	02-Aug-99	6:00	3, 5
3	22-Aug-99	9:00	1, 2, 3, 5
4	03-Aug-03	0:00	7, 8
5	14-Aug-03	1:00	6, 7, 8
6	N/A		
7	31-Jul-08	16:00	10
8	21-Aug-08	17:00	9, 11
9	03-Aug-09	5:00	12 - 17, 19, 22
10	08-Aug-09	4:00	18, 20, 21
11	18-Aug-09	1:00	21
12	30-Jul-11	3:13	27, 30
13	20-Aug-11	10:26	23 - 29, 31 - 34
14	27-Aug-11	6:21	34

Table 3-2: Capture locations of White Sturgeon eggs.

Site#	Easting (m)	Northing (m)
1	413787	5652074
2	413709	5651991
3	413406	5651784
4	413357	5651761
5	413258	5651646
6	413479	5651874
7	413376	5651792
8	413320	5651695
9	414276	5652502
10	413275	5651676
11	413197	5651459
12	413731	5652041
13	413634	5651966
14	413483	5651914
15	413403	5651798
16	413380	5651799
17	413364	5651766
18	413259	5651774
19	413302	5651733
20	413281	5651633
21	413174	5651372
22	413196	5651427
23	413957	5652299
24	414083	5652336
25	413945	5652261
26	413684	5652016
27	413667	5652034
28	413522	5651906
29	413447	5651864
30	413395	5651830
31	413391	5651795
32	413319	5651733
33	413353	5651757
34	413221	5651519

Table 3-3: Model cases for White Sturgeon spawning events.

Model Cases	Revelstoke Dam flow		Jordan River flow (m^3/s)	Arrow Lake level at Nakusp (m)	Revelstoke Dam flow temperature (°C)	Jordan River flow temperature (°C)
	(m^3/s)	(kcfs)				
Event1 (31-Jul-99)	1520	53.7	26.6	440.0	8.8	11.0
Event2 (02-Aug-99)	633	22.4	26.5	439.7	9.4	11.0
Event3 (22-Aug-99)	1573	55.5	14.4	438.7	10.2	11.0
Event4 (03-Aug-03)	611	21.6	25.8	438.1	9.7	11.0
Event5 (14-Aug-03)	381	13.5	19.0	437.5	10.5	11.0
Event7 (31-Jul-08)	1127	39.8	26.6	439.1	9.4	11.0
Event8 (21-Aug-08)	1454	51.4	14.9	439.0	10.4	11.0
Event9 (03-Aug-09)	269	9.5	25.8	436.4	13.0	11.4
Event10 (08-Aug-09)	249	8.8	21.4	436.2	12.1	11.0
Event11 (18-Aug-09)	0	0.0	16.7	436.0	11.1	11.4
Event12 (30-Jul-11)	156	5.5	26.6	439.5	11.9	7.4
Event13 (20-Aug-11)	1286	45.4	16.4	439.1	12.0	9.4
Event14 (27-Aug-11)	243	8.6	16.8	438.4	12.2	9.7

Table 3-4: Summary of near-bottom velocities at sites where White Sturgeon eggs were captured and at the estimated time of egg deposition for all spawning events recorded in the Revelstoke spawning area between 1999 and 2011.

Event #	Date	Time (24h)	Site #	Near-bottom velocity (m/s)
1	31-Jul-99	00:00	3	0.23
			4	1.06
			5	1.55
2	02-Aug-99	06:00	3	0.09
			5	0.78
3	22-Aug-99	09:00	1	0.78
			2	0.00
			3	0.19
			5	2.06
4	03-Aug-03	00:00	7	0.77
			8	0.71
5	14-Aug-03	01:00	6	0.65
			7	0.62
			8	0.59
7	31-Jul-08	16:00	10	1.44
8	21-Aug-08	17:00	9	2.19
			11	2.04
9	03-Aug-09	05:00	12	0.55
			13	0.00
			14	1.17
			15	0.26
			16	0.61
			17	0.49
			19	0.98
			22	0.54
10	08-Aug-09	04:00	18	0.79
			20	0.70
			21	0.14
11	18-Aug-09	01:00	21	0.02
12	30-Jul-11	03:13	27	0.25
			30	0.18
13	20-Aug-11	10:26	23	2.09
			24	1.85
			25	2.20
			26	1.26
			27	1.82
			28	1.35
			29	1.50
			31	0.91
			32	1.40
			33	1.08
			34	1.58
14	27-Aug-11	06:21	34	0.49

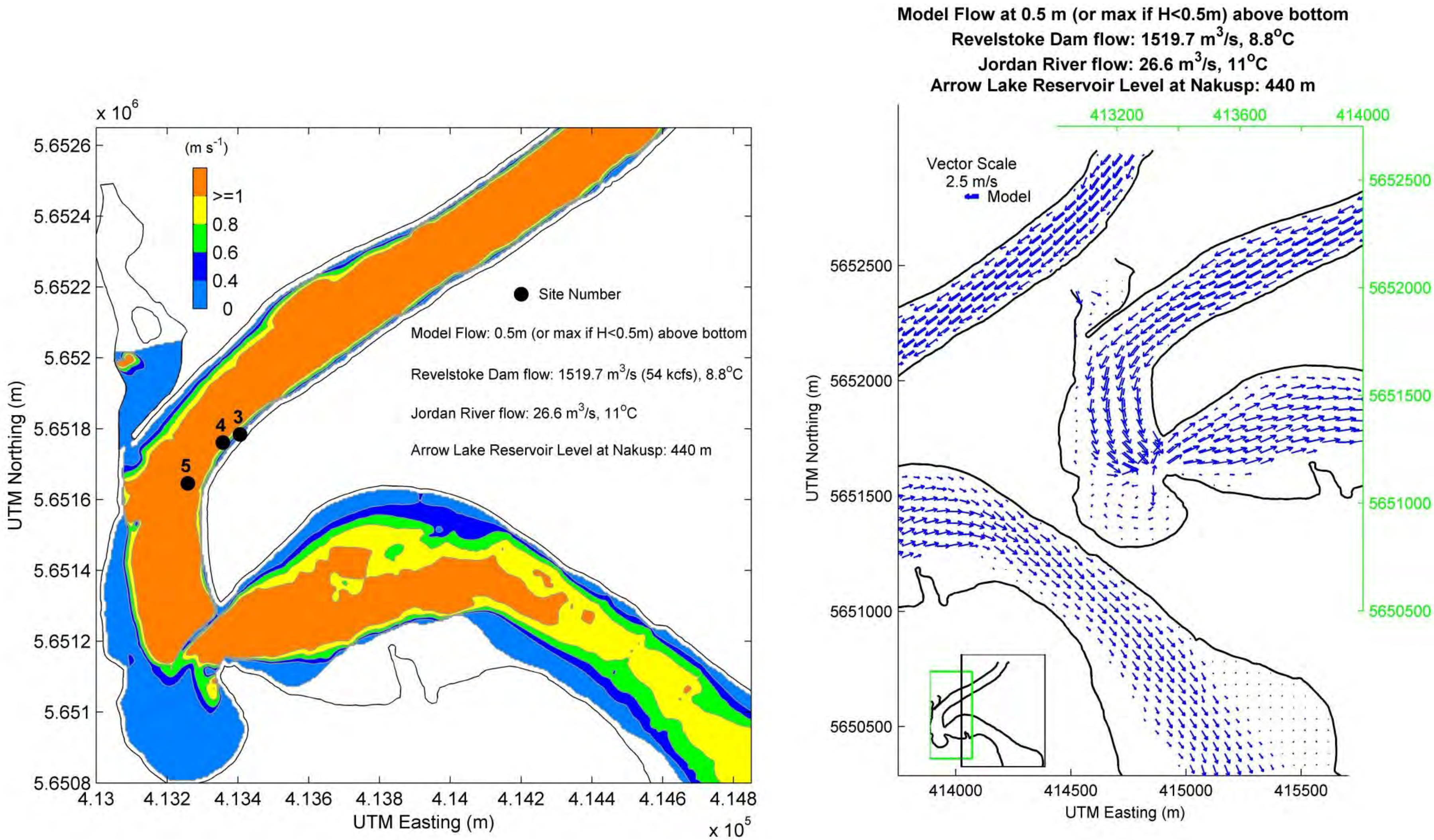


Figure 3-1: Near bottom flow velocities in the Revelstoke White Sturgeon spawning and egg incubation area (left panel: speed; right panel: flow vectors) for Spawning Event 1 on July 31, 1999 at approximately 00:00h.The black dots on the left panel are sites where eggs from Spawning Event 1 were captured.

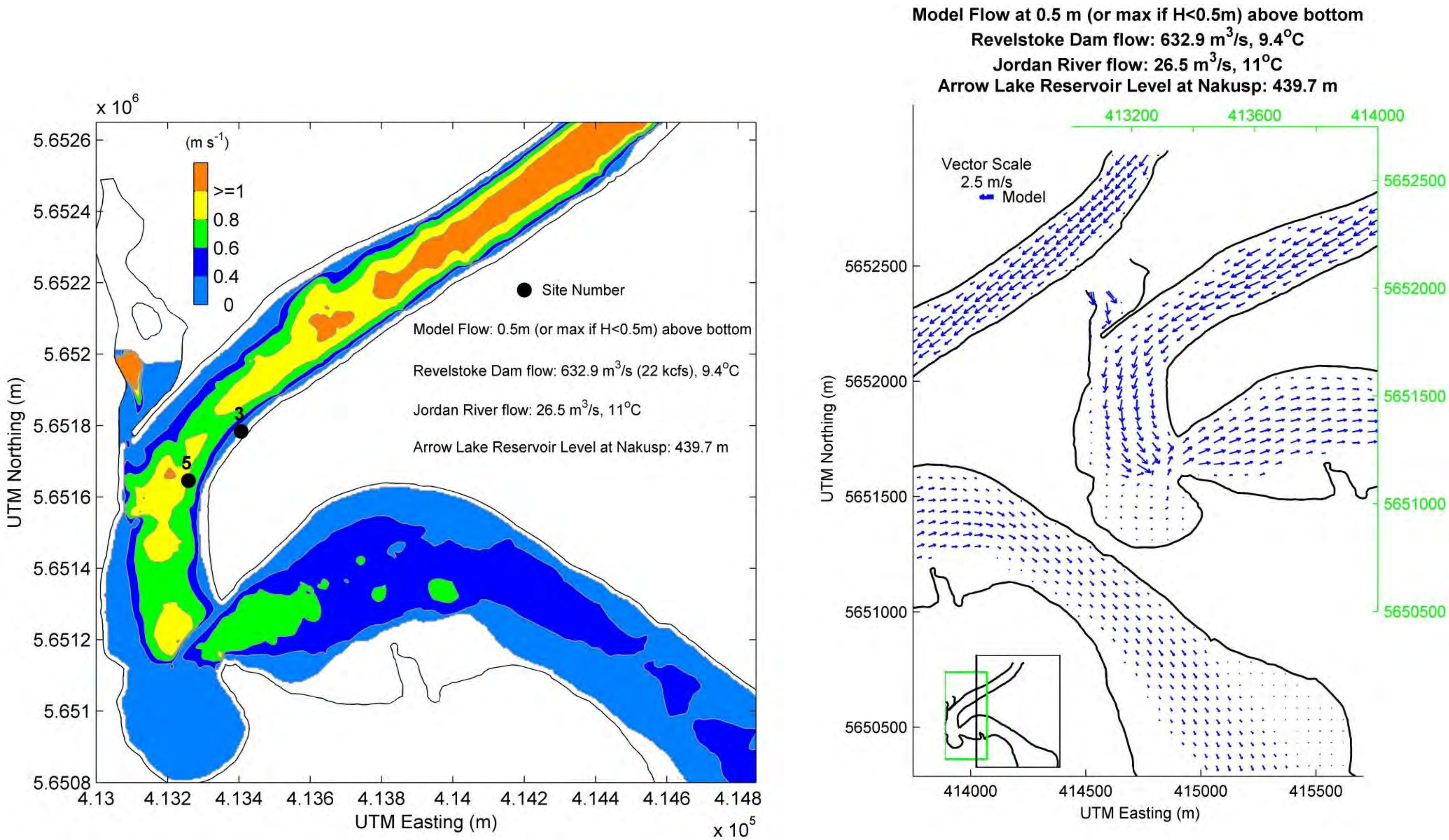


Figure 3-2: Near bottom flow velocities in the Revelstoke White Sturgeon spawning and egg incubation area (left panel: speed; right panel: flow vectors) for Spawning Event 2 on August 2, 1999 at approximately 06:00h. The black dots on the left panel are sites where eggs from Spawning Event 2 were captured.

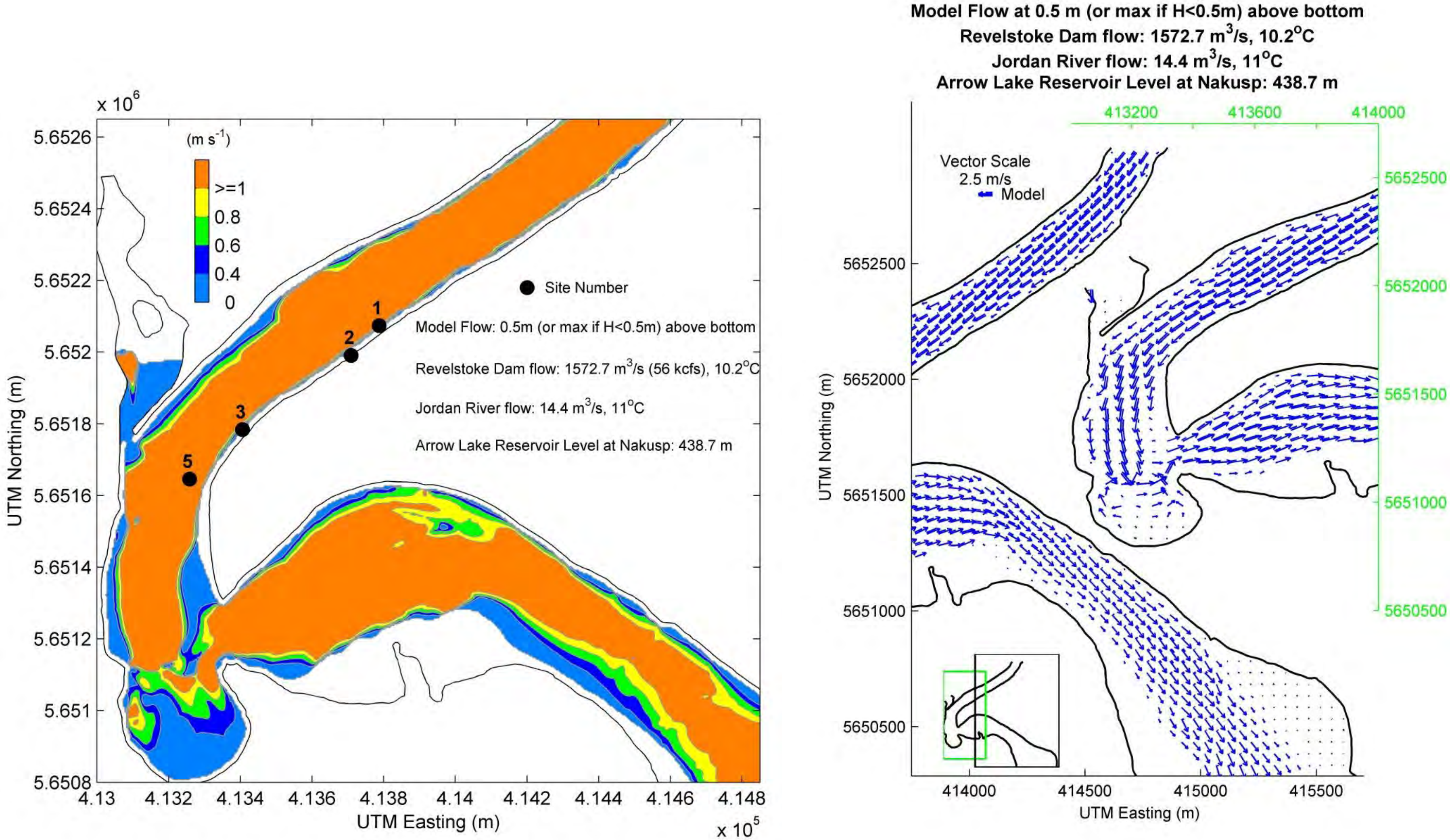


Figure 3-3: Near bottom flow velocities in the Revelstoke White Sturgeon spawning and egg incubation area (left panel: speed; right panel: flow vectors) for Spawning Event 3 on August 22, 1999 at approximately 09:00h. The black dots on the left panel are sites where eggs from Spawning Event 3 were captured.

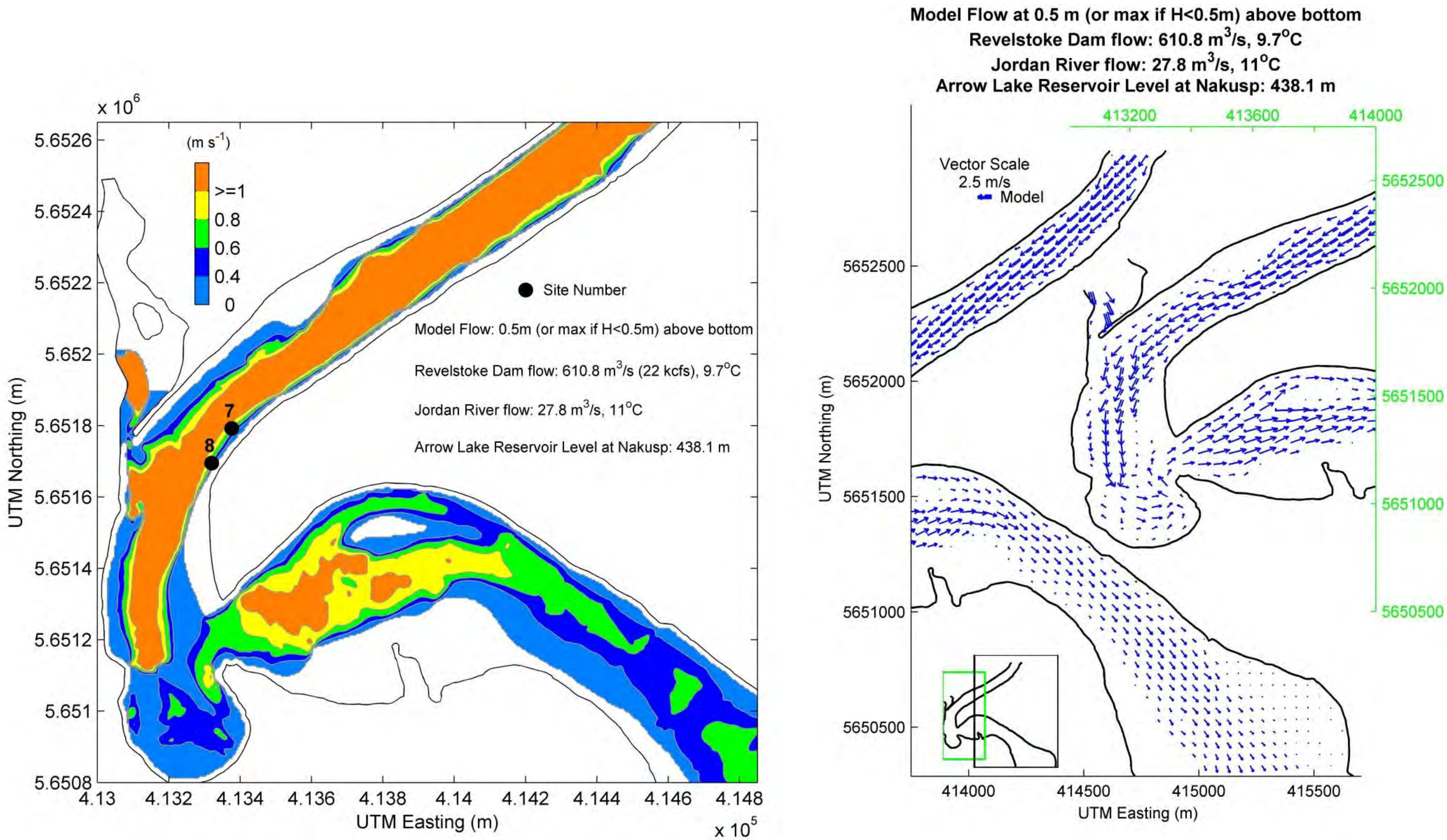


Figure 3-4: Near bottom flow velocities in the Revelstoke White Sturgeon spawning and egg incubation area (left panel: speed; right panel: flow vectors) for Spawning Event 4 on August 3, 2003 at approximately 00:00h. The black dots on the left panel are sites where eggs from Spawning Event 4 were captured.

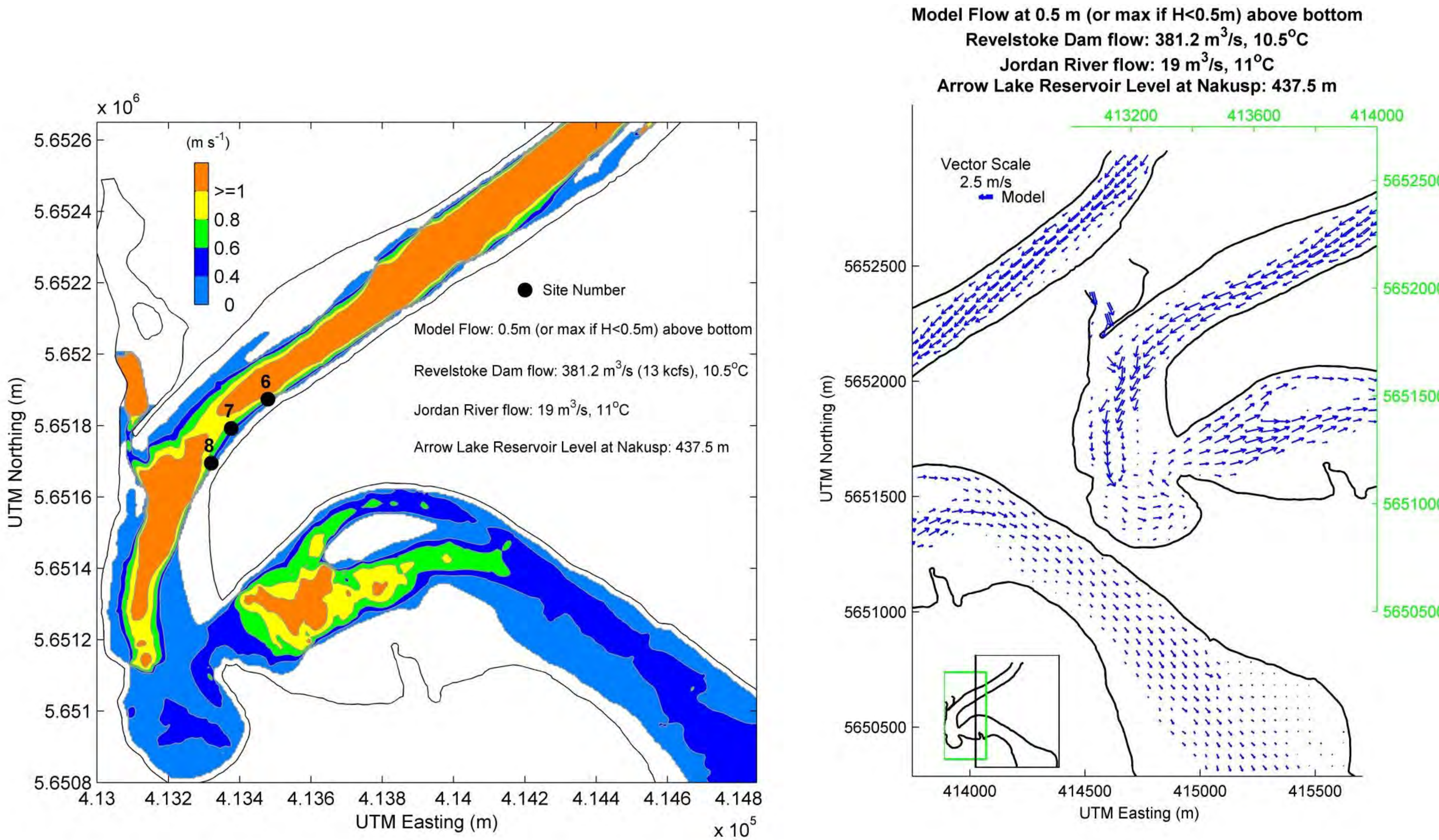


Figure 3-5: Near bottom flow velocities in the Revelstoke White Sturgeon spawning and egg incubation area (left panel: speed; right panel: flow vectors) for Spawning Event 5 on August 14, 2003 at approximately 01:00h. The black dots on the left panel are sites where eggs from Spawning Event 5 were captured.

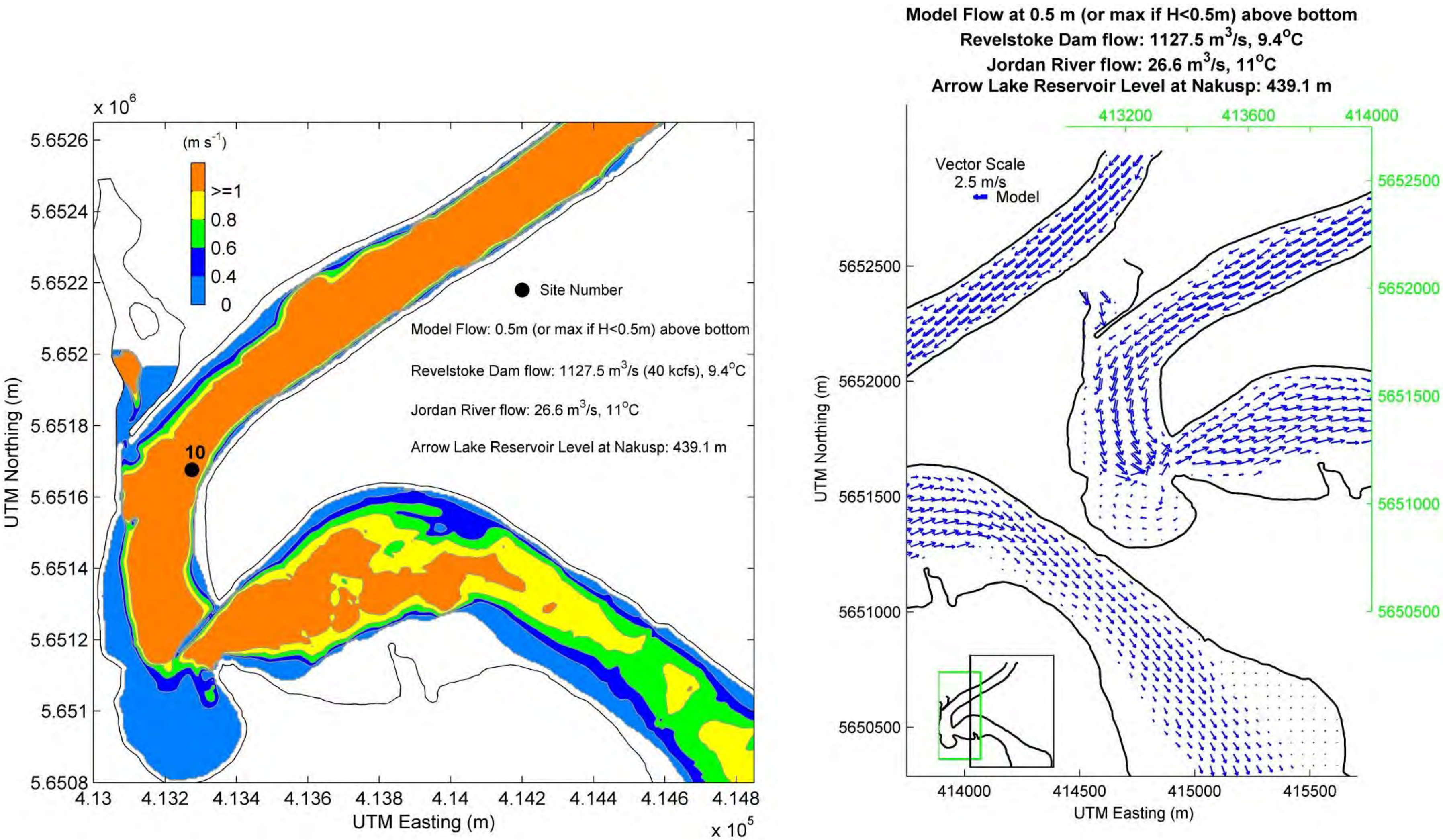


Figure 3-6: Near bottom flow velocities in the Revelstoke White Sturgeon spawning and egg incubation area (left panel: speed; right panel: flow vectors) for Spawning Event 7 on July 31, 2008 at approximately 16:00h. The black dots on the left panel are sites where eggs from Spawning Event 7 were captured.

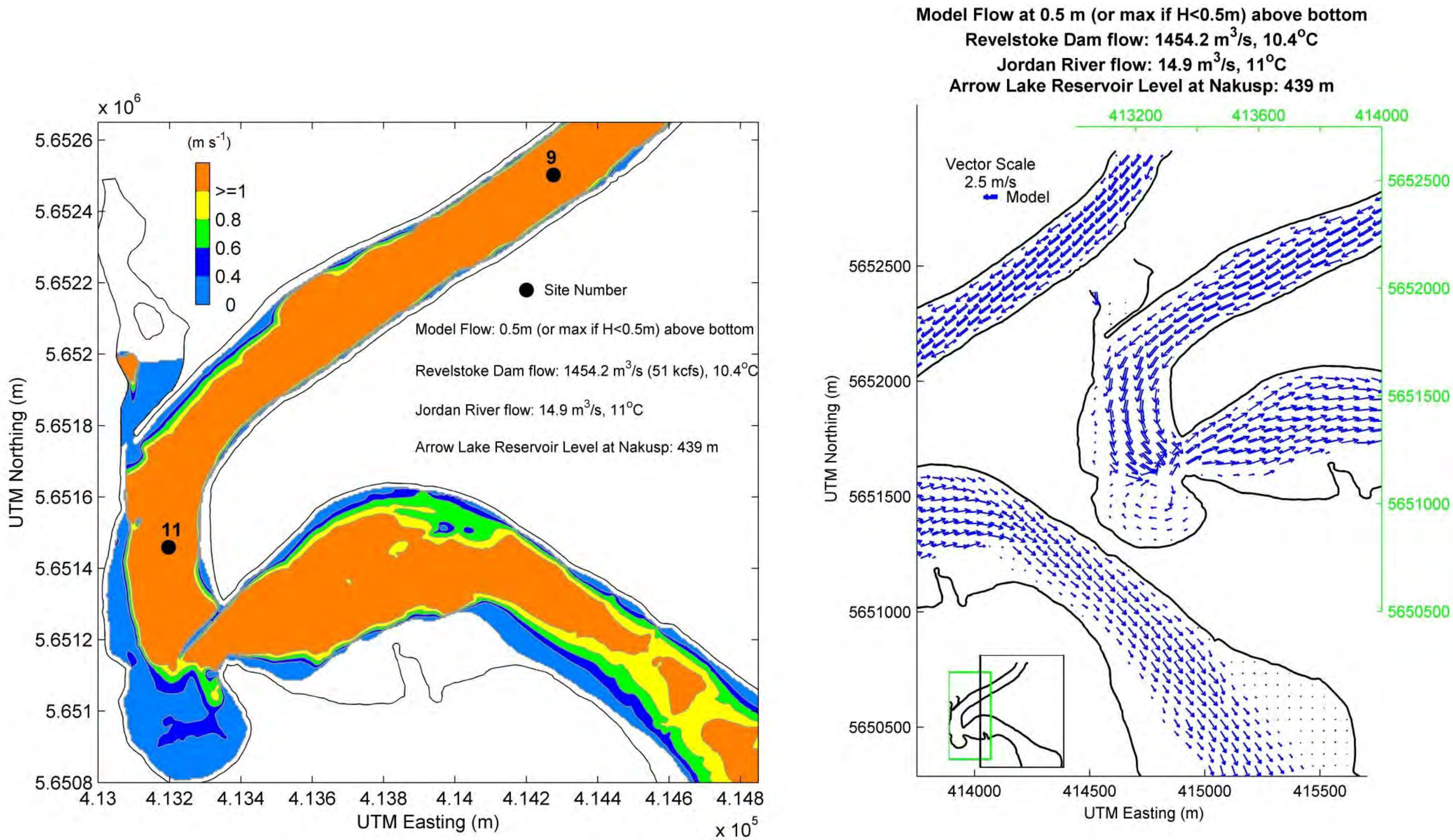


Figure 3-7: Near bottom flow velocities in the Revelstoke White Sturgeon spawning and egg incubation area (left panel: speed; right panel: flow vectors) for Spawning Event 8 on August 21, 2008 at approximately 17:00h. The black dots on the left panel are sites where eggs from Spawning Event 8 were captured.

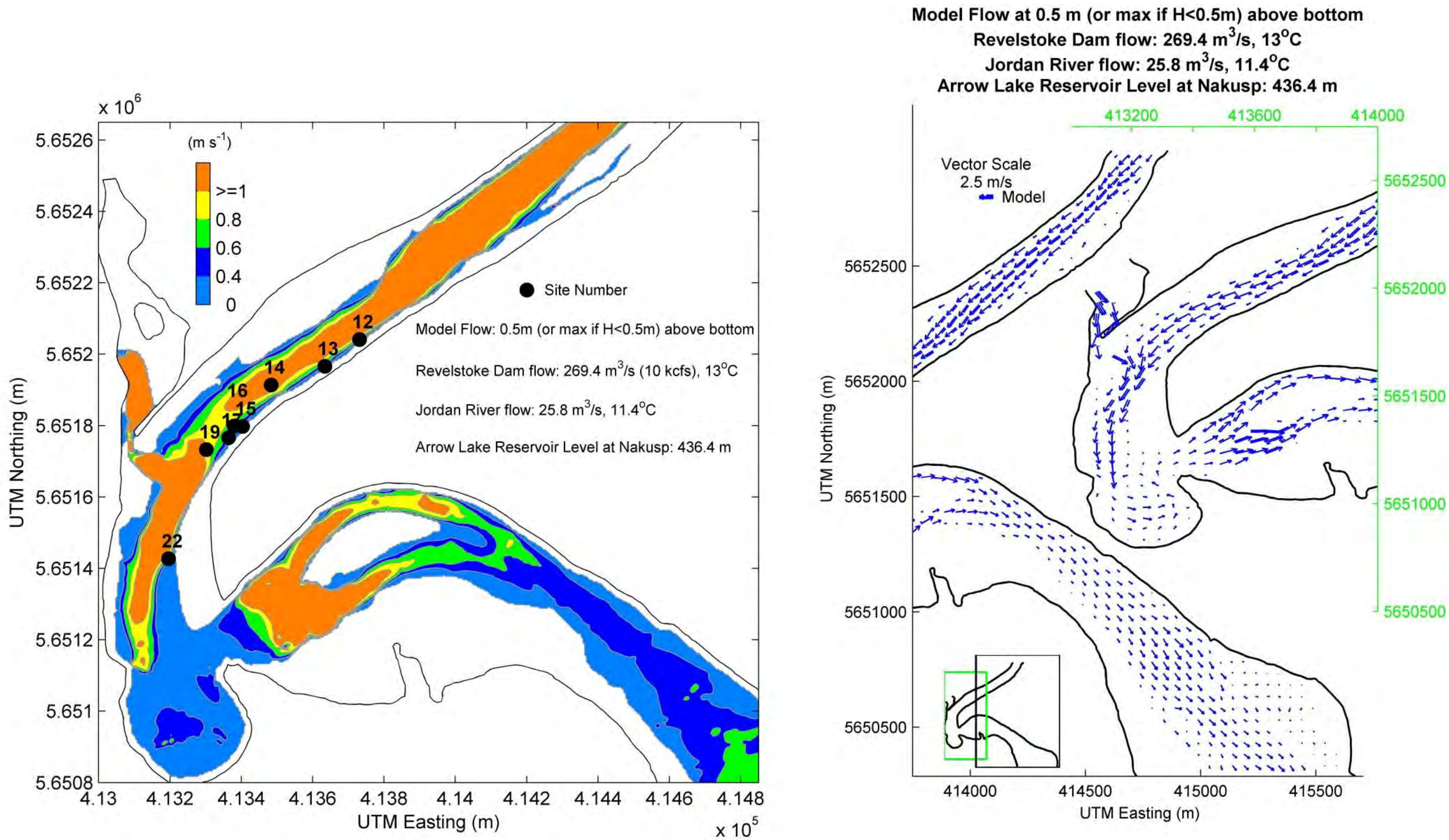


Figure 3-8: Near bottom flow velocities in the Revelstoke White Sturgeon spawning and egg incubation area (left panel: speed; right panel: flow vectors) for Spawning Event 9 on August 3, 2009 at approximately 05:00h. The black dots on the left panel are sites where eggs from Spawning Event 9 were captured.

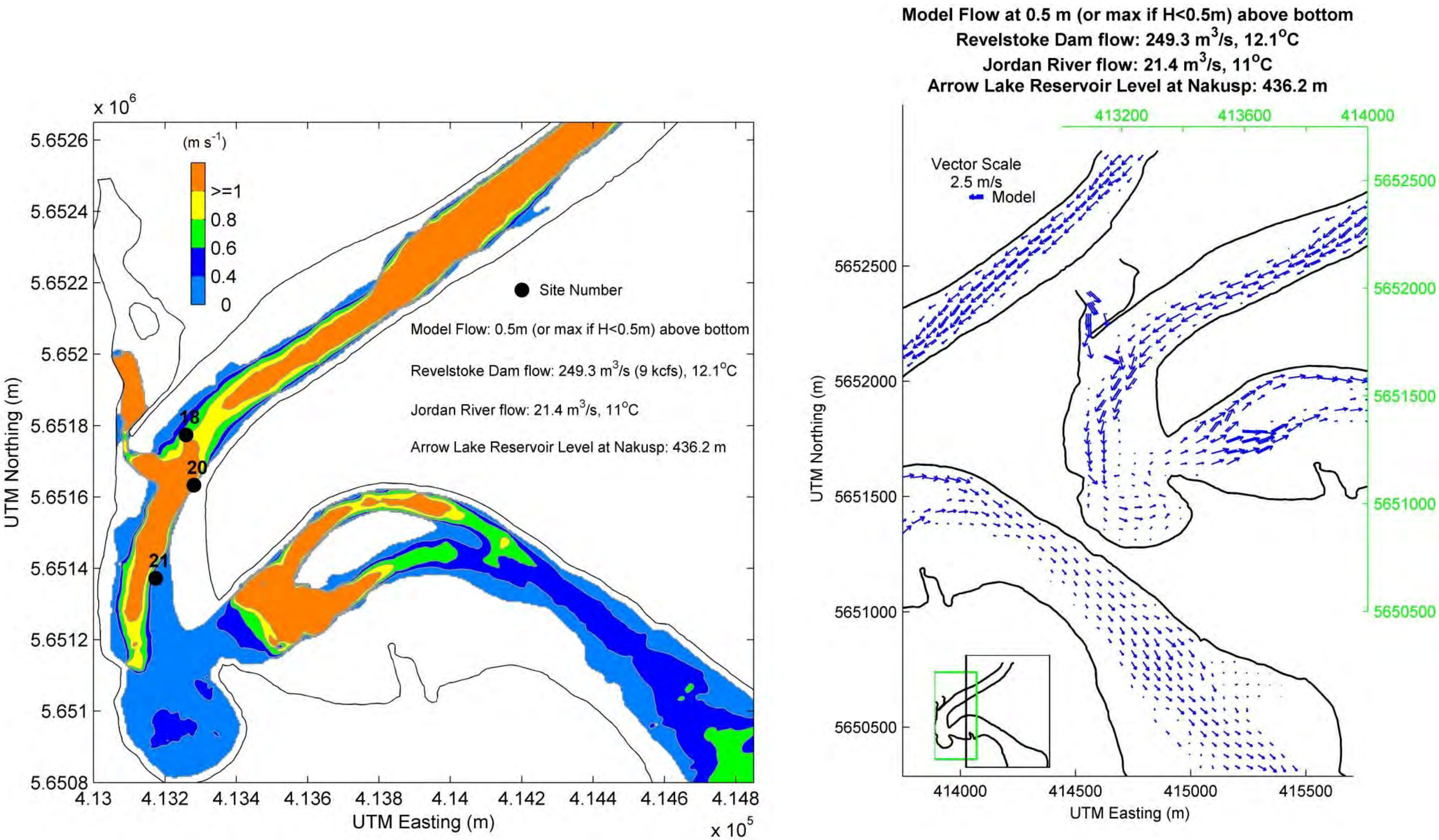


Figure 3-9: Near bottom flow velocities in the Revelstoke White Sturgeon spawning and egg incubation area (left panel: speed; right panel: flow vectors) for Spawning Event 10 on August 8, 2009 at approximately 04:00h. The black dots on the left panel are sites where eggs from Spawning Event 10 were captured.

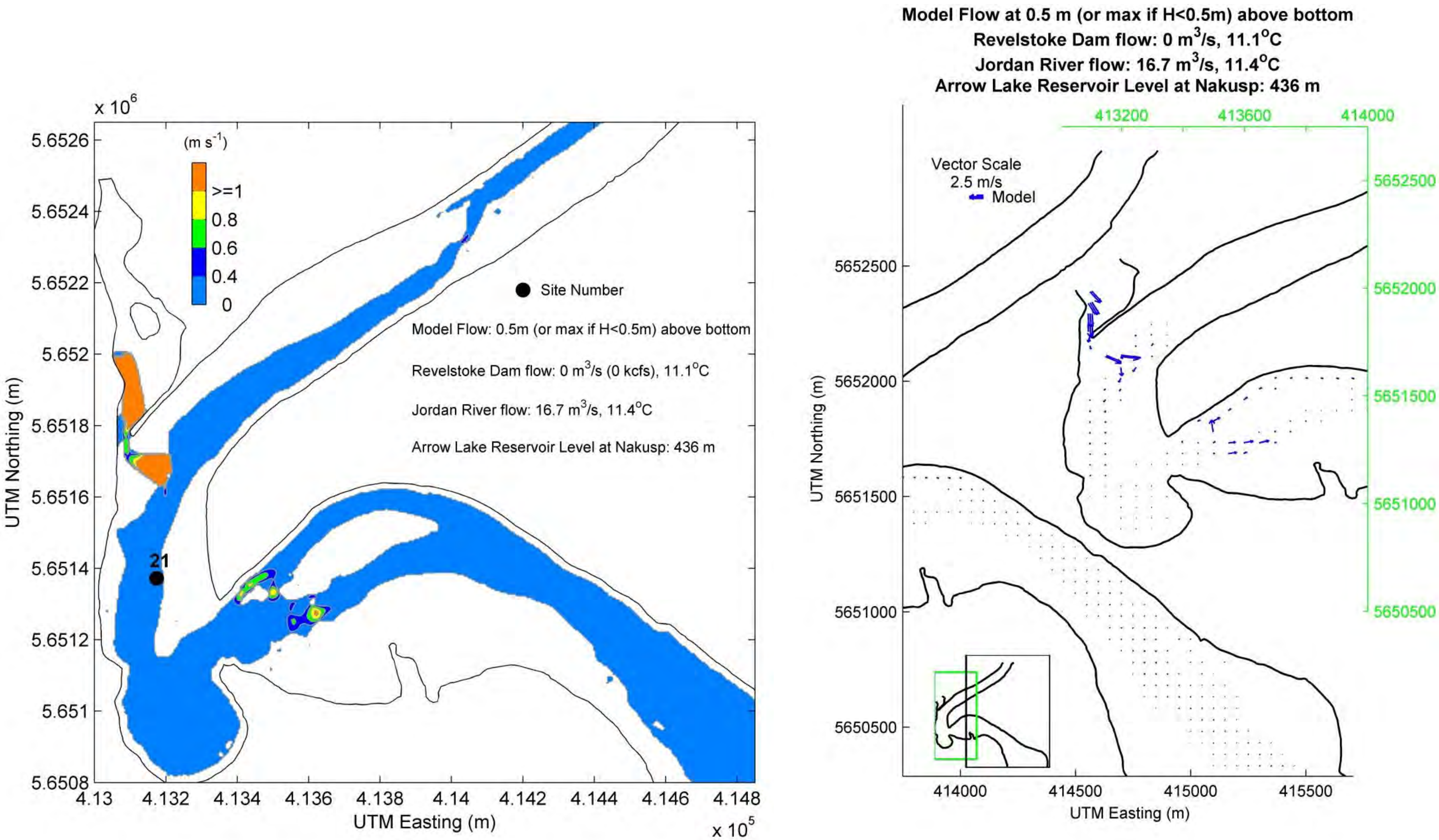


Figure 3-10: Near bottom flow velocities in the Revelstoke White Sturgeon spawning and egg incubation area (left panel: speed; right panel: flow vectors) for Spawning Event 11 on August 18, 2009 at approximately 01:00h. The black dots on the left panel are sites where eggs from Spawning Event 11 were captured.

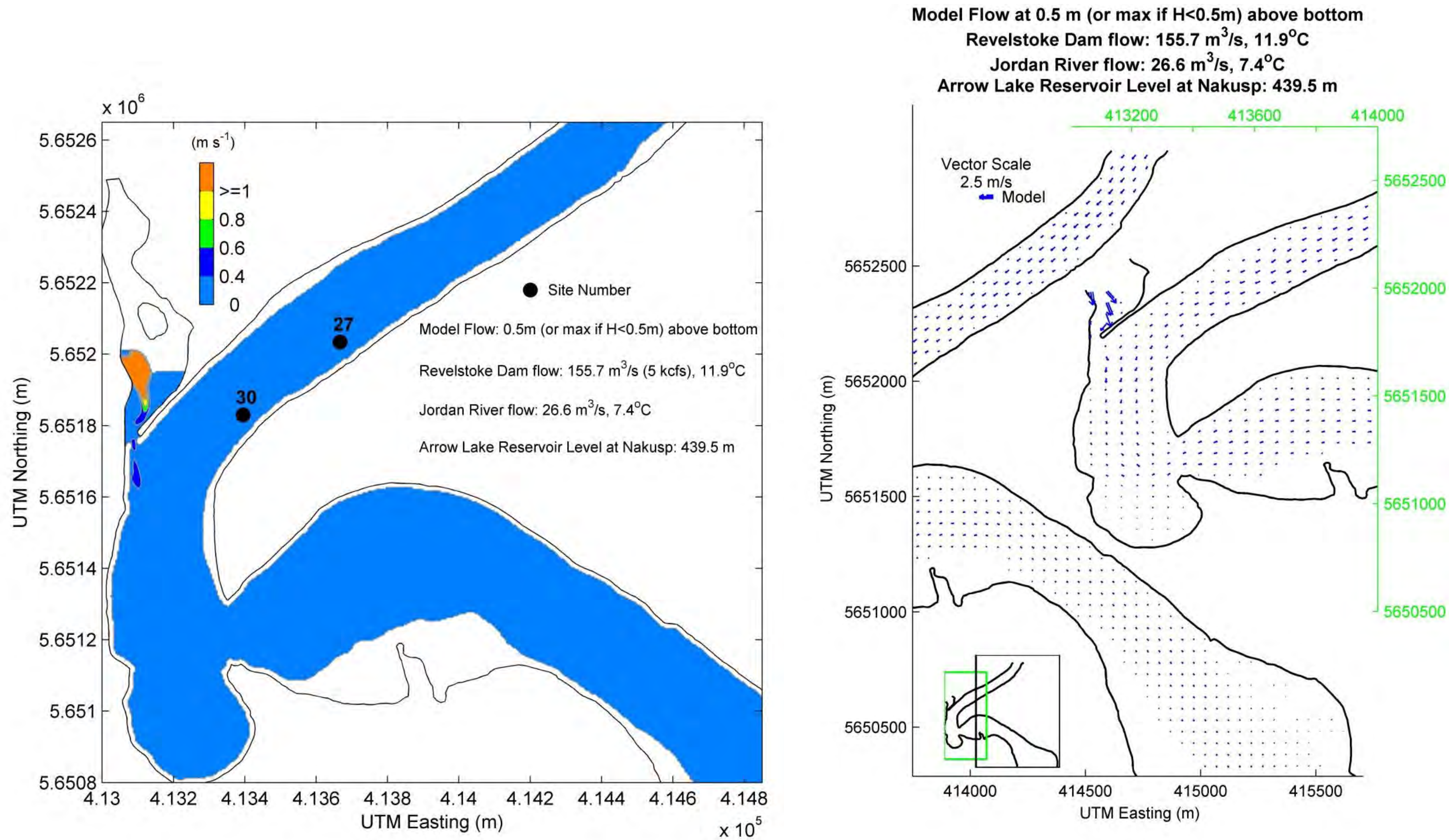


Figure 3-11: Near bottom flow velocities in the Revelstoke White Sturgeon spawning and egg incubation area (left panel: speed; right panel: flow vectors) for Spawning Event 12 on July 30, 2011 at approximately 03:13h. The black dots on the left panel are sites where eggs from Spawning Event 12 were captured.

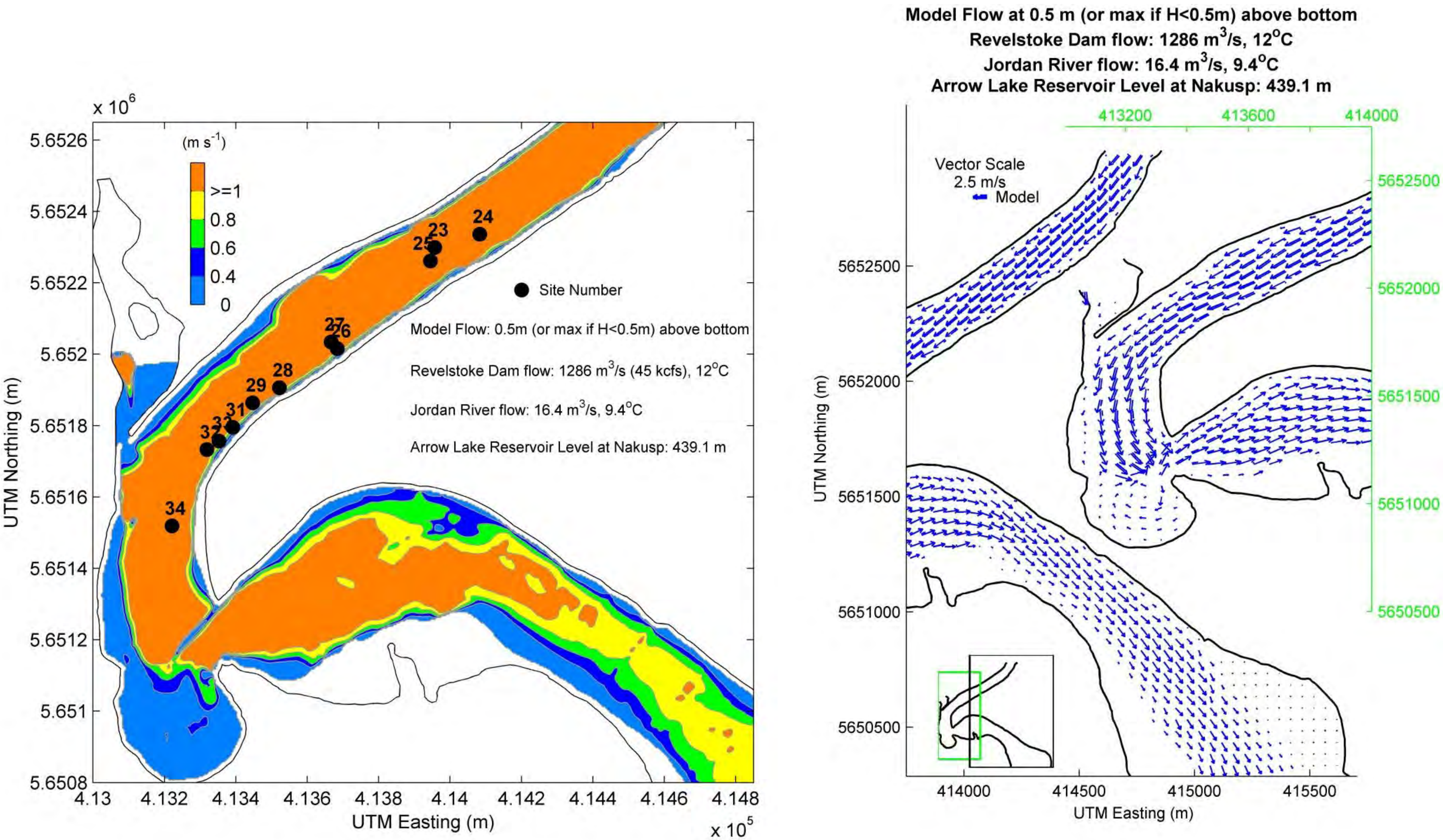


Figure 3-12: Near bottom flow velocities in the Revelstoke White Sturgeon spawning and egg incubation area (left panel: speed; right panel: flow vectors) for Spawning Event 13 on August 20, 2011 at approximately 10:26h. The black dots on the left panel are sites where eggs from Spawning Event 13 were captured.

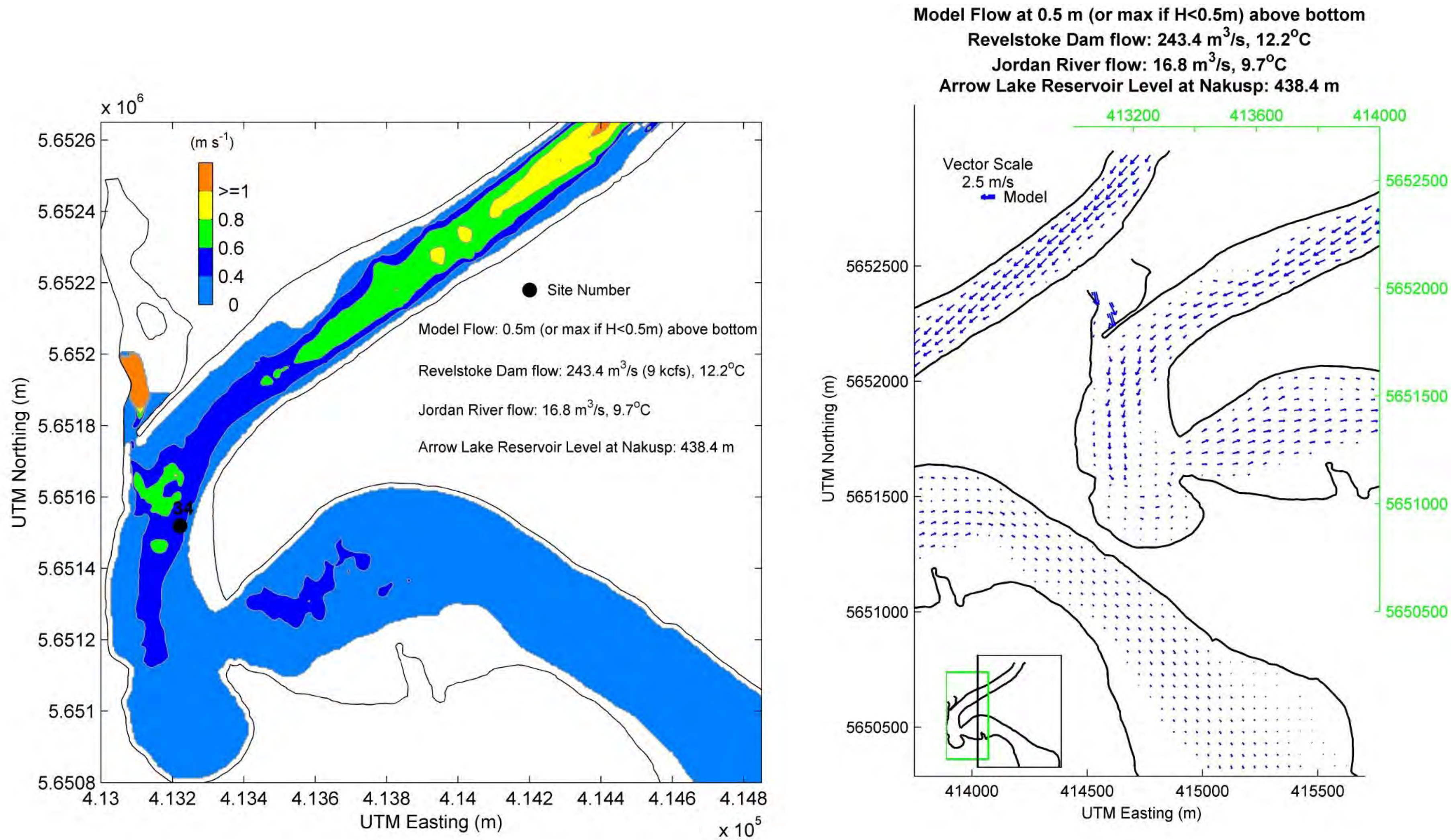


Figure 3-13: Near bottom flow velocities in the Revelstoke White Sturgeon spawning and egg incubation area (left panel: speed; right panel: flow vectors) for Spawning Event 14 on August 27, 2011 at approximately 06:21h. The black dots on the left panel are sites where eggs from Spawning Event 14 were captured.

4. Actual Near Bottom Flows during Egg Incubation Period

Near bottom flow conditions were examined in egg incubation/early rearing areas over a 15 day period following each documented spawning event. The study period of each event is shown in Figure 4-1. However, because of the long term study period, flow regimes are statistically estimated based on the empirical function derived from historical model results (see Tables 1-1 and 1-2, and Figure 1-5) for each selected egg mat site.

The model cases summarized in Tables 1-1 and 1-2 were used to derive near-bottom velocity statistical relationships as a function of the total discharge of Revelstoke Dam and Jordan River, and the Arrow Lake water level at Nakusp. The model cases were applied to the 34 selected egg mat sites that captured eggs from all the recorded spawning events.

By fitting the data from all model cases summarized in Table 1-1 and 1-2, a unique empirical function was derived for each selected egg mat site (34 in total), as an equation of (1) Arrow Lake water level at Nakusp (hereinafter WL) and (2) the total discharge of Revelstoke Dam and Jordan River (hereinafter Q).

As shown in Appendix A, for each site, the top panel presents the contours of near-bottom velocity ($V_{0.5m}$) as a 2-D distribution of WL and Q based on the derived empirical function. The bottom panel at each site provides the assessment of the empirical function by comparing the real modeled $V_{0.5m}$ and the predicted $V_{0.5m}$ (using the empirical function at each site), based on the model runs summarized in Table 1-1 and 1-2. The correlation coefficients between the modeled and predicted near bottom velocities are all greater than 95%, which means that the derived empirical functions represent the distribution of $V_{0.5m}$ very well. The derived equation for each site is shown in the top-left corner of the bottom panel of each site.

To apply the statistical relationships, first, hourly WL at Nakusp and hourly discharge Q from upstream were obtained from observational data over the 15 day period following each spawning event. Then hourly near-bottom velocities ($V_{0.5m}$) were calculated as a function of WL and Q based on the empirical equation derived for each selected egg mat site.

The velocity distribution during 15-day windows of all events is shown in Figure 4-2. Figures 4-3 presents the flow distribution for each event (at each site).

Near bottom velocities were also examined at the 34 sites based on their daily distribution over the 15 day period following each spawning event. The associated plots can be found in Appendix B.

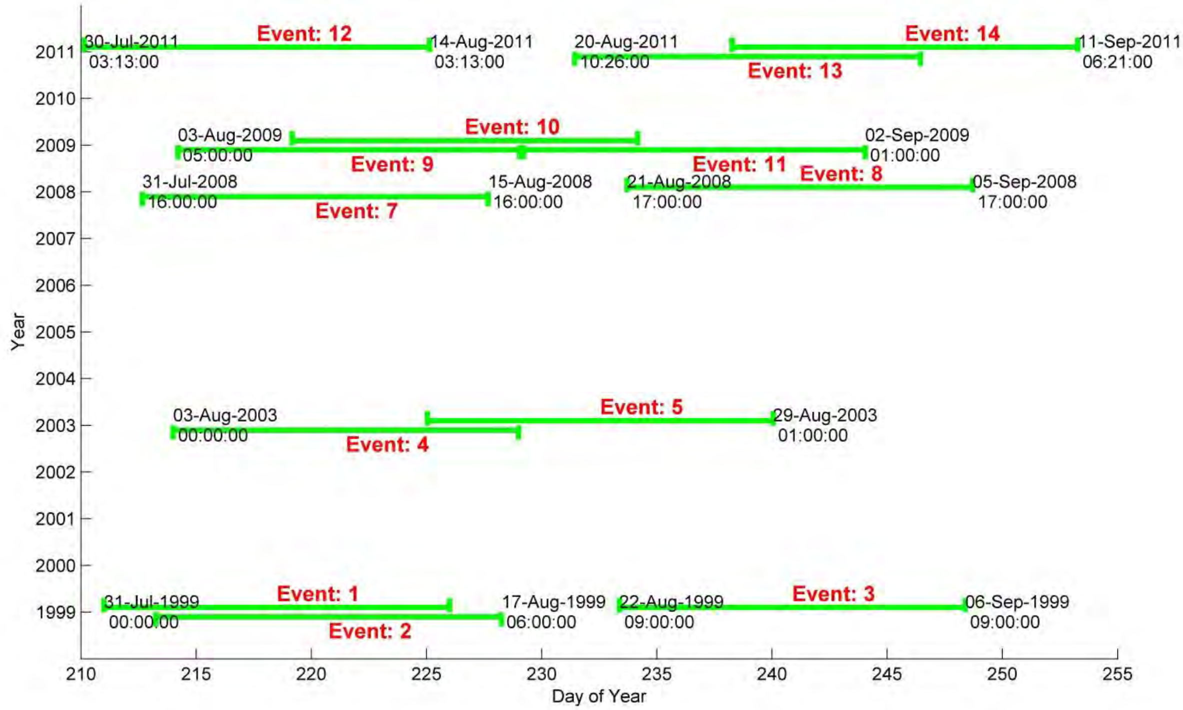


Figure 4-1: White sturgeon spawning events and the following 15 day egg incubation periods after each documented spawning event.

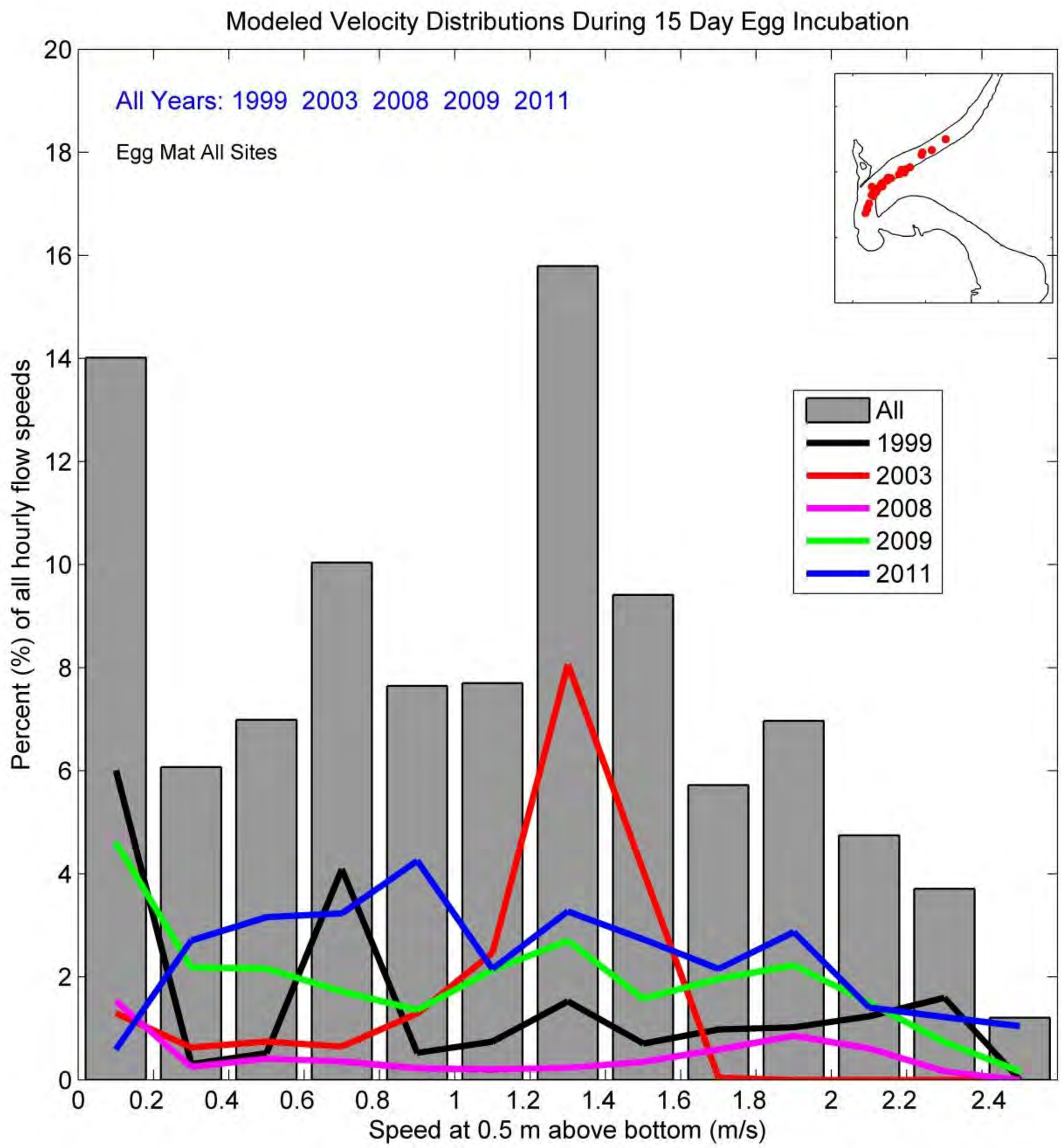


Figure 4-2: Near-bottom velocity distributions during the 15-day egg incubation window at each of the 34 egg mat sites where White Sturgeon eggs were collected during all recorded spawning events. The grey bars are the cumulative values of the individual years

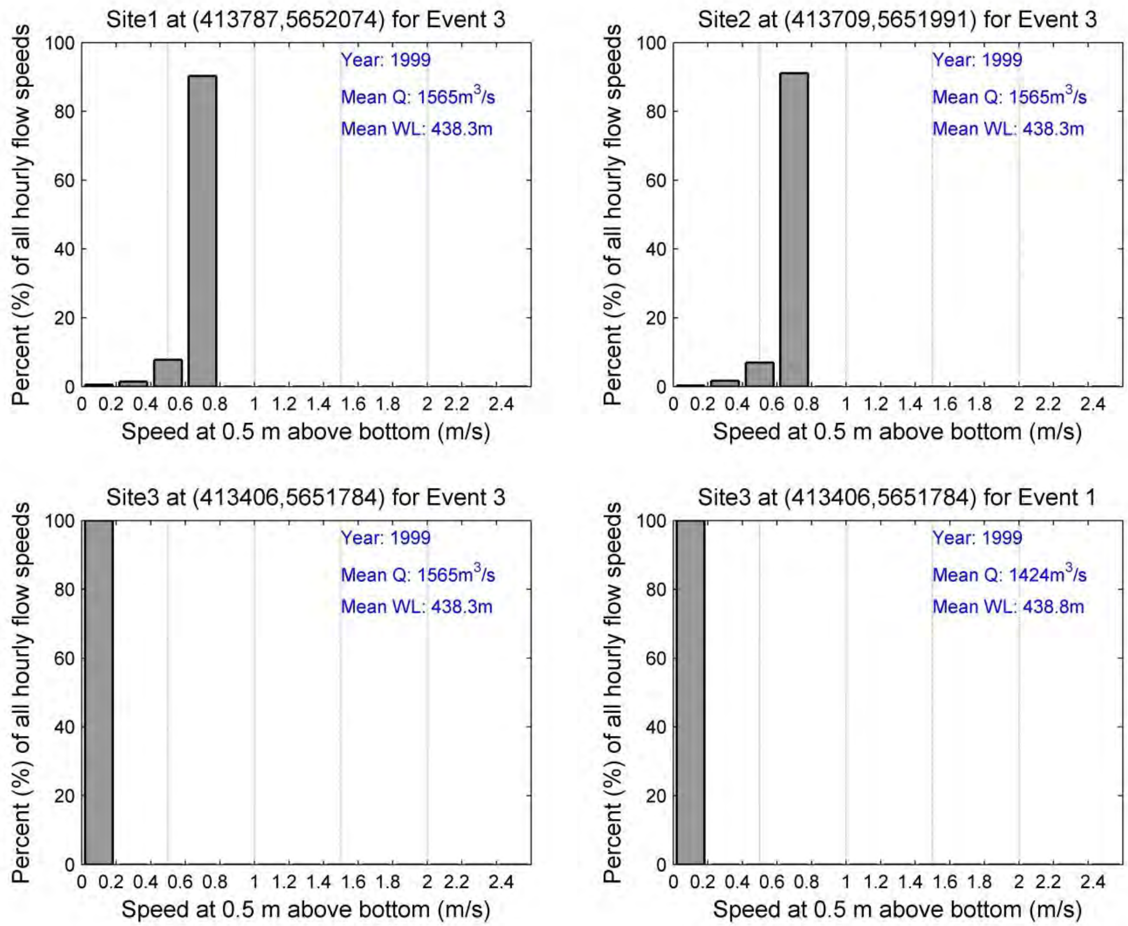


Figure 4-3: Near-bottom velocity distribution during the estimated 15-day egg incubation windows following each White Sturgeon spawning event.

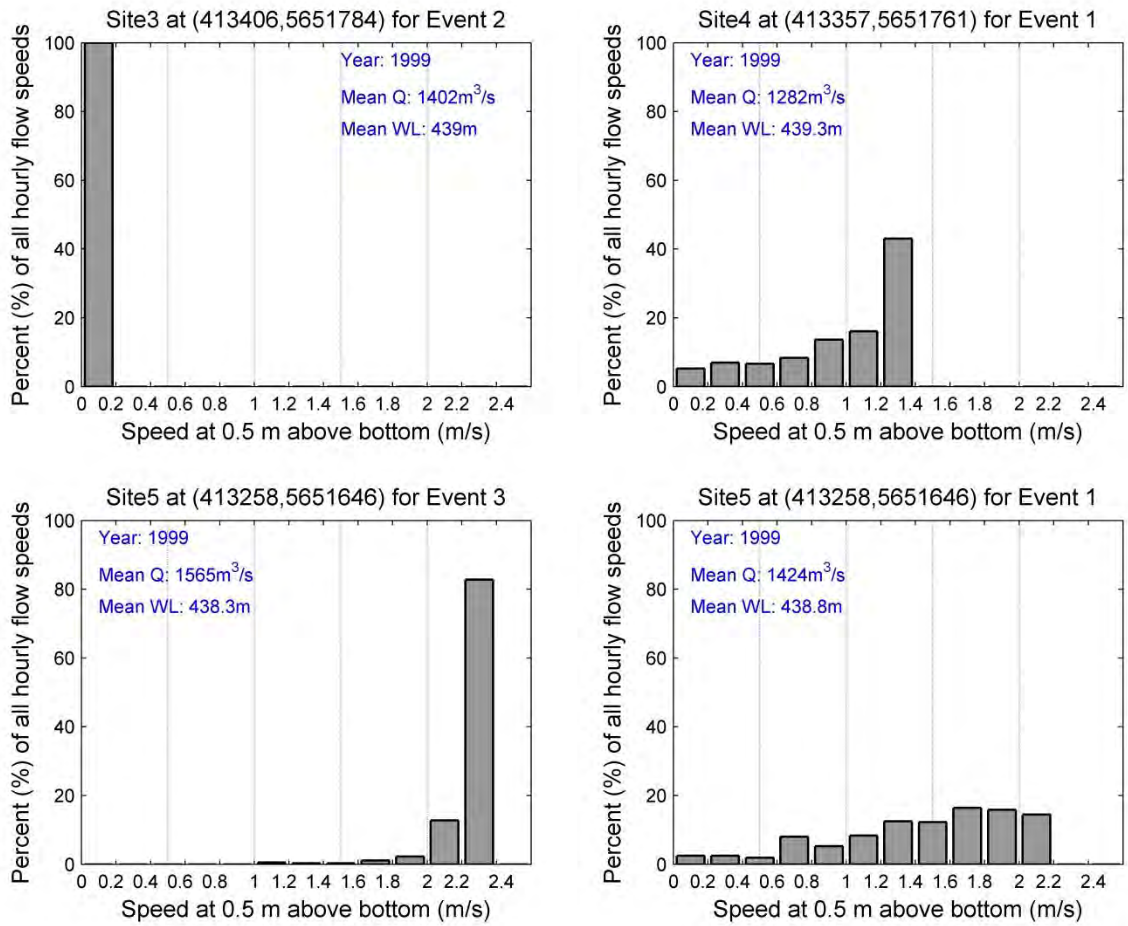


Figure 4-3: Continued.

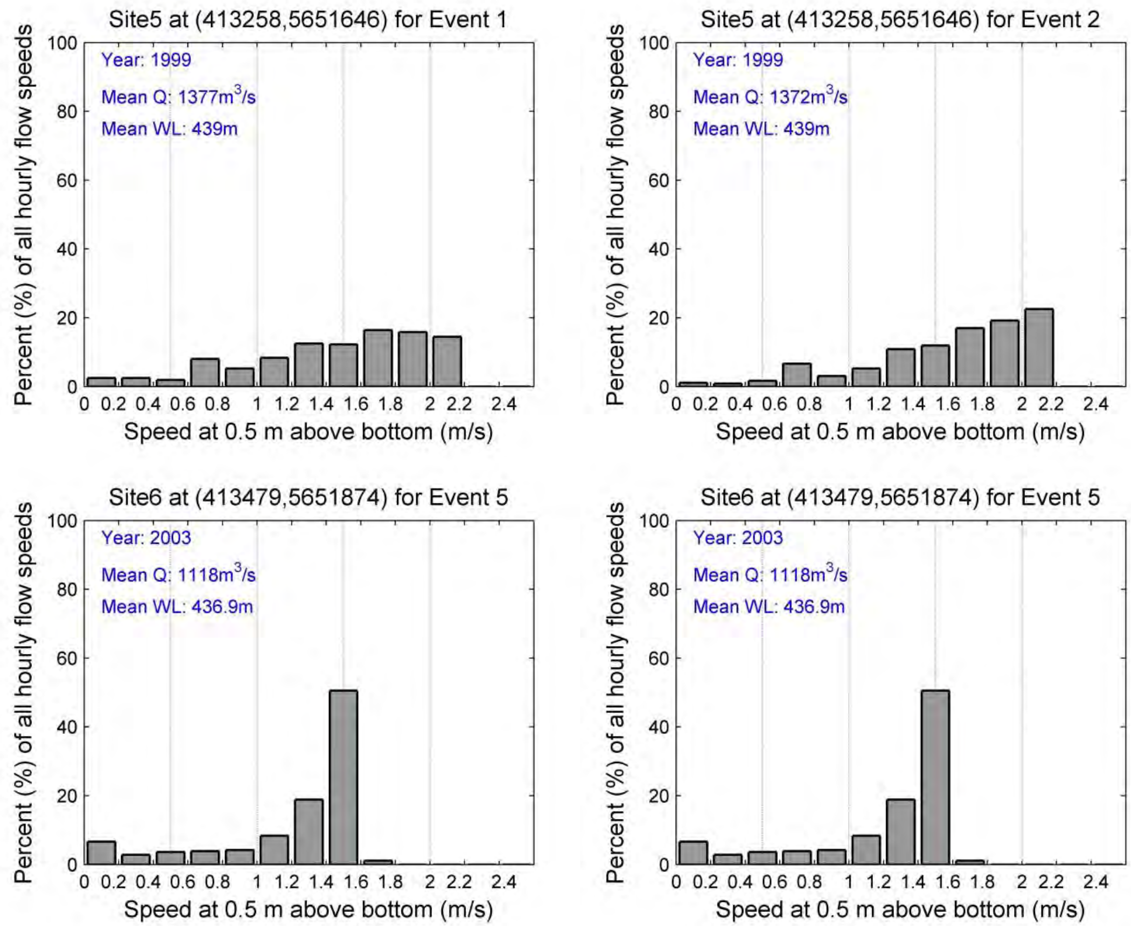


Figure 4-3: Continued.

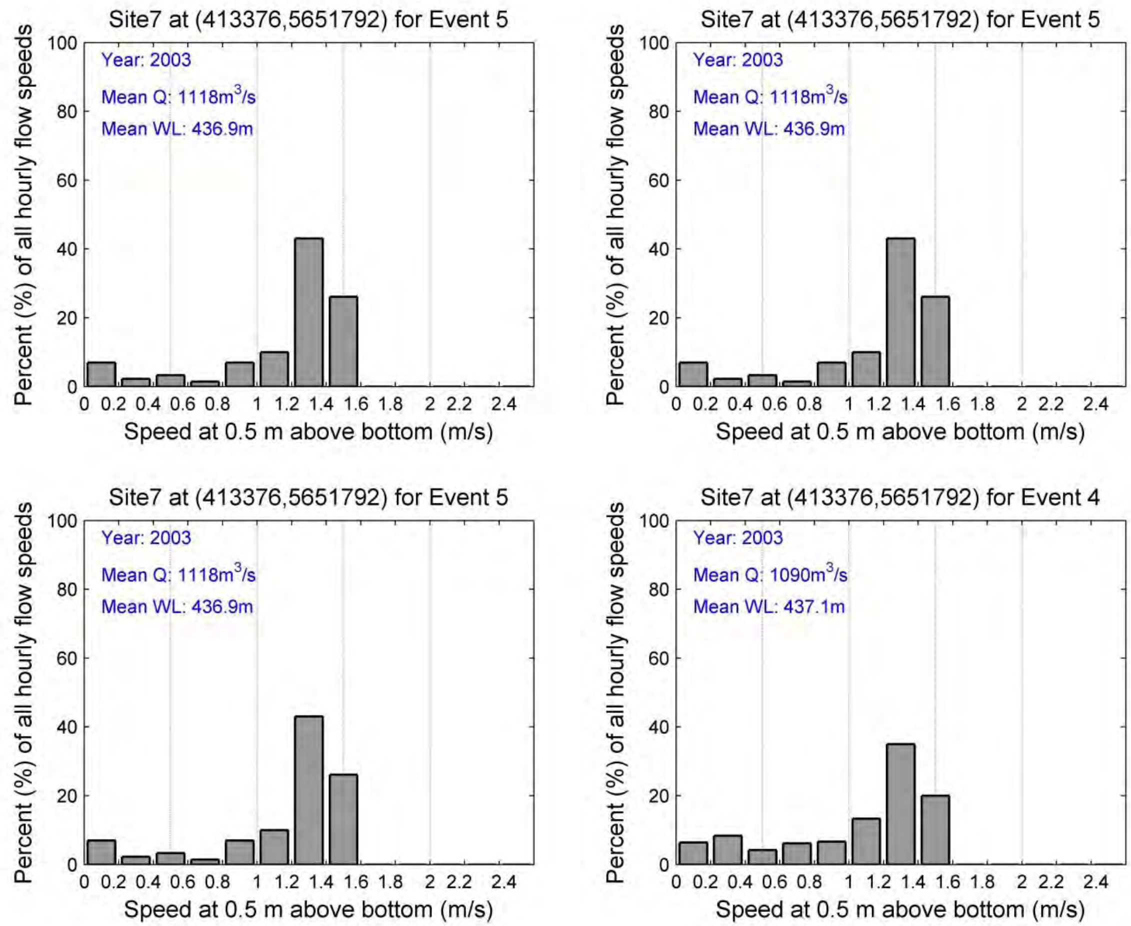


Figure 4-3: Continued.

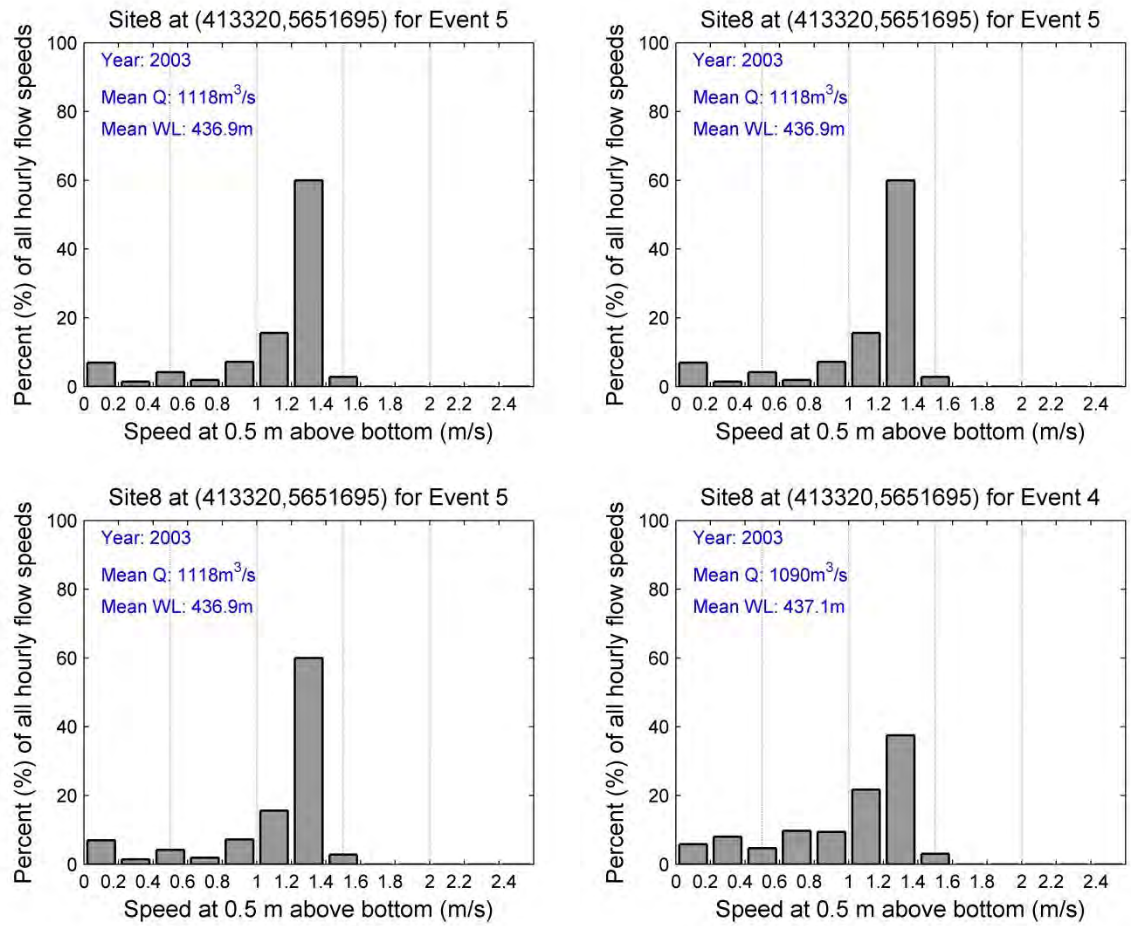


Figure 4-3: Continued.

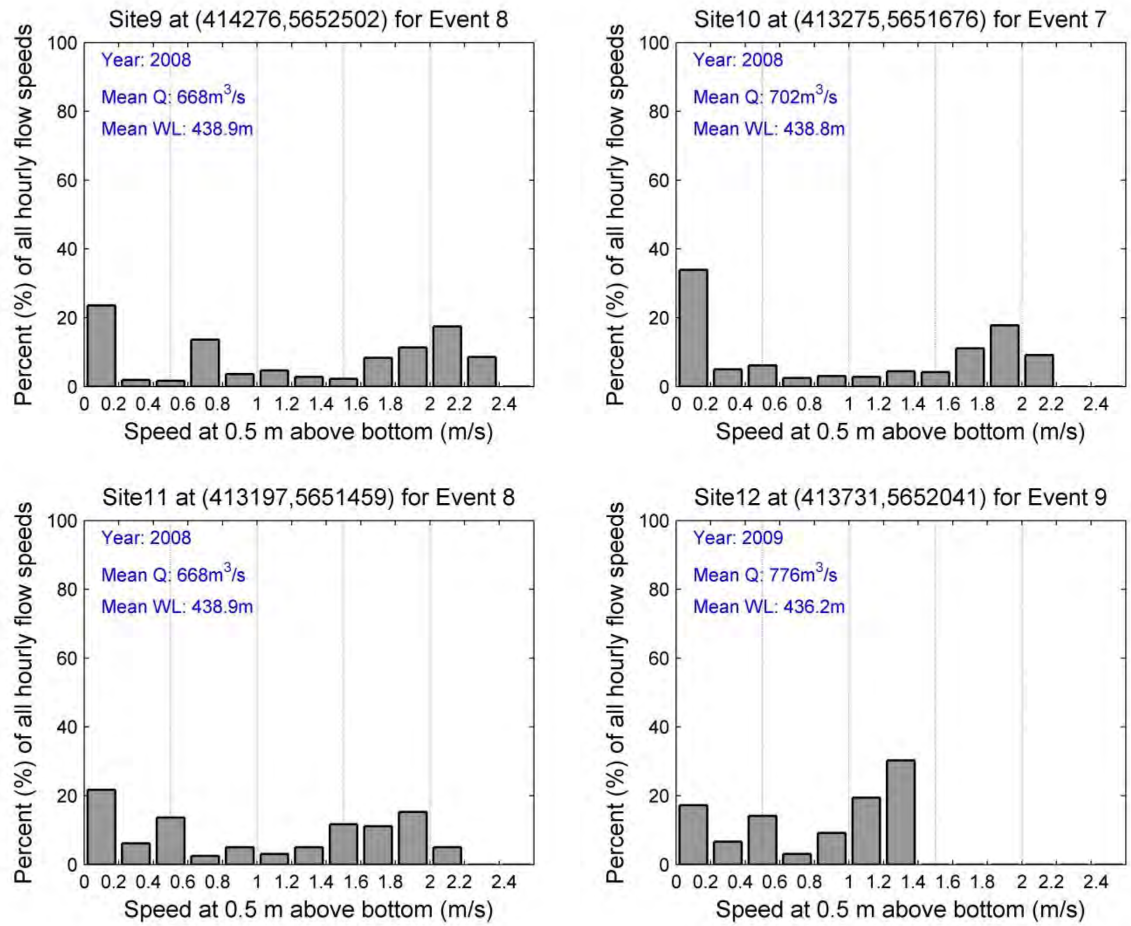


Figure 4-3: Continued.

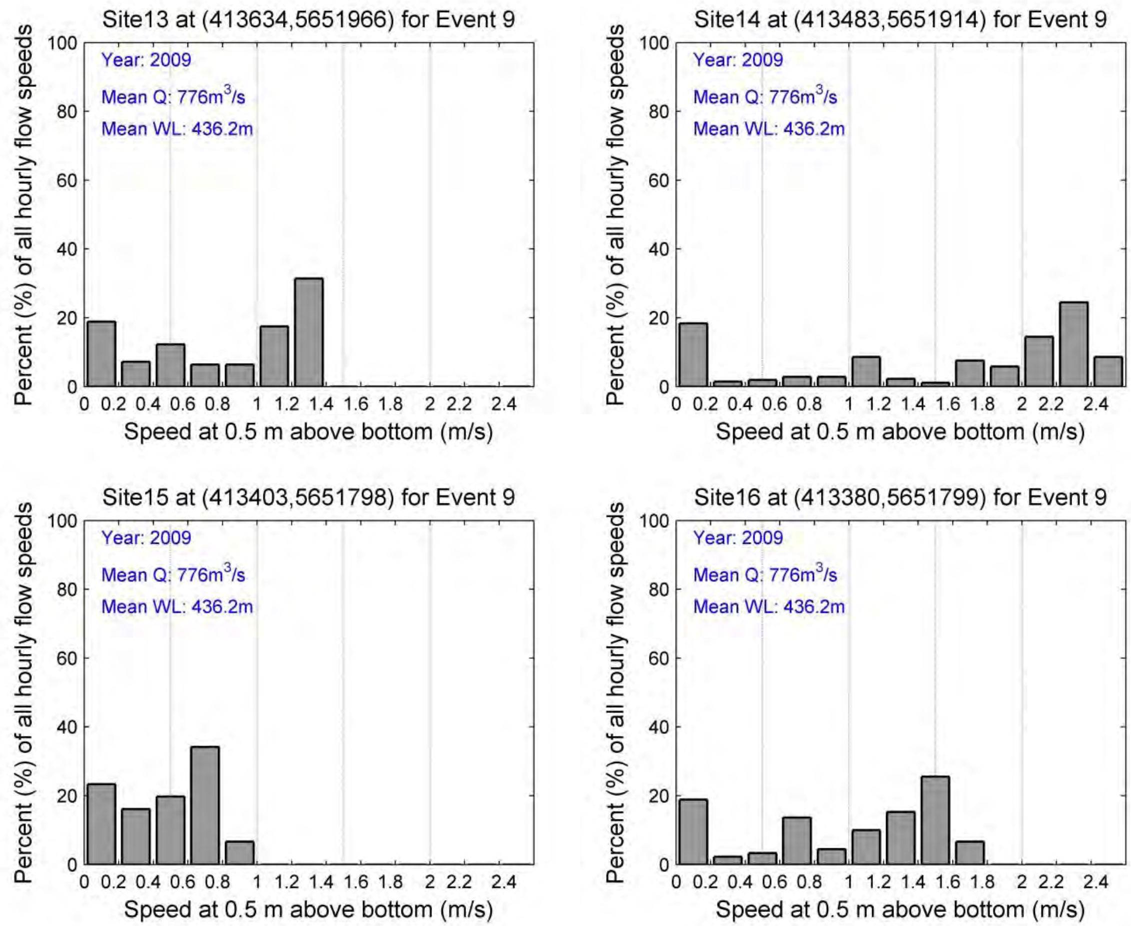


Figure 4-3: Continued.

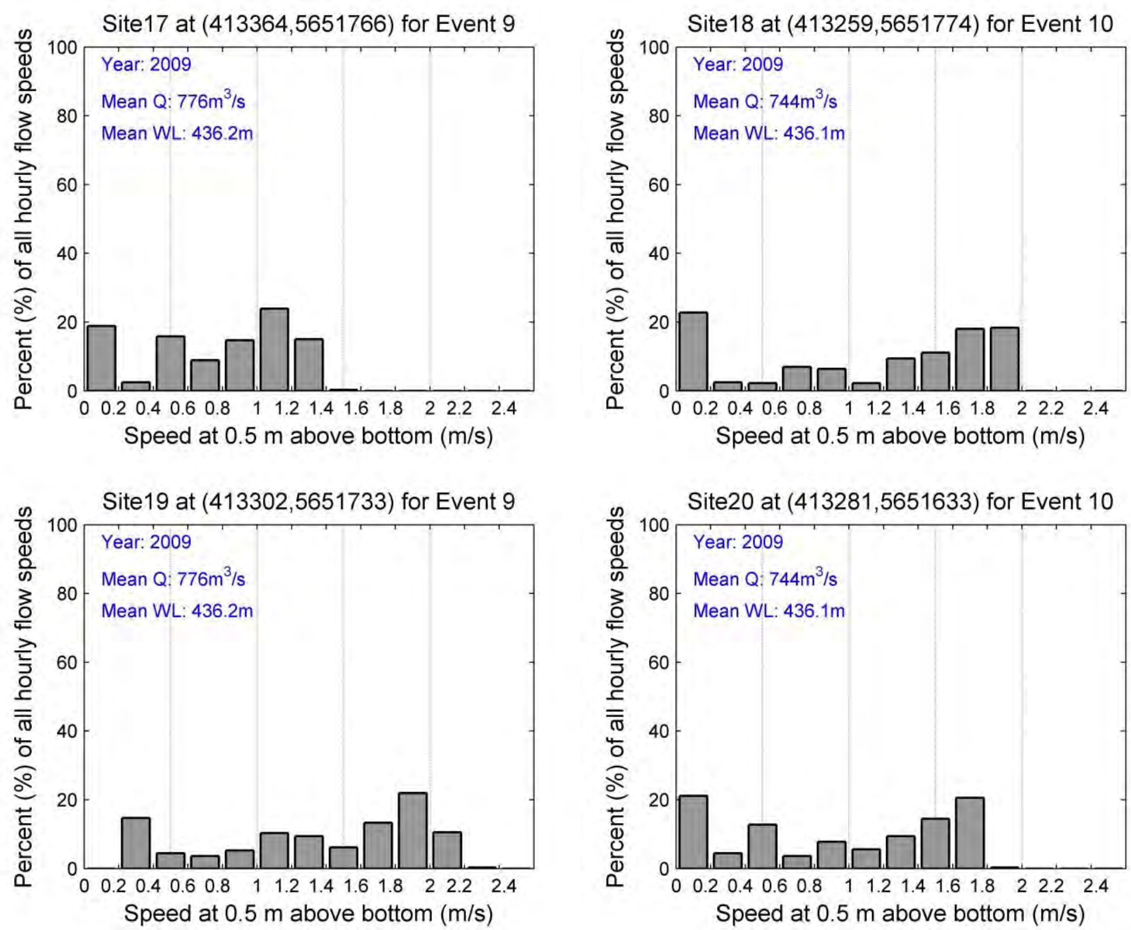


Figure 4-3: Continued.

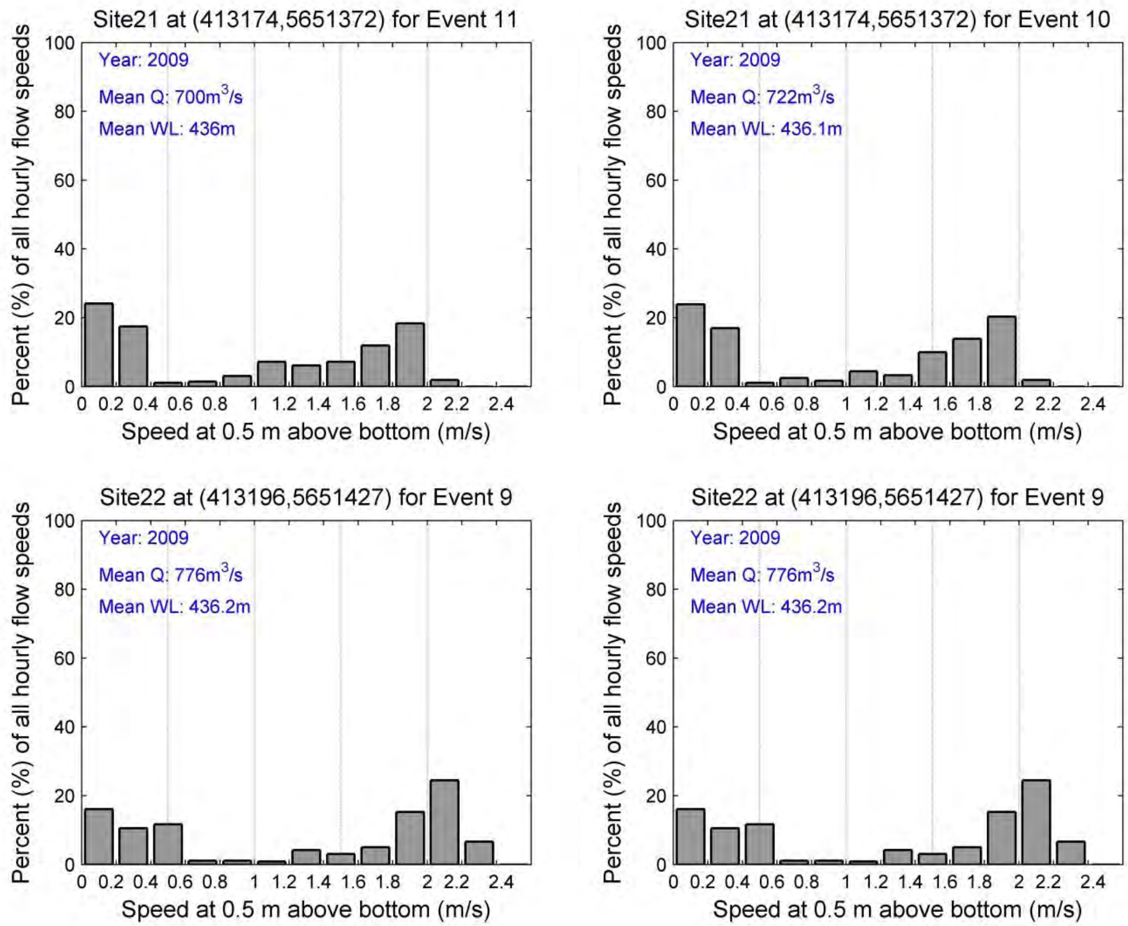


Figure 4-3: Continued.

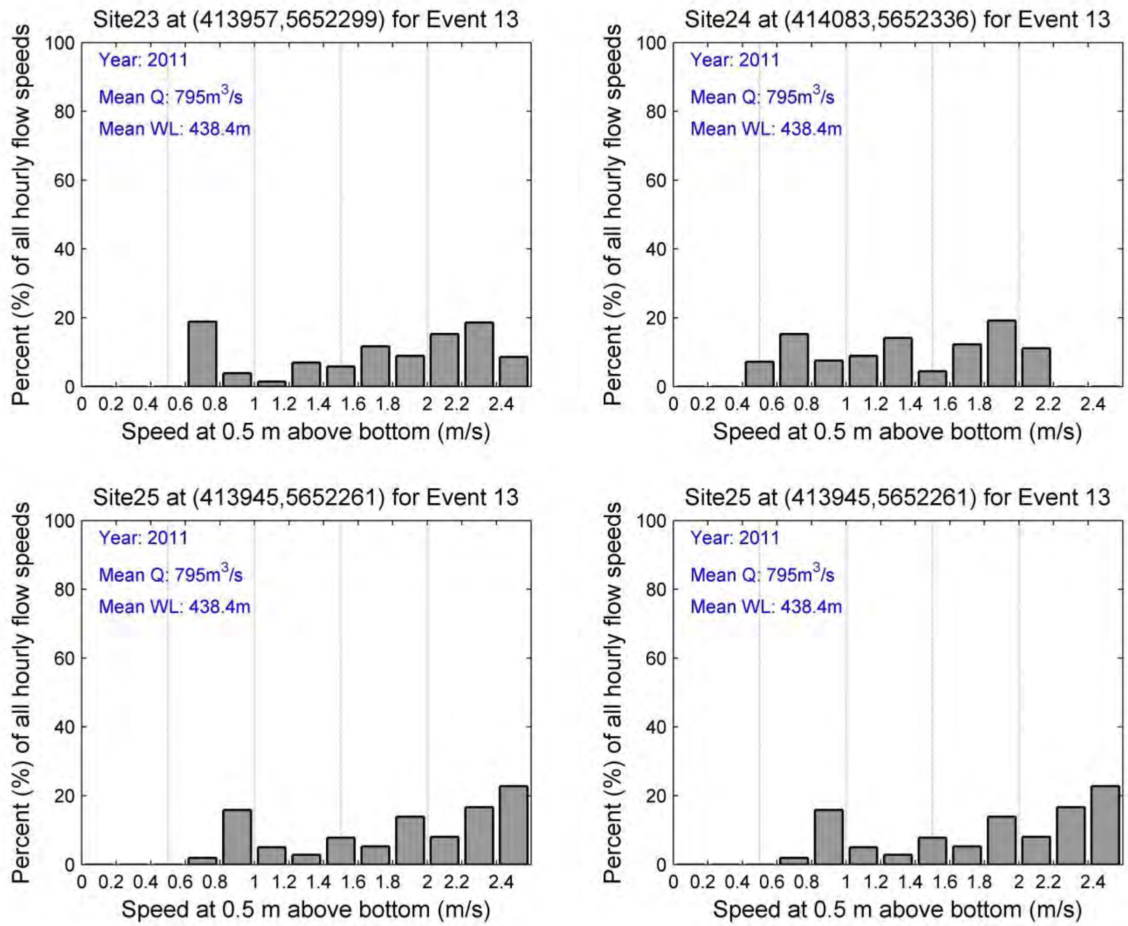


Figure 4-3: Continued.

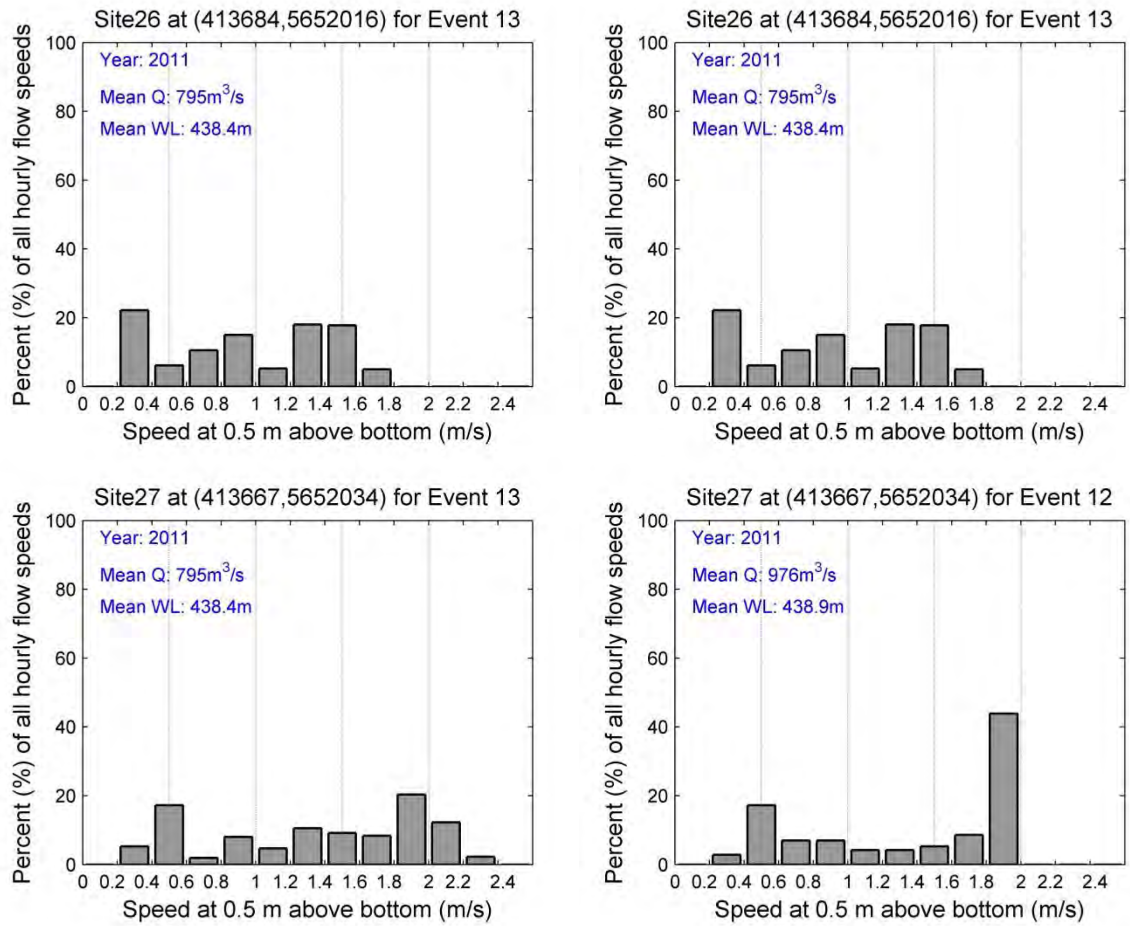


Figure 4-3: Continued.

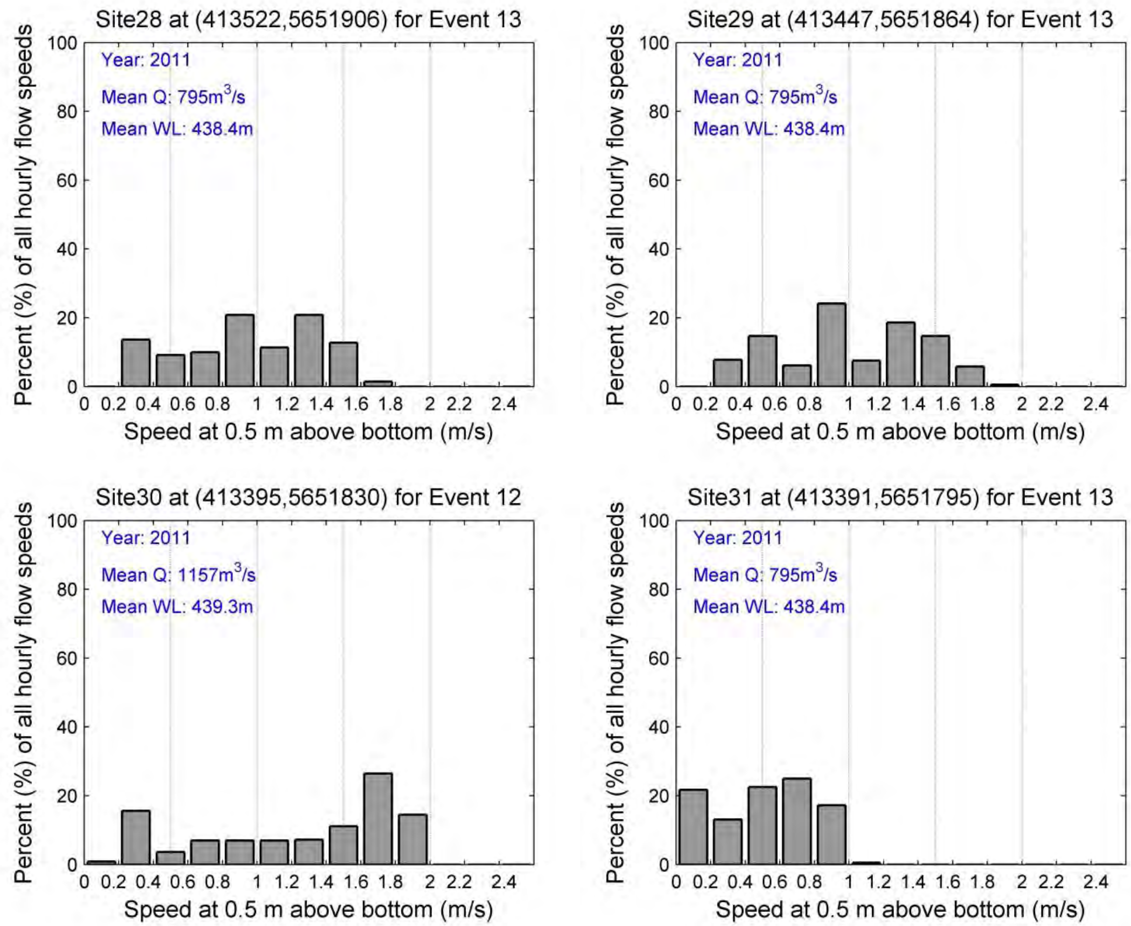


Figure 4-3: Continued.

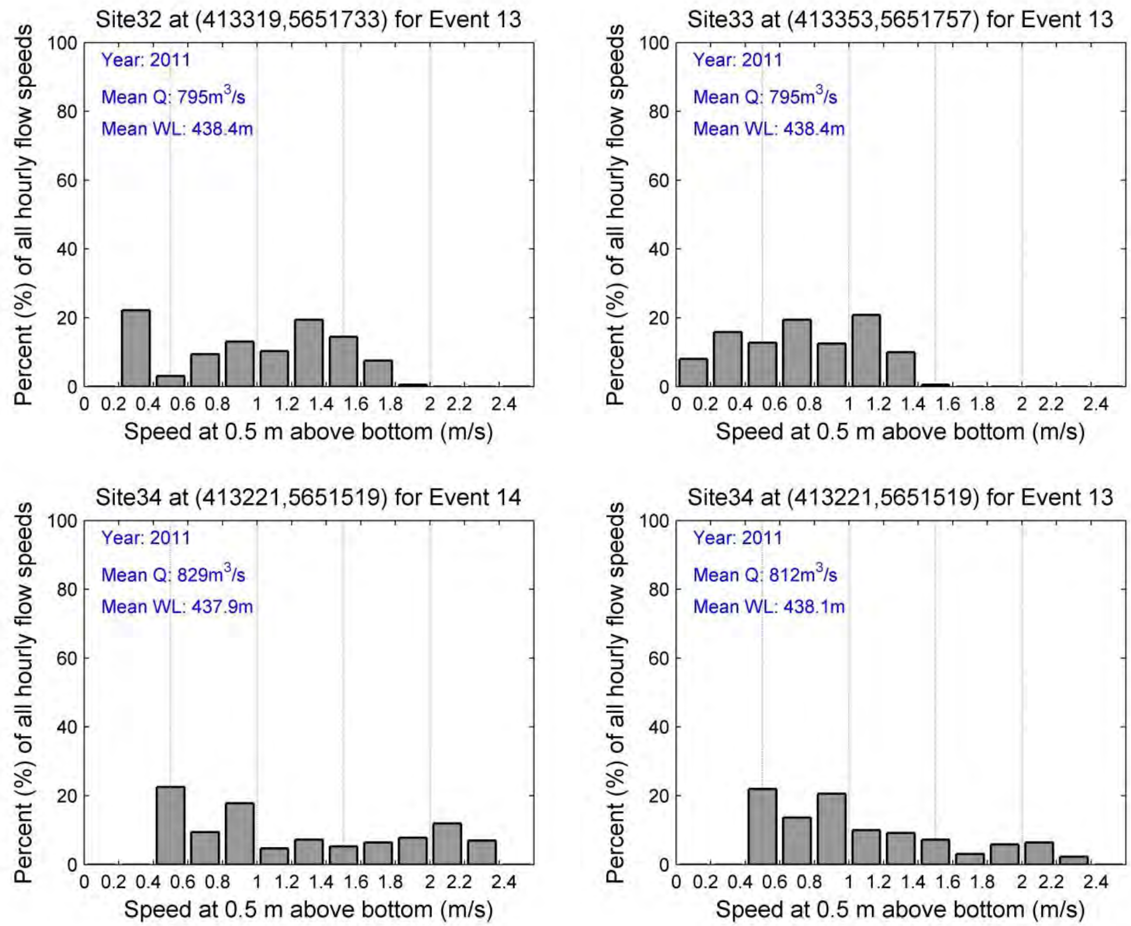


Figure 4-3: Continued.

5. Minimum REV5 Flow

The effects of 142 m^3/s (5 kcfs) REV5 minimum flow on near-bottom velocities in the White Sturgeon spawning/egg incubation/early larval rearing area were studied. Model flow conditions used in the modeling are listed in Table 5-1. The areal extent of near-bottom flow velocity increments in the White Sturgeon egg deposition/incubation area (see Figure 1-3) were analyzed and are shown in Table 5-1.

Modeled near bottom flow velocities in the Revelstoke White Sturgeon spawning and egg deposition area were plotted for each model scenario in Figures 5-1 to 5-6.

Table 5-1: Model cases for the 0 kcfs minimum flow (Revelstoke with 4 units) and the 5 kcfs minimum flow (Revelstoke with 5 units) flow (Q) showing the effects of the 5 kcfs increase in flow on the areal extent of near-bottom flow velocity increments in the White Sturgeon spawning and early larval rearing areas.

Model Designation	Revelstoke Dam Flow		Jordan River Flow (m^3/s) [a]	Arrow Lakes Reservoir Level at Nakusp (m)	Areal Extent (Percent of total area) of Flow Velocity Increments					
	kcfs	m^3/s			0-0.5 m/s	0.6-1 m/s	1.1-1.5 m/s	1.6-2.0 m/s	2.1-2.5 m/s	>2.5 m/s
$H_{ALR}0_{REVQ}$	0	0	19.0	441	100.00	0.00	0.00	0.00	0.00	0.00
$M_{ALR}0_{REVQ}$				437	95.78	1.58	1.09	0.73	0.83	0.00
$L_{ALR}0_{REVQ}$				434	94.78	1.38	0.96	0.97	1.70	0.22
$H_{ALR}5_{REVQ}$	5	142		441	100.00	0.00	0.00	0.00	0.00	0.00
$M_{ALR}5_{REVQ}$				437	48.58	45.58	4.60	0.73	0.52	0.00
$L_{ALR}5_{REVQ}$				434	35.48	46.85	13.30	3.23	1.03	0.10

[a] Daily average for August (range = 12.6-26.6 m^3/s).

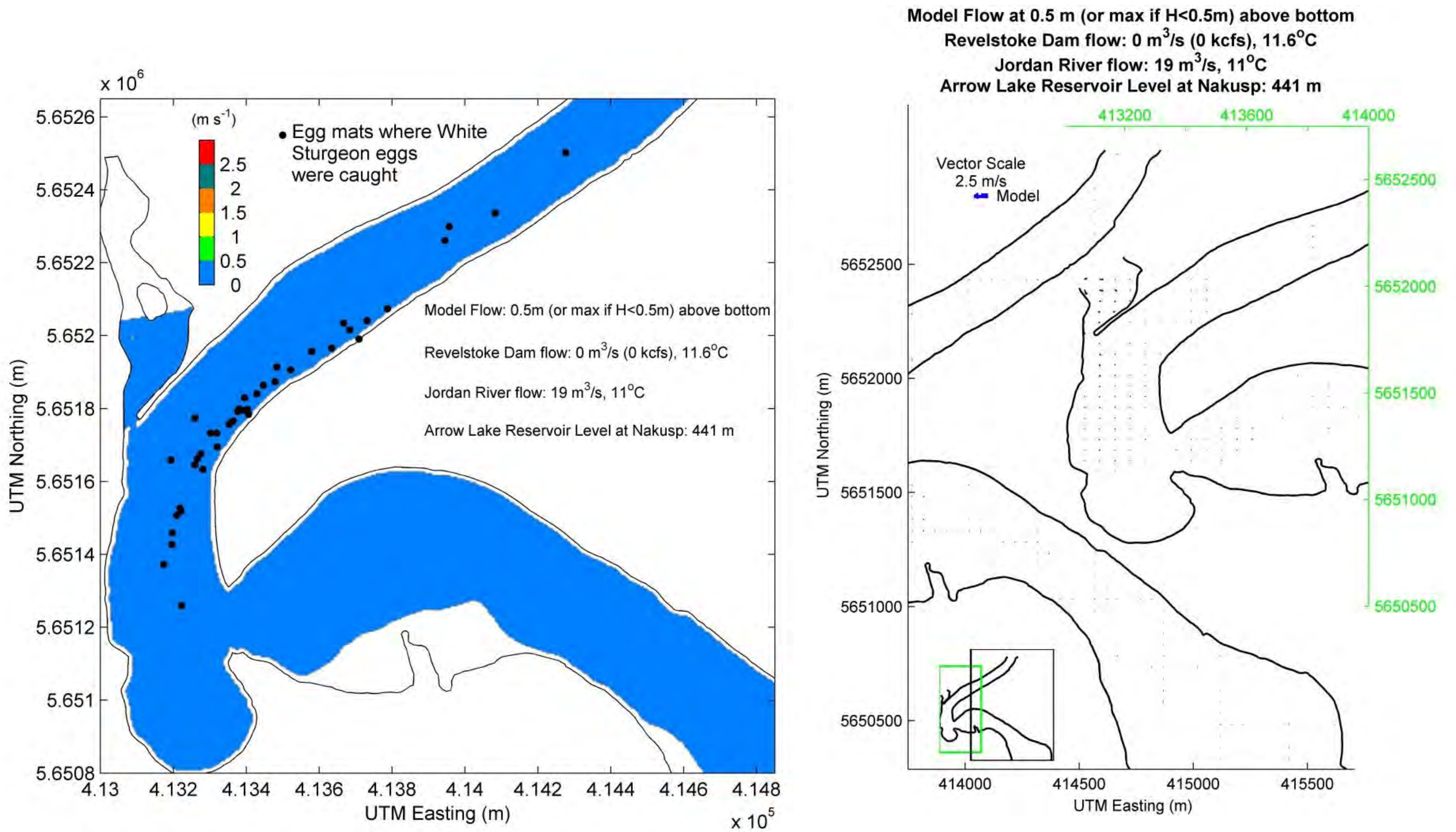


Figure 5-1: Modeled near bottom flow velocities in the Revelstoke White Sturgeon spawning and early larval rearing areas at a Revelstoke Dam discharge of 0 m^3/s and at a High Arrow Lakes Reservoir level (left panel); associated flow vectors plotted every 10th grid (right panel).

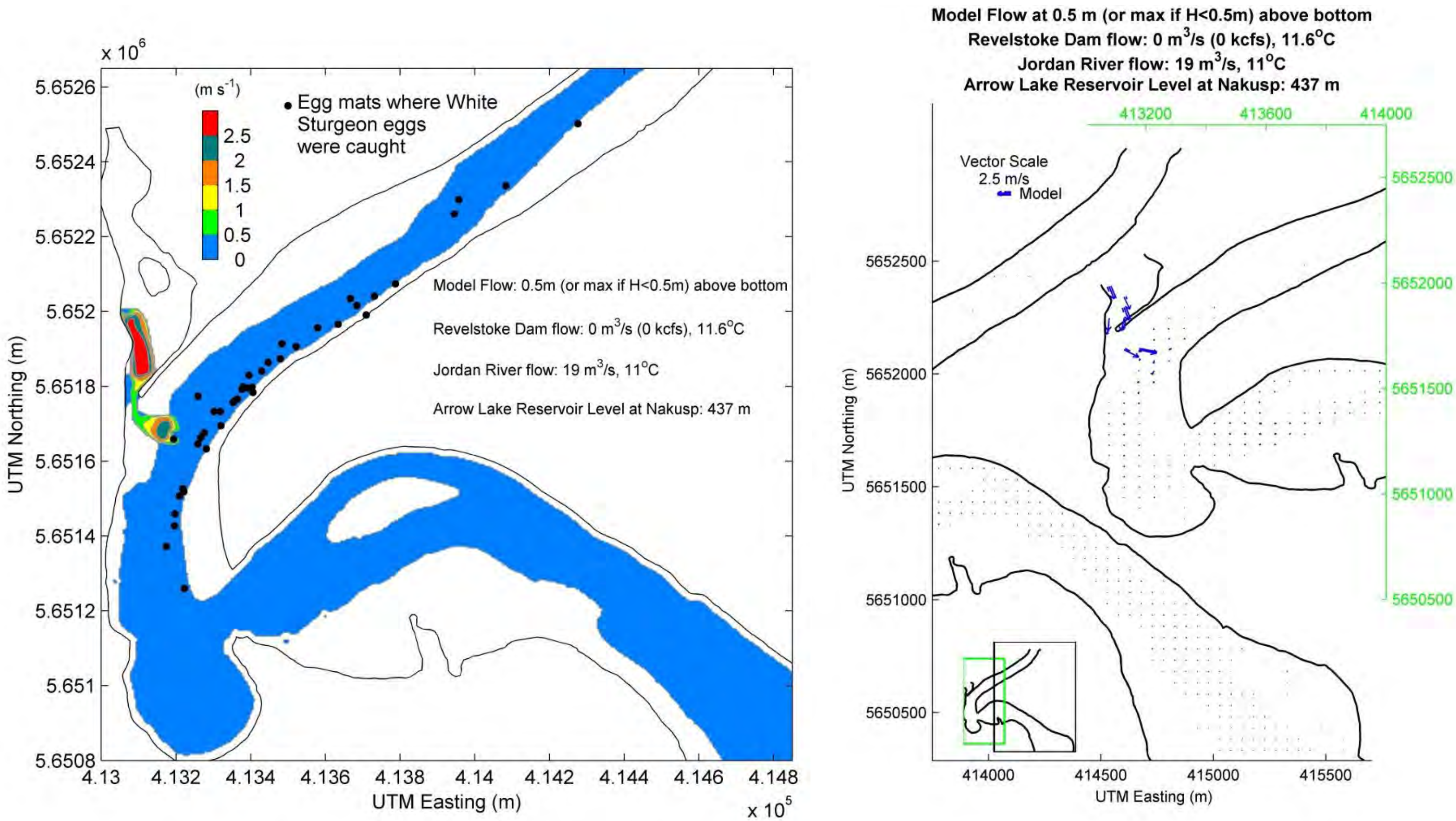


Figure 5-2: Modeled near bottom flow velocities in the Revelstoke White Sturgeon spawning and early larval rearing areas at a Revelstoke Dam discharge of 0 m^3/s and an Intermediate Arrow Lakes Reservoir level (left panel); associated flow vectors plotted every 10th grid (right panel).

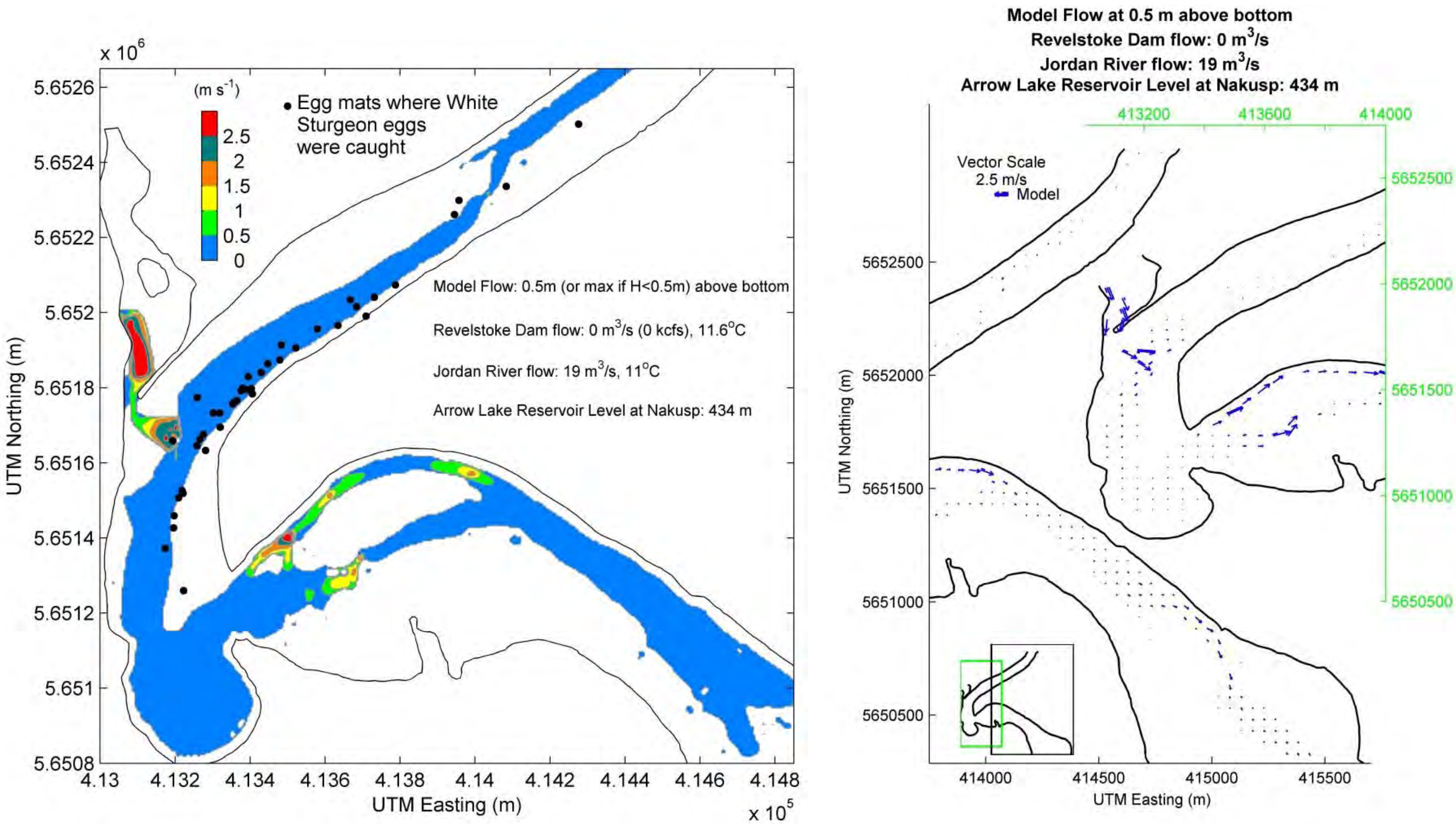


Figure 5-3: Modeled near bottom flow velocities in the Revelstoke White Sturgeon spawning and early larval rearing areas at a Revelstoke Dam discharge of 0 m^3/s and a Low Arrow Lakes Reservoir level (left panel); associated flow vectors plotted every 10th grid (right panel).

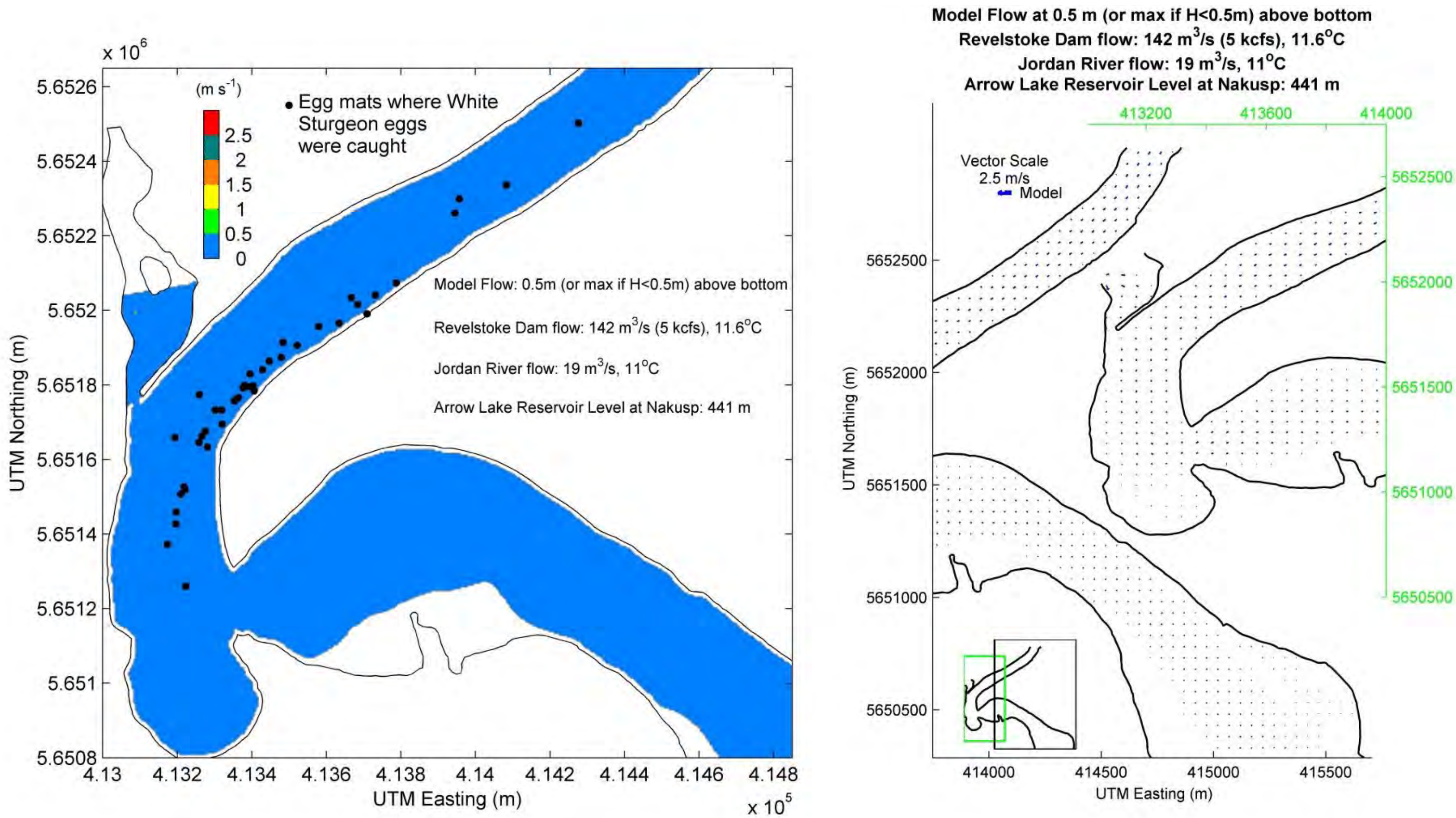


Figure 5-4: Modeled near bottom flow velocities in the Revelstoke White Sturgeon spawning and early larval rearing areas at a Revelstoke Dam discharge of 142 m^3/s anda High Arrow Lakes Reservoir level (left panel); associated flow vectors plotted every 10th grid (right panel).

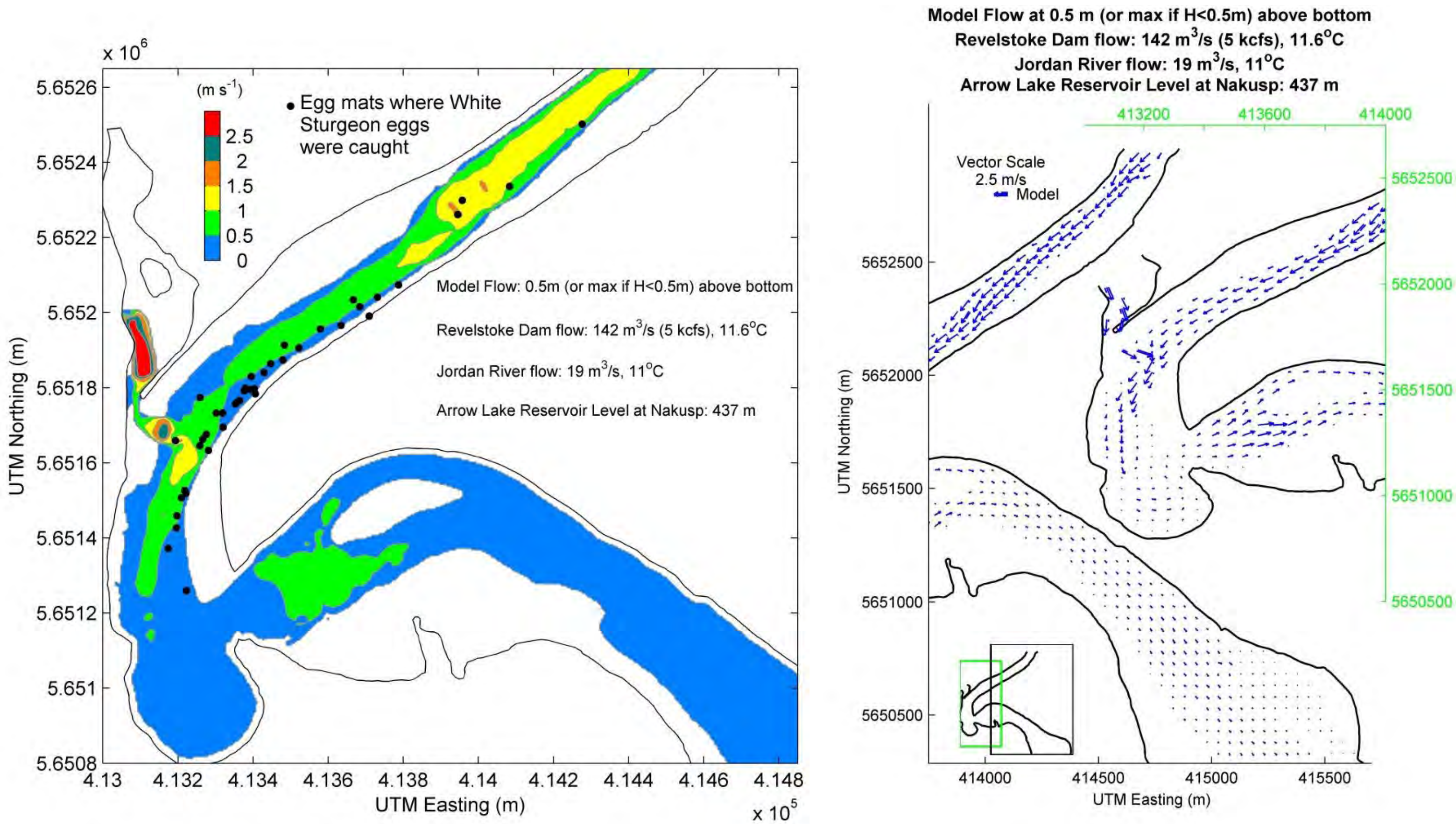


Figure 5-5: Modeled near bottom flow velocities in the Revelstoke White Sturgeon spawning and early larval rearing areas at a Revelstoke Dam discharge of 142 m^3/s and an Intermediate Arrow Lakes Reservoir level (left panel); associated flow vectors plotted every 10th grid (right panel).

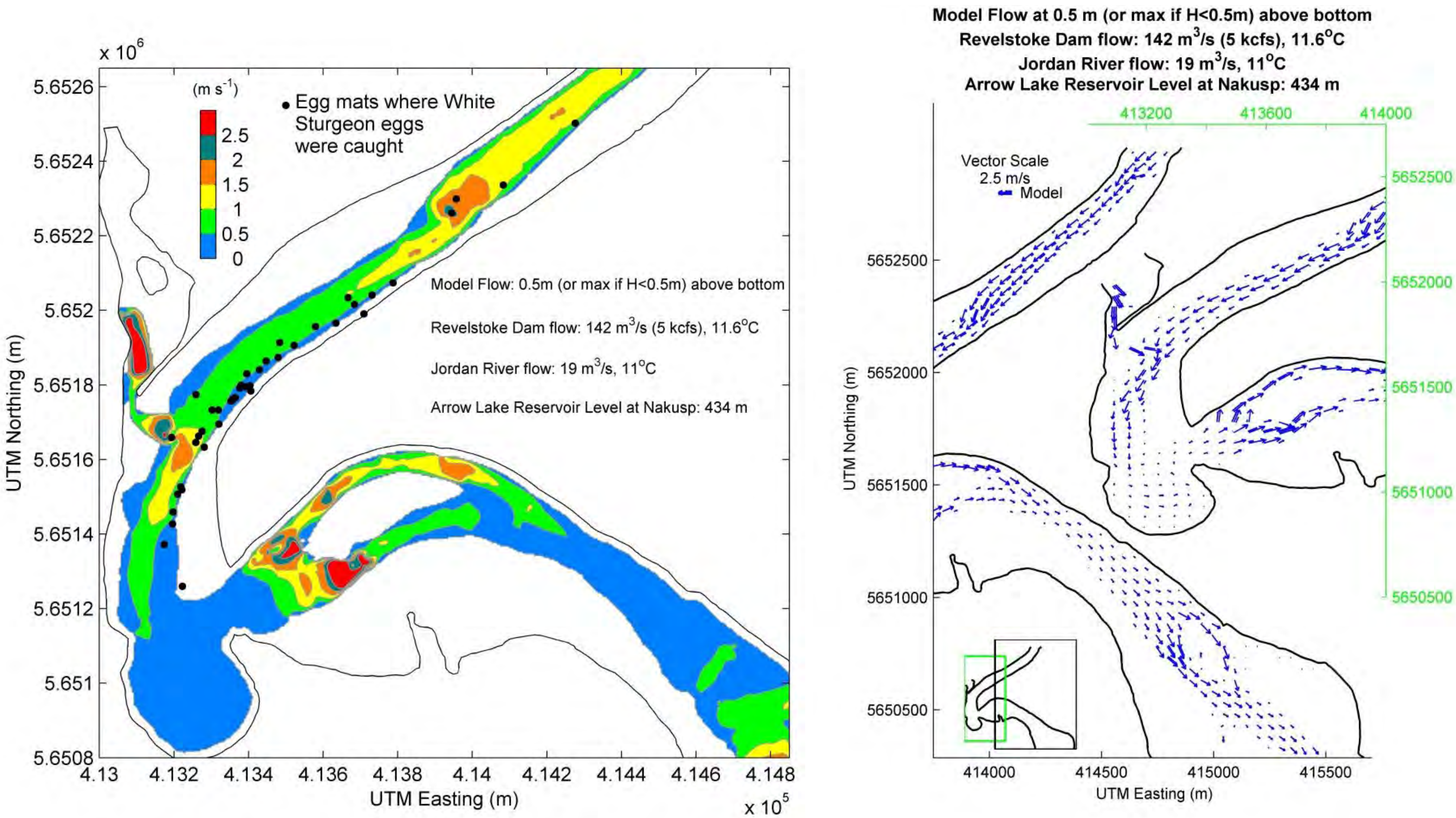


Figure 5-6: Modeled near bottom flow velocities in the Revelstoke White Sturgeon spawning and early larval rearing areas at a Revelstoke Dam discharge of 142 m^3/s and a Low Arrow Lakes Reservoir level (left panel); and associated flow vectors plotted every 10th grid (right panel).

6. PRE VS POST REV5 Flows

The effects of 15 kcfs increase in maximum REV5 flow, 60 kcfs (1699 m^3/s) to 75 kcfs (2124 m^3/s), on near-bottom velocities in the spawning and early larval rearing areas were studied in this section. Model flow conditions used in the modeling are listed in Table 6-1. The areal extent of near-bottom flow velocity increments in the White Sturgeon egg deposition/incubation area (see Figure 1-3) were analyzed and are shown in Table 6-1.

Modeled near bottom flow velocities in the Revelstoke White Sturgeon spawning and egg incubation area and associated vectors were plotted for each model scenario in Figures 6-1 to 6-6.

Table 6-1: Model cases for the 60 kcfs (Revelstoke with 4 units) and 75 kcfs (Revelstoke with 5 units) showing the effects of the 15 kcfs increase in flow on the areal extent of near-bottom flow velocity increments in the White Sturgeon spawning and early larval rearing areas.

Model Designation	Revelstoke Dam Flow		Jordan River Flow (m^3/s) [a]	Arrow Lakes Reservoir Level at Nakusp (m)	Areal Extent (Percent of total area) of Flow Velocity Increments					
	kcfs	m^3/s			0-0.5 m/s	0.6-1 m/s	1.1-1.5 m/s	1.6-2.0 m/s	2.1-2.5 m/s	>2.5 m/s
$H_{ALR}60_{REVQ}$	60	1699	19.0	441	18.06	21.96	58.15	1.83	0.00	0.00
$M_{ALR}60_{REVQ}$				437	16.55	11.36	11.82	15.67	29.77	14.84
$L_{ALR}60_{REVQ}$				434	16.59	11.21	11.73	15.16	29.58	15.72
$H_{ALR}75_{REVQ}$ (Verification 6)	75	2124		441	16.67	14.97	31.38	36.81	0.17	0.00
$M_{ALR}75_{REVQ}$				437	14.16	8.43	11.27	14.36	27.13	24.66
$L_{ALR}75_{REVQ}$				434	14.16	8.53	11.14	14.55	27.42	24.21

[a] Daily average for August(range = 12.6-26.6 m^3/s).

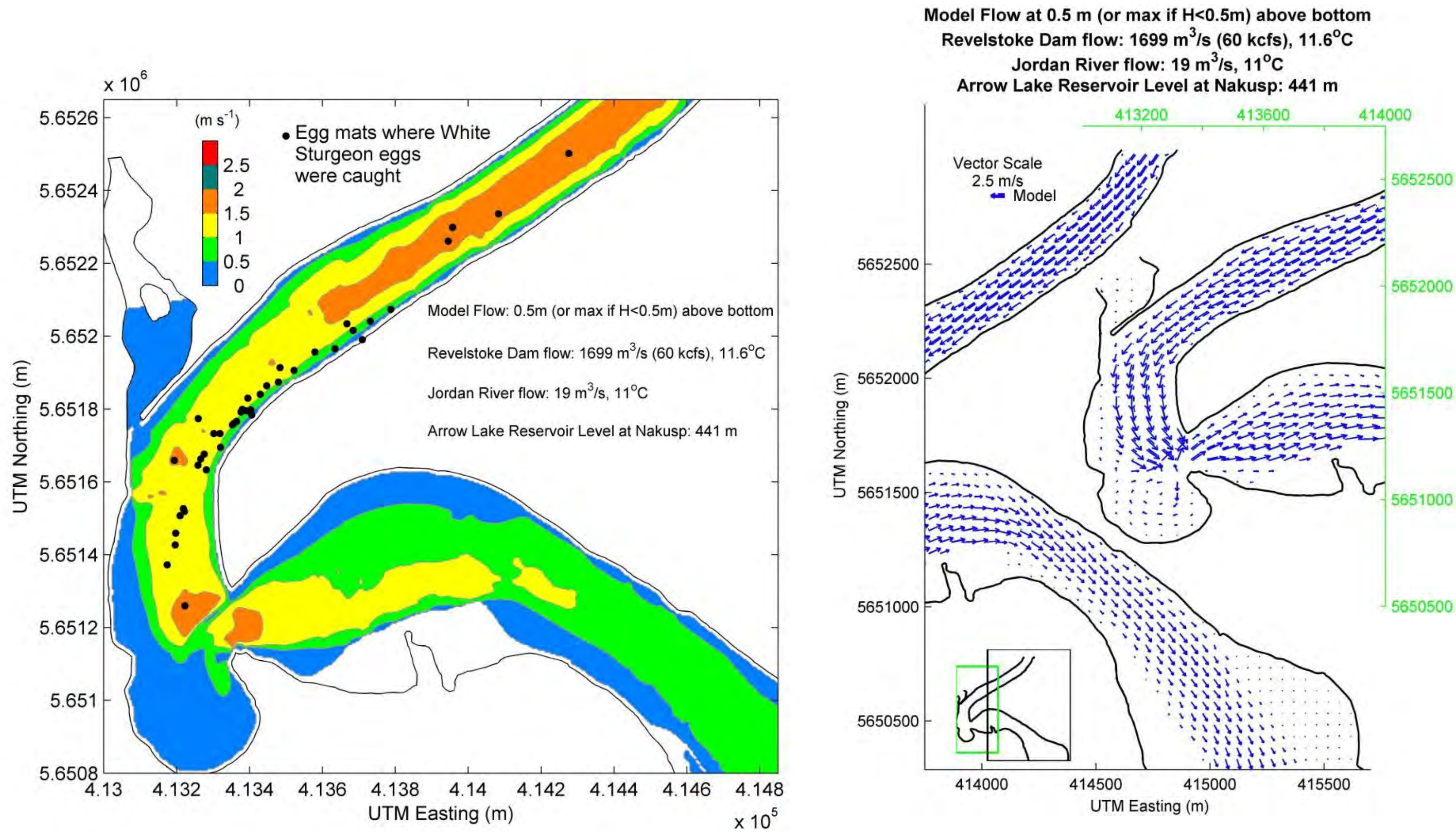


Figure 6-1: Modeled near bottom flow velocities in the Revelstoke White Sturgeon spawning and early larval rearing areas at a Revelstoke Dam discharge of 1699 m^3/s and a High Arrow Lakes Reservoir levels (left panel) and associated vectors plotted every 10th grid (right panel).

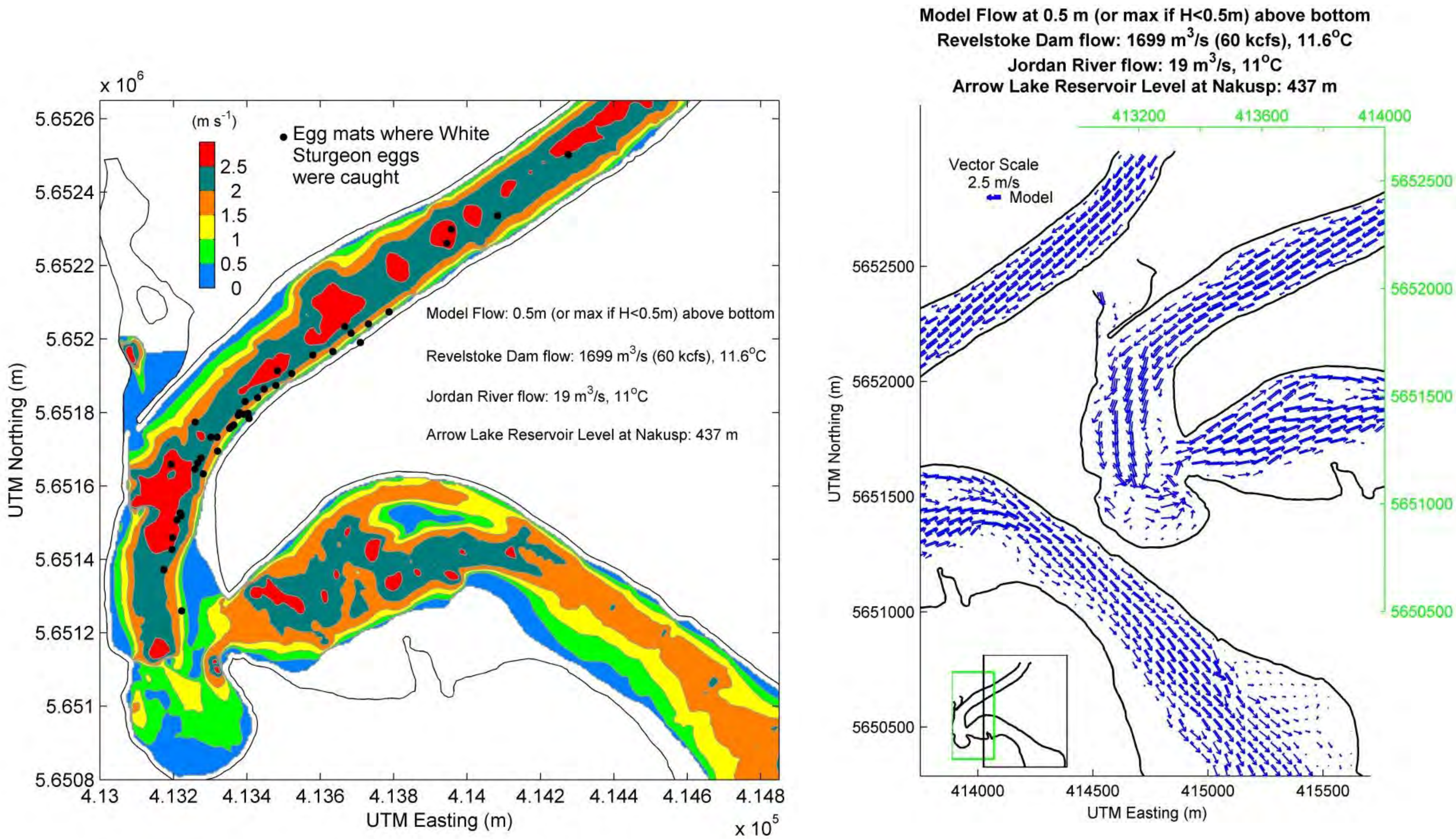


Figure 6-2: Modeled near bottom flow velocities in the Revelstoke White Sturgeon spawning and early larval rearing areas at a Revelstoke Dam discharge of 1699 m^3/s and an Intermediate Arrow Lakes Reservoir level (left panel); associated vectors flow plotted every 10th grid (right panel).

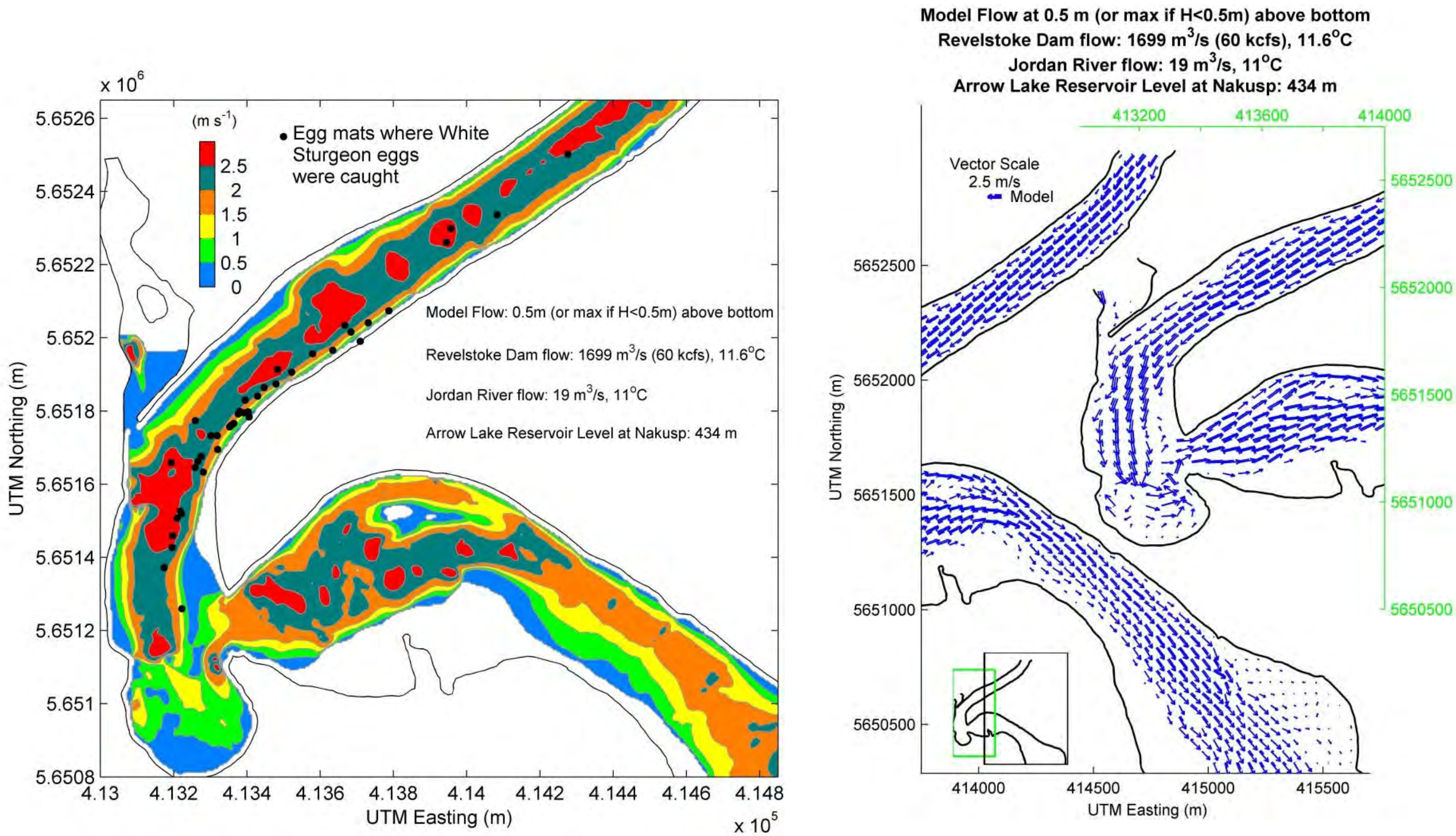


Figure 6-3: Modeled near bottom flow velocities in the Revelstoke White Sturgeon spawning and early larval rearing areas at a Revelstoke Dam discharge of 1699 m^3/s at a Low Arrow Lakes Reservoir level (left panel); associated flow vectors plotted every 10th grid (right panel).

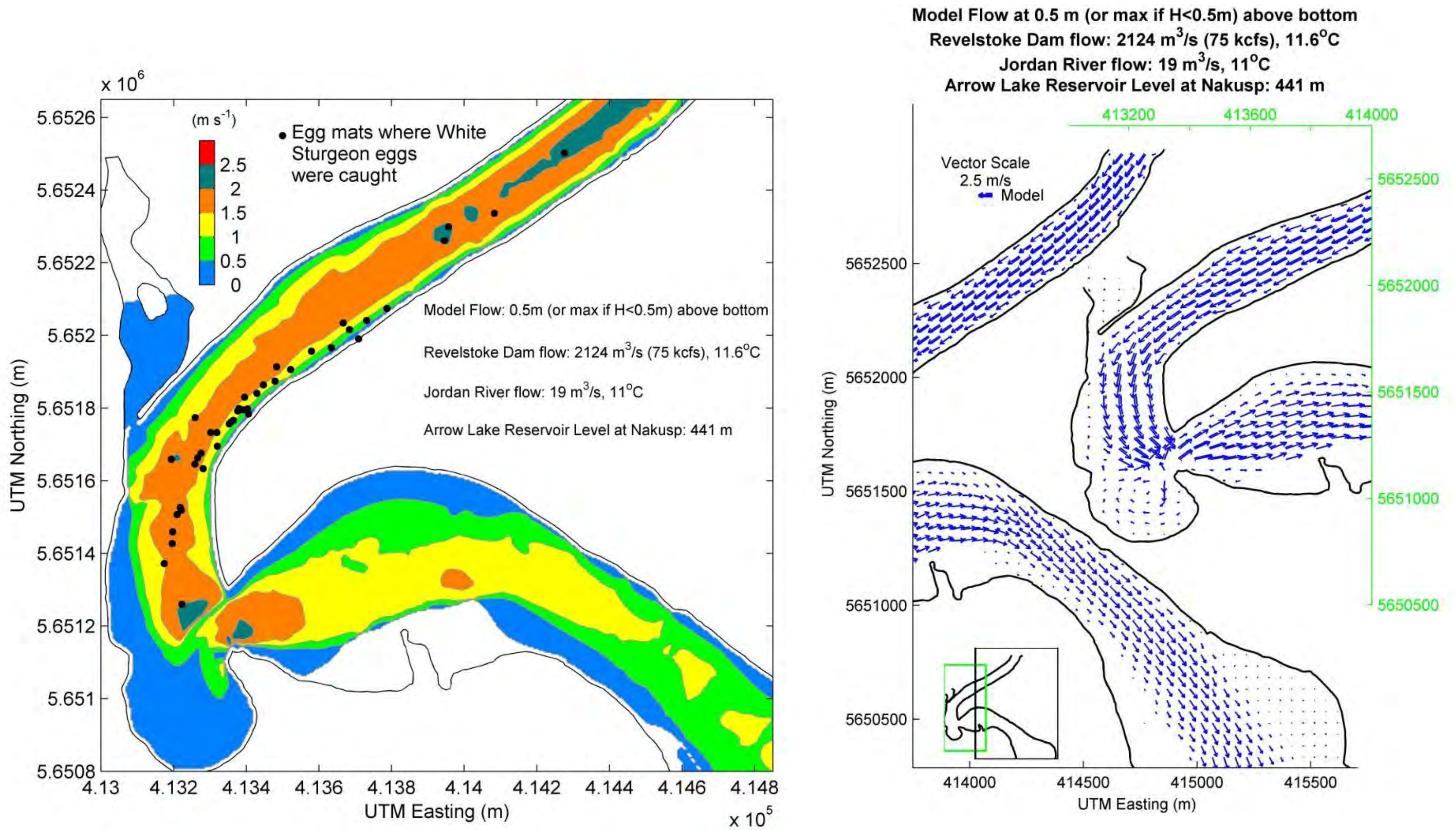


Figure 6-4: Modeled near bottom flow velocities in the Revelstoke White Sturgeon spawning and early larval rearing areas at a Revelstoke Dam discharge of 2124 m^3/s at a High Arrow Lakes Reservoir level (left panel); associated flow vectors plotted every 10th grid (right panel).

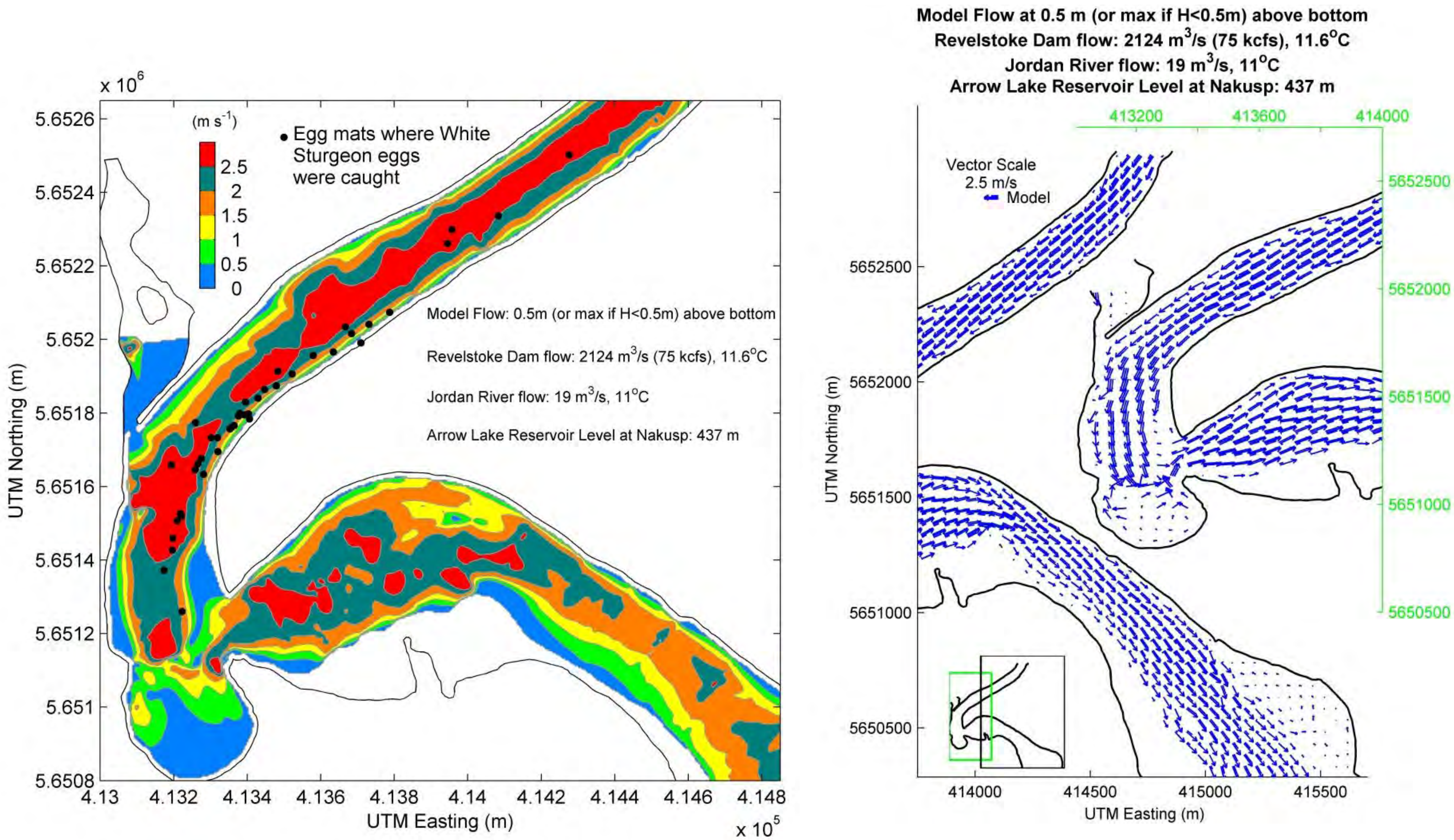


Figure 6-5: Modeled near bottom flow velocities in the Revelstoke White Sturgeon spawning and early larval rearing areas at a Revelstoke Dam discharge of 2124 m^3/s and an Intermediate Arrow Lakes Reservoir level (left panel); associated flow vectors plotted every 10th grid (right panel).

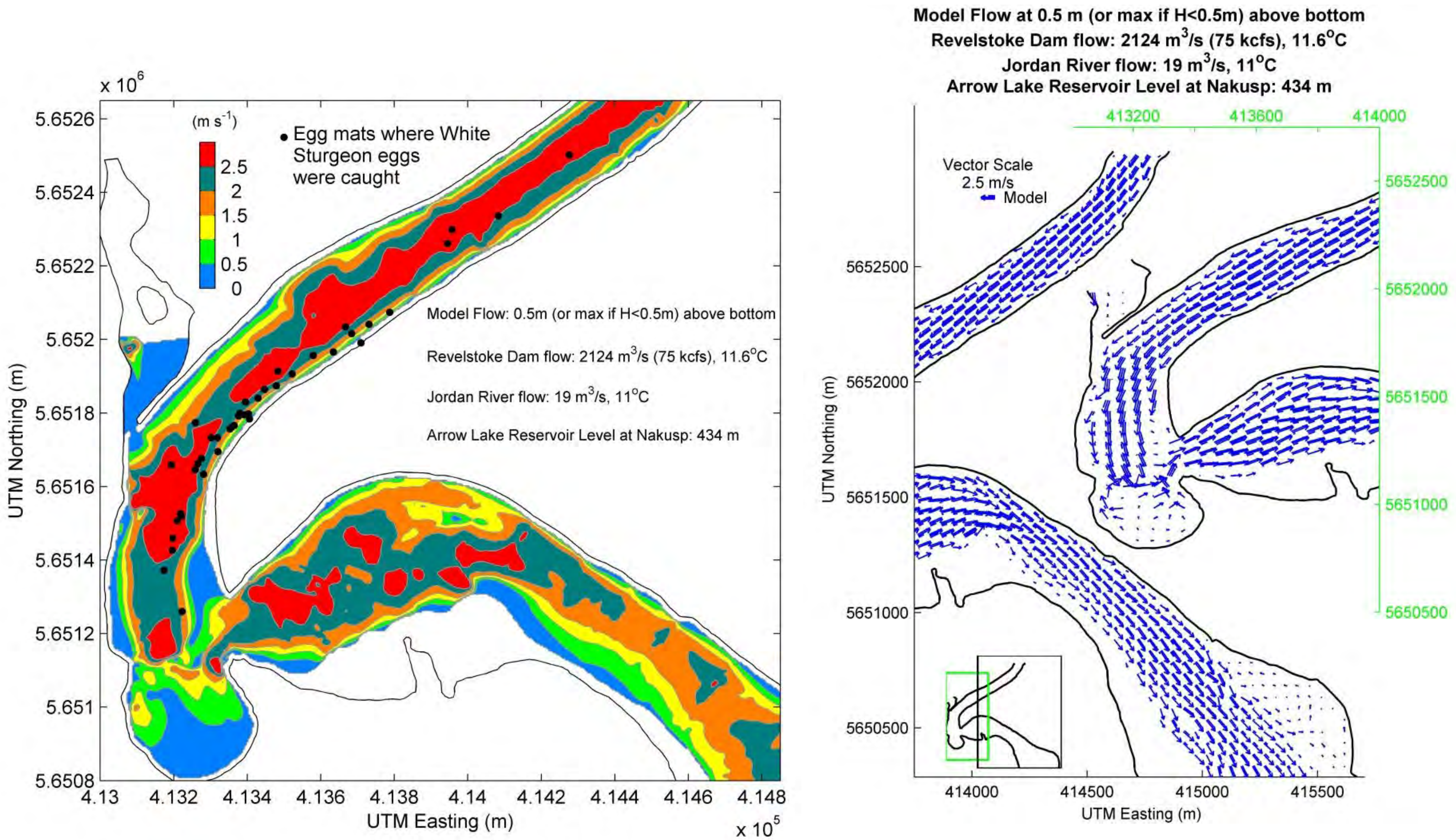


Figure 6-6: Modeled near bottom flow velocities in the Revelstoke White Sturgeon spawning and early larval rearing areas at a Revelstoke Dam discharge of 2124 m^3/s and a Low Arrow Lakes Reservoir level (left panel); associated flow vectors plotted every 10th grid (right panel).

7. Spawning Enhancement Flows

The effects of the proposed 20 kcfs (566 m^3/s) and 30 kcfs (850 m^3/s) White Sturgeon spawning enhancement flow releases on near-bottom velocities in the White Sturgeon spawning and early larval rearing areas were studied in this section. Model flow conditions used in the modeling are listed in Table 7-1. The areal extent of near-bottom flow velocity increments in the White Sturgeon spawning and egg deposition area (Figure 1-3) were analyzed and shown in Table 7-1.

Modeled near bottom flow velocities in the Revelstoke White Sturgeon white sturgeon spawning and early larval rearing areas and associated vectors were plotted for each model scenario in Figures 7-1 to 7-6.

Table 7-1: Model cases for proposed 20 kcfs and 30 kcfs White Sturgeon spawning enhancement flows and the model results for areal extent of near-bottom flow velocity increments in the White Sturgeon egg deposition/incubation area.

Model Designation	**Revelstoke Dam Flow**		**Jordan River Flow (m^3/s)** [a]	**Arrow Lakes Reservoir Level at Nakusp (m)**	**Areal Extent (Percent of total area) of Flow Velocity Increments**					
	kcfs	**m^3/s**			**0-0.5 m/s**	**0.6-1 m/s**	**1.1-1.5 m/s**	**1.6-2.0 m/s**	**2.1-2.5 m/s**	**>2.5 m/s**
$H_{ALR}20_{REVQ}$	20	566	19.0	441	84.62	15.38	0.00	0.00	0.00	0.00
$M_{ALR}20_{REVQ}$				437	26.81	17.17	26.36	22.79	6.76	0.12
$L_{ALR}20_{REVQ}$				434	25.37	16.74	23.66	23.64	9.83	0.75
$H_{ALR}30_{REVQ}$	30	850		441	34.71	65.26	0.03	0.00	0.00	0.00
$M_{ALR}30_{REVQ}$				437	23.34	15.07	17.42	28.87	13.37	1.93
$L_{ALR}30_{REVQ}$				434	23.51	14.56	16.26	28.20	14.11	3.35

[a] Daily average for August(range = 12.6-26.6 m^3/s).

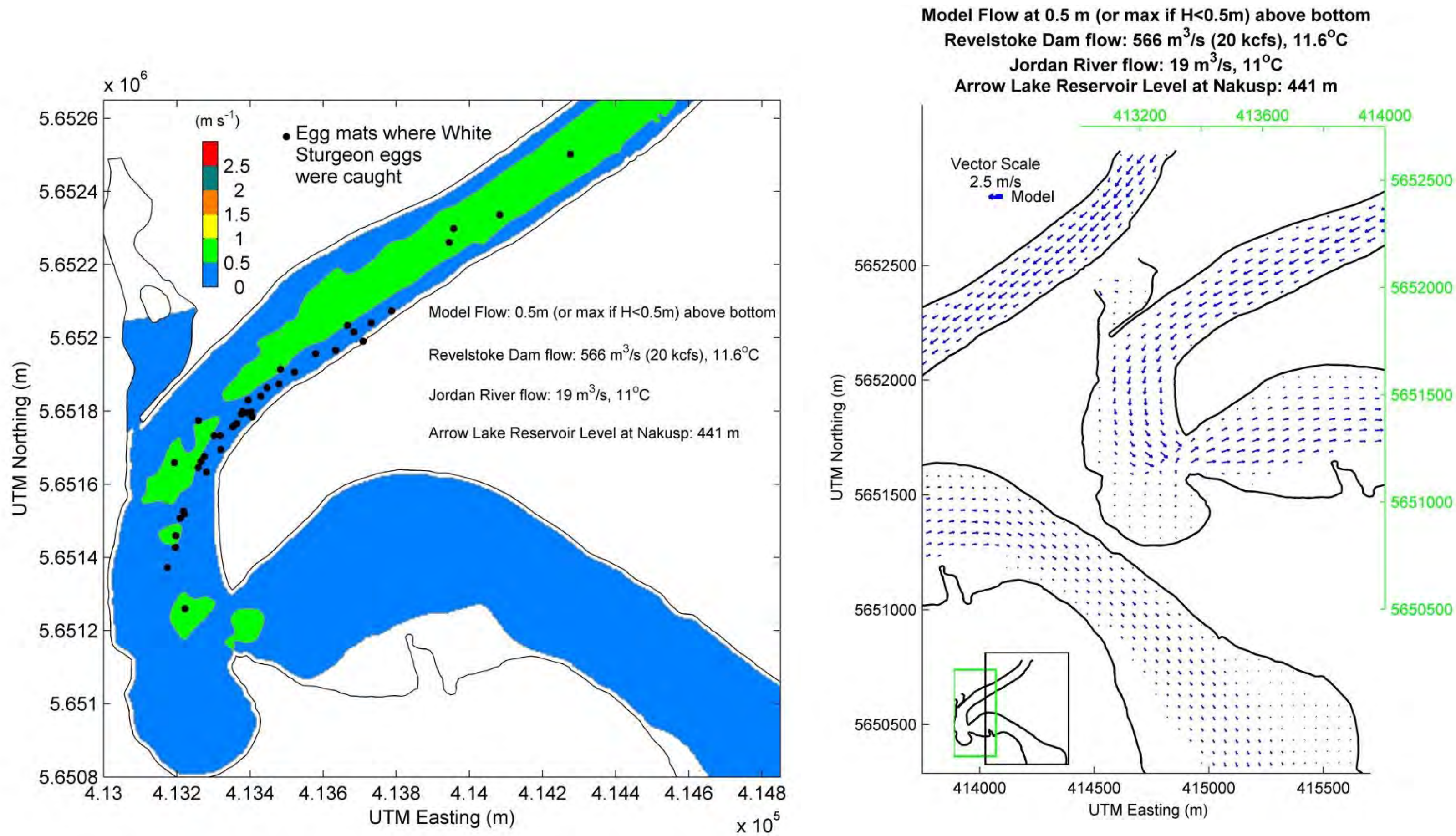


Figure 7-1: Modeled near bottom flow velocities in the Revelstoke White Sturgeon spawning and early larval rearing areas at a Revelstoke Dam discharge of 566 m^3/s and a High Arrow Lakes Reservoir level (left panel); associated flow vectors plotted every 10th grid (right panel).

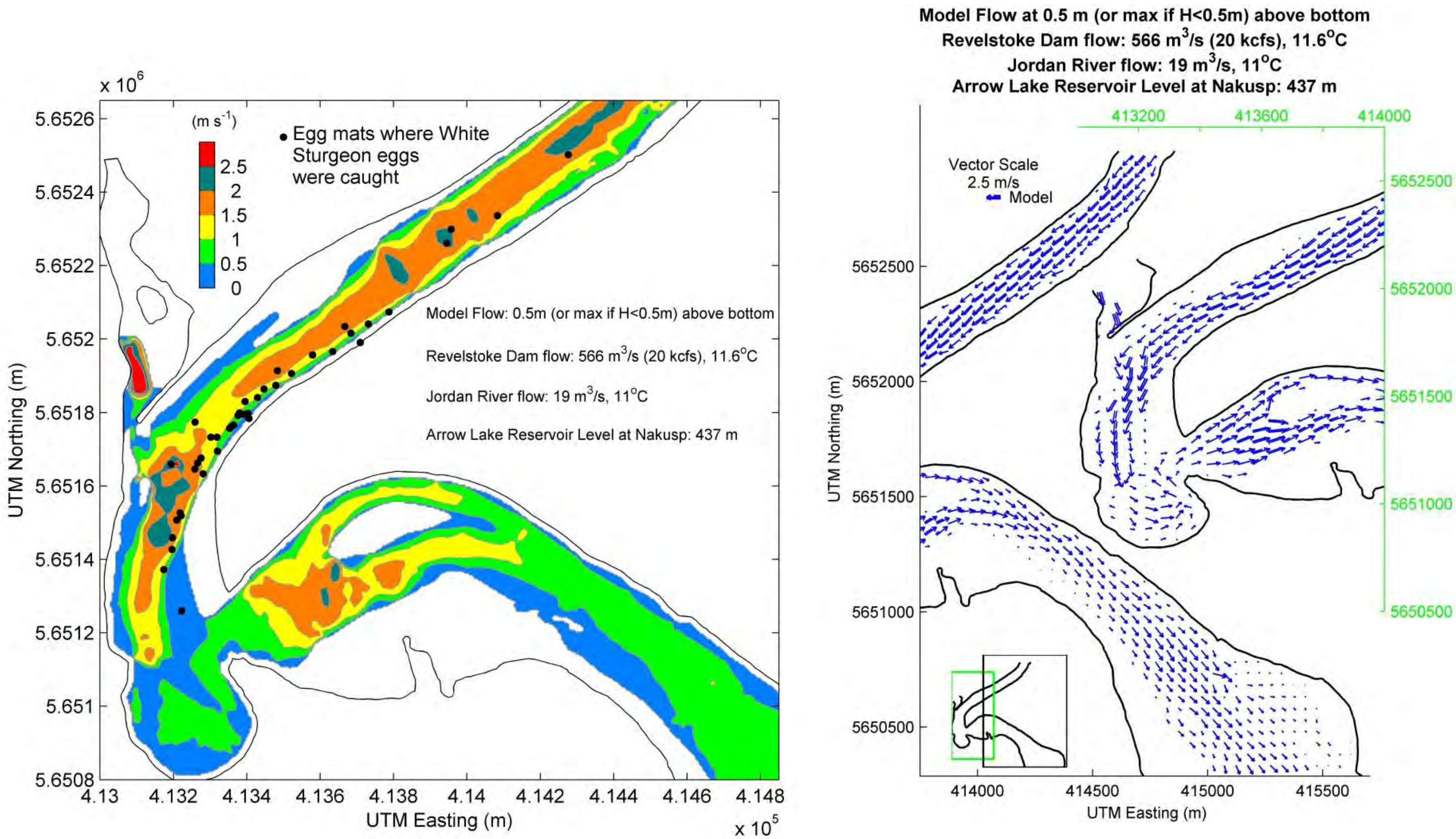


Figure 7-2: Modeled near bottom flow velocities in the Revelstoke White Sturgeon spawning and early larval rearing areas at a Revelstoke Dam discharge equivalent to 566 m^3/s and an Intermediate Arrow Lakes Reservoir levels (left panel); associated flow vectors plotted every 10th grid (right panel).

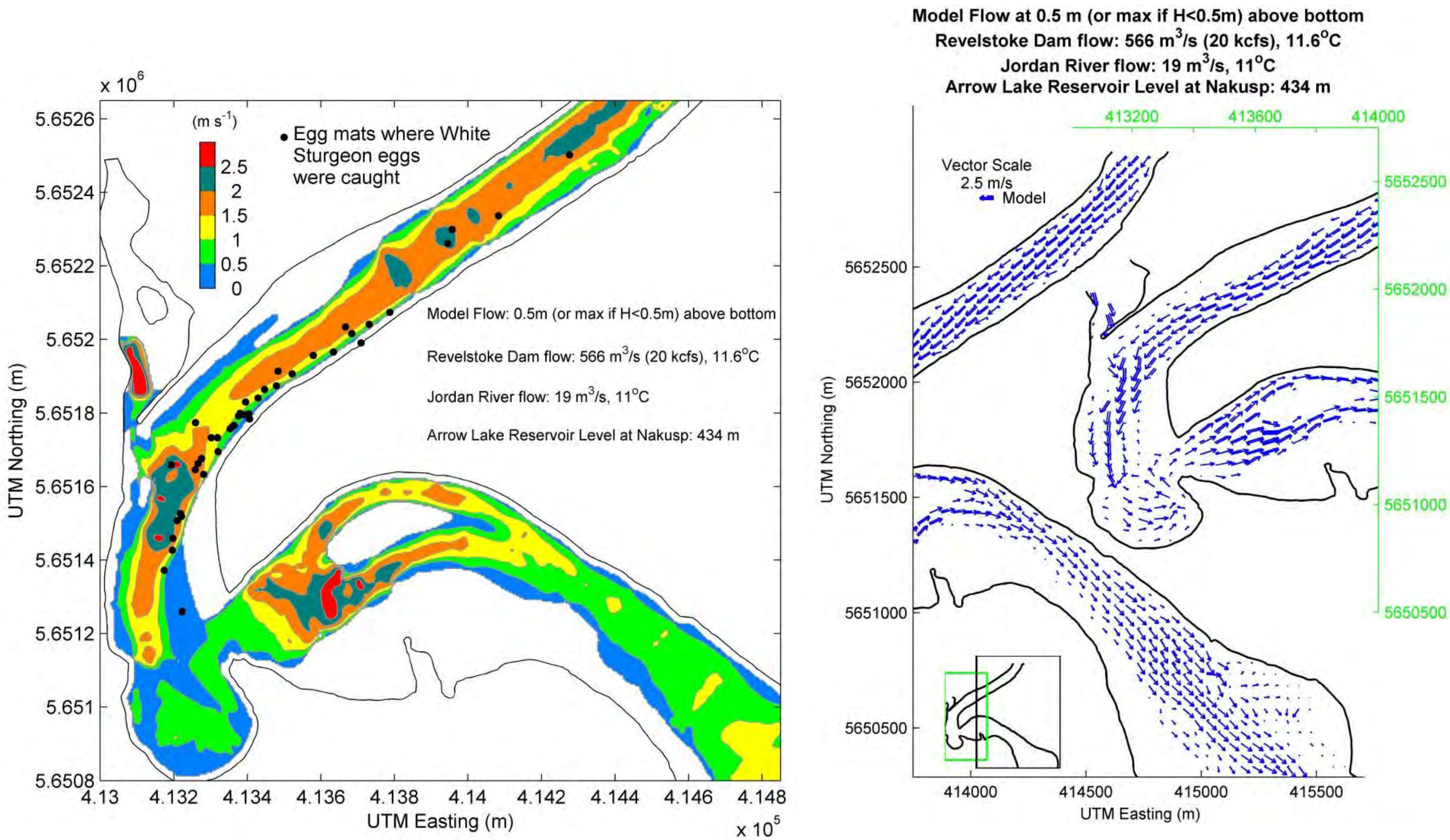


Figure 7-3: Modeled near bottom flow velocities in the Revelstoke White Sturgeon spawning and early larval rearing areas at a Revelstoke Dam discharge of 566 m^3/s at a Low Arrow Lakes Reservoir level (left panel); associated flow vectors plotted every 10th grid (right panel).

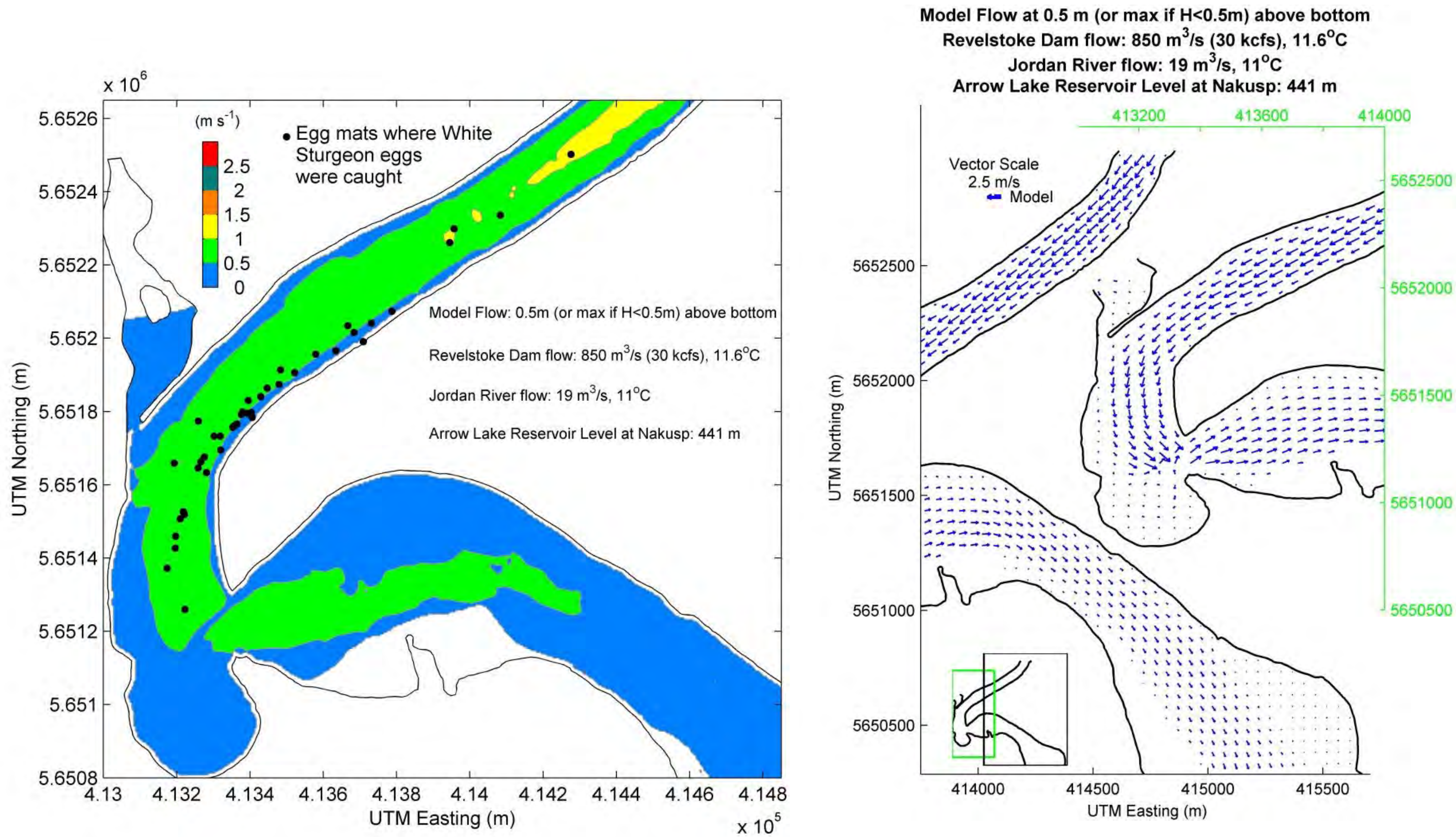


Figure 7-4: Modeled near bottom flow velocities in the Revelstoke White Sturgeon spawning and early larval rearing areas at a Revelstoke Dam discharge of 850 m^3/s at a High Arrow Lakes Reservoir level (left panel); associated flow vectors plotted every 10th grid (right panel).

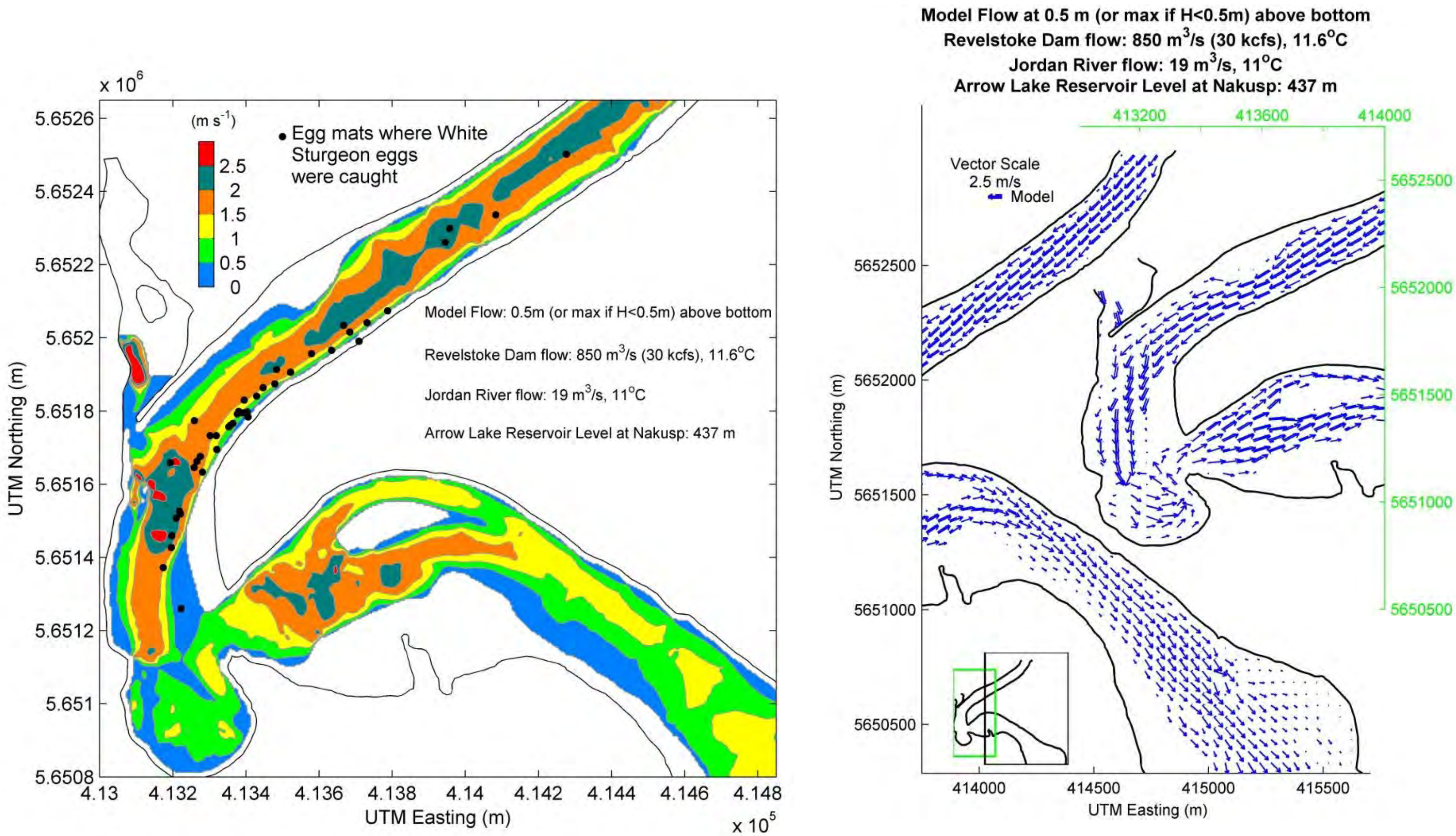


Figure 7-5: Modeled near bottom flow velocities in the Revelstoke White Sturgeon spawning and early larval rearing areas at a Revelstoke Dam discharge of 850 m^3/s and an Intermediate Arrow Lakes Reservoir level (left panel); associated flow vectors plotted every 10th grid (right panel).

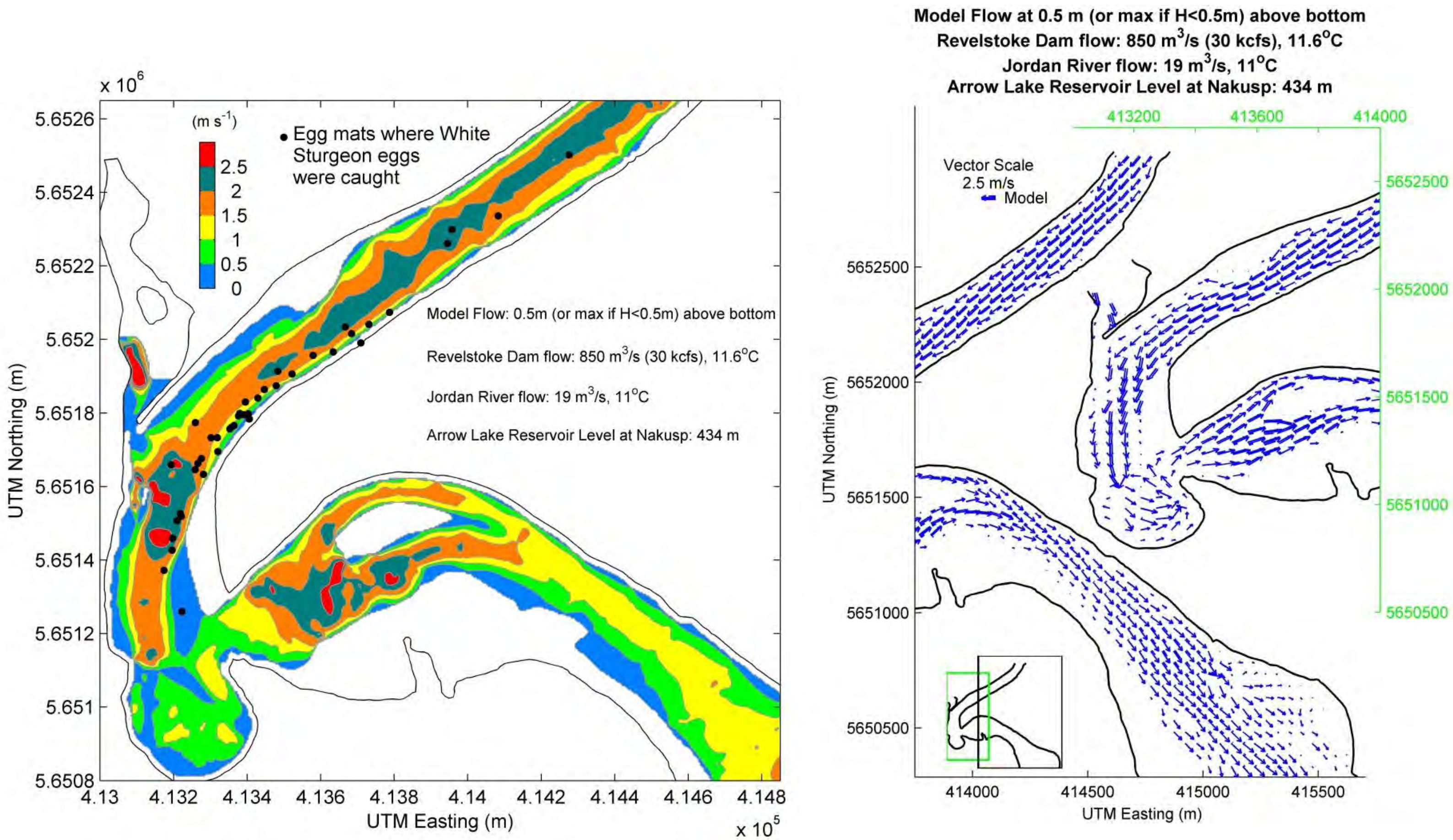


Figure 7-6: Modeled near bottom flow velocities in the Revelstoke White Sturgeon spawning and early larval rearing areas at a Revelstoke Dam discharge of 850 m^3/s at a Low Arrow Lakes Reservoir level (left panel); associated flow vectors plotted every 10th grid (right panel).

8. Substrate Alterations under Post REV5 Discharges

8.1 Introduction

The objective of this modeling component was to examine the effects of the full 2124 m^3/s (75 kcfs) discharge capacity of Revelstoke dam with REV5 in operation on substrate size composition and distribution in the White Sturgeon spawning and early larval rearing areas (see Figure 1-3 and Figure 8-1).

Two model cases, using the same parameters as provided for Newmodelrun15 ($L_{ALR}60_{REVQ}$) and Newmodelrun17 ($L_{ALR}75_{REVQ}$) (see Table 1-2), were conducted with the sediment transport module activated. They are associated with low ALR levels (434 m) and PRE and POST REV5 flow conditions, i.e. Columbia River discharges equivalent to 1699 m^3/s (60 kcfs) and 2124 m^3/s (75 kcfs).

Observations include (1) videography surveys conducted during September 11 to 13, 2010 (see Figures 8-1 and 8- 2); (2) bottom sediment size distributions at 5 sites based on sieve analysis samples collected on March 31, 2011 (Golder, 2011; Figure 8-3).

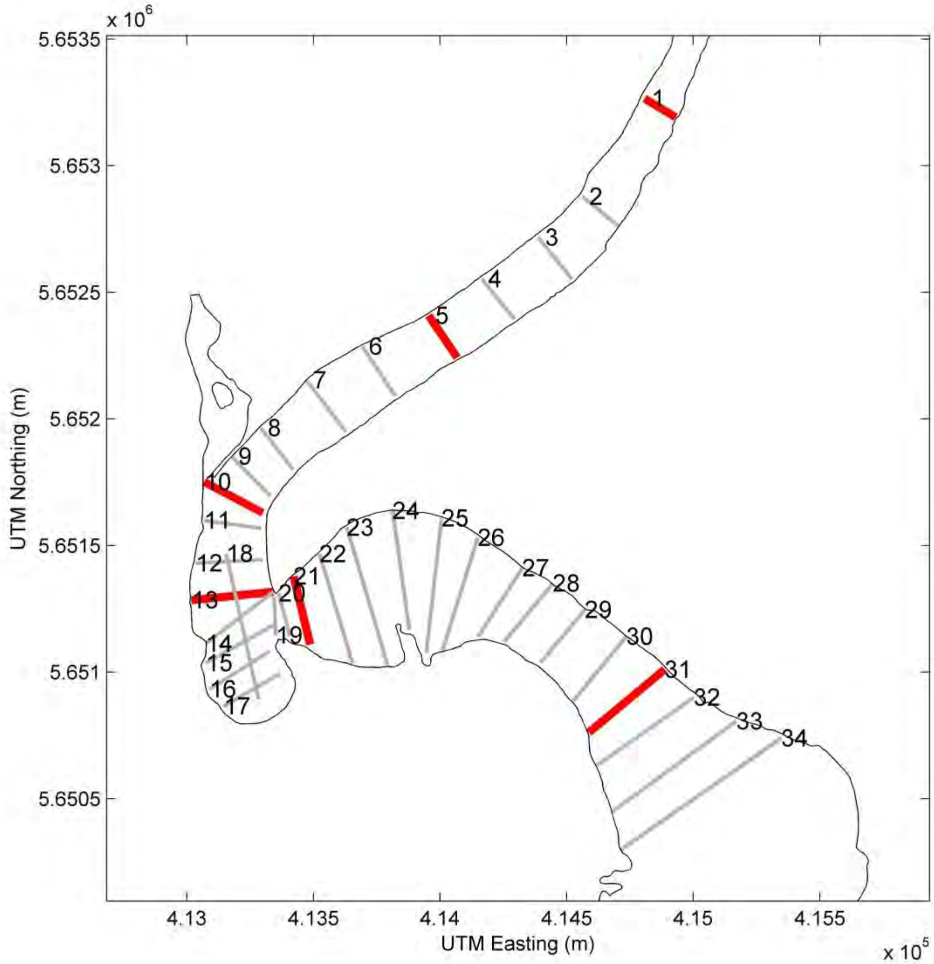


Figure 8-1. Locations of the 34 substrate videography transects surveyed in 2010. Of these, six representative transects (red lines) were selected for detailed substrate analysis.

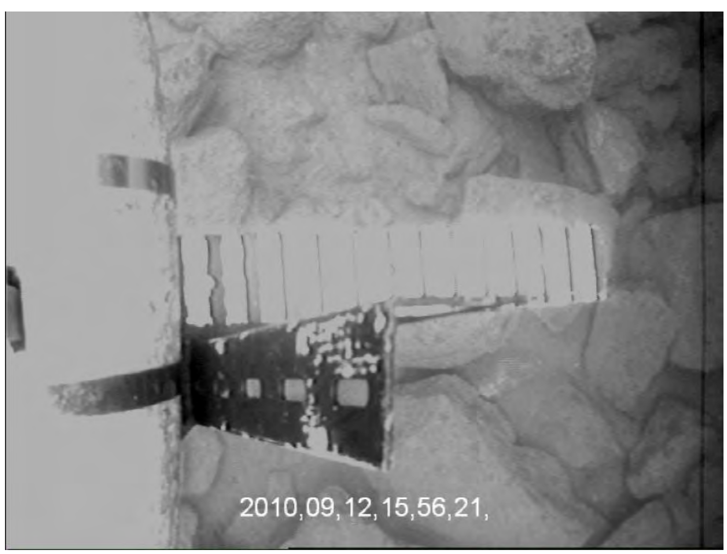


Figure 8-2. A typical video frame capture at transect 21. The object on the left is the lead fish and the bright object in the center of the frame is the scaling bar.

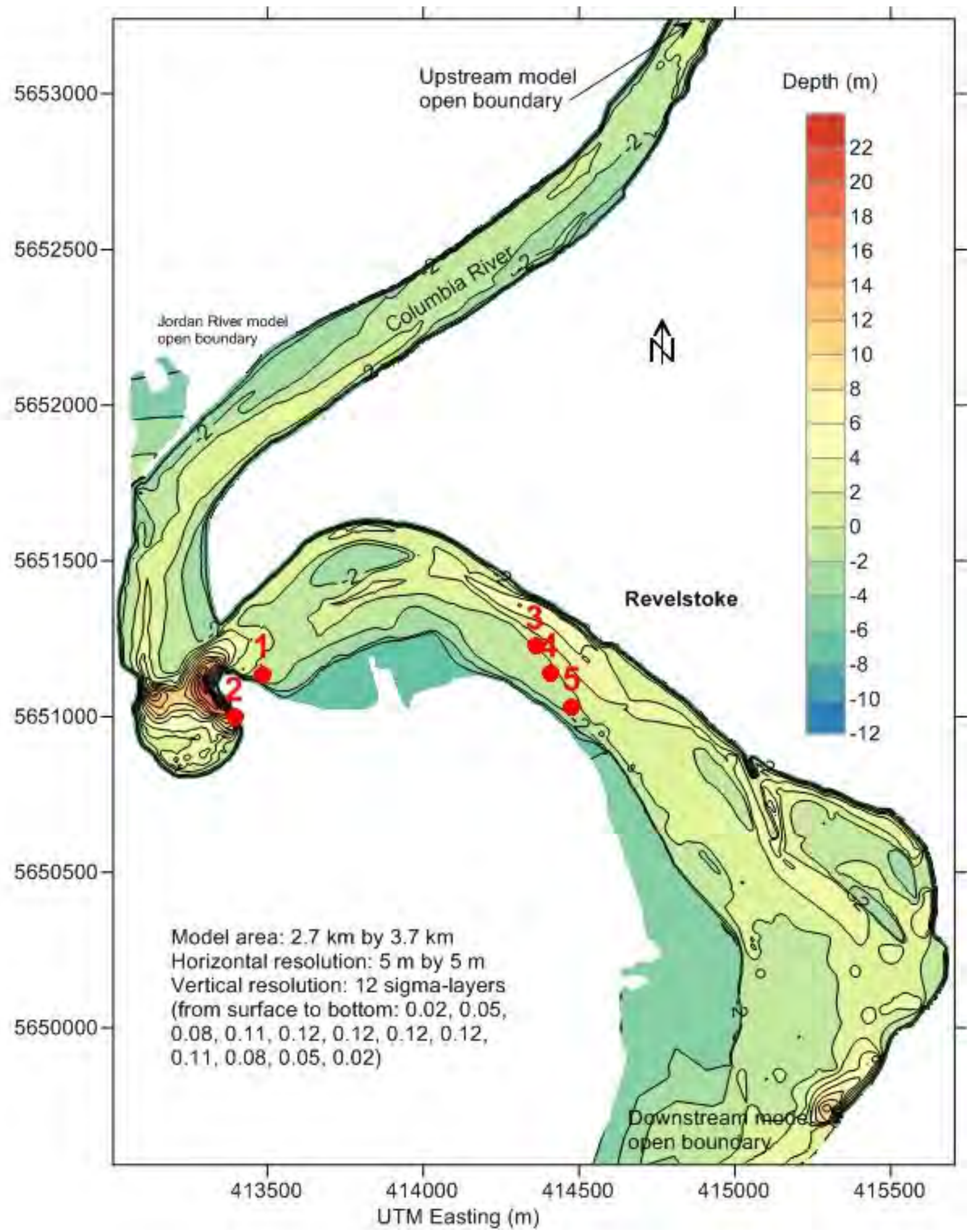


Figure 8-3. Map showing model domain and bathymetry. Red dots represent sites where bottom sediment categories were quantified using sieve analysis.

Table 8-1. Hydrodynamic conditions during the videography survey (Verification 2 Run) and the parameters that were used in the PRE and POST REV5 model runs.

	Revelstoke Dam flow		Arrow Lake level at Nakusp (m)
	(m^3/s)	(kcfs)	
Verification 2 Run	1274	45.0	435.6
PRE REV5 Model Run	1699	60	434
POST REV5 Model Run	2124	75	434

8.2 Analysis of Substrate

The videography survey images from the transects were analyzed to obtain the sediment distribution data needed for the modeling study on bottom substrate erosion and deposition. This analysis included the following five steps:

(1) Image analysis to derive the relative sediment size distribution along the videography survey transects.
(2) Regression analysis to derive the correlation between the bed sediment size distribution and near bottom flow regime along the videography survey transects.
(3) Using modeled 2-D near bottom flow regime to derive the bed sediment size distribution.
(4) Verifying the results at sieve analysis sites
(5) Determining the bed sediment size distribution for the White Sturgeon spawning and early larval rearing areas.

An initial examination of the videography frames indicated substrates at neighboring survey locations (both within and among transects) were very similar. Therefore, along the main channel in the model domain, six representative transects (red lines in Figure 8-1) were selected for more detailed substrate analysis.

In addition, sediment samples were collected from five locations in the study area (Figure 8-3) and sediment properties were quantified using sieve analysis (Golder 2011, see Table 8-2). Based on the substrates collected, the bed sediment size distribution was separated into four fractions: gravel (>4.75 mm), coarse sand (0.25-4.75 mm), fine sand (0.075-0.25 mm), and silt and clay (<0.075 mm). Sediment size distributions at Sites 4 and 5, which were exposed and dry when sampled, were significantly different than the distribution at Sites 1, 2, and 3 that were wet when sampled (Figure 8-3; Table 8-2). As a result, in this substrate study, only the sieve analysis results from Sites 1-3 were used to derive the sediment property in the model.

At each of the six representative transects, the MATLAB Image Processing Toolbox™ was used to pixelate the videography frames. Then each 2-D pixel array was filtered numerically using specified length scales to identify the proportion of different substrate material (gravel, coarse sand, and fine sand). The sieve analysis result at Site 1 (Figure 8-3) was used to calibrate the image analysis processes. The sieve analysis results at sites 2 and 3 (Figure 8-3) were used for model verification. Given the low resolution of the video frames, only the distribution for sediment coarser than the fine sand (up to 0.25 mm) was obtained. The percentage of silt and clay was estimated based on the known ratio between the fine sand and the silt / clay found in the sediment sampling data (Golder 2011).

Table 8-2. Hydrodynamic conditions during the videography survey and the parameters that were used in the PRE and POST REV5 model runs.

Site	**Location**		**Gravel**	**Coarse Sand**	**Fine Sand**	**Silt & Clay**
	UTM Easting (m)	**UTM Northing (m)**	**>4.75 (mm)**	**0.25-4.75 (mm)**	**0.075-0.25 (mm)**	**<0.075 (mm)**
1	414480	5651031	64.8%	30.6%	4.2%	0.4%
2	414409	5651139	72.7%	25.1%	1.9%	0.3%
3	414362	5651228	67.7%	30.3%	1.8%	0.2%
4	413392	5650997	33.9%	43.4%	22.3%	0.4%
5	413482	5651135	25.2%	37.6%	37.0%	0.2%

Second, the primary bottom sediment size distribution as determined from the video frames was compared with modeled near bottom velocities along the selected transects. The model near bottom flow results were from the Verification-2, which modeled hydrodynamic conditions similar to those present during the videography survey (Table 8-1). During the videography survey period (i.e. September 11-13, 2010), the maximum Revelstoke Dam flow was 1295 m^3/s, and the ALR level at Nakusp was 435.7 m. The Jordan River flow at the time was unknown, but its effect was considered minimal considering the much larger Colombia River discharges.

All data derived from videography frames for the area where near bottom velocities were less than 1.8 m/s are shown in Figure 8-4 (blue dots). The percentage of fine-grained sediment, i.e. coarse sand, fine sand, and silt and clay, is negatively correlated with the near bottom velocities. The percentage of gravel is proportionately larger. For the areas where near bottom flow is stronger than 1.8 m/s, the data exhibits a large amount of scatter, with no apparent relationship between the flow speed and sediment size distributions (not shown).

These results are compatible with known sediment transport mechanisms: the stronger the near bottom flow, the lower proportion of fine grained bottom sediment. This compatibility indicates our image analysis results are reasonable. However, if the flow is much larger than the incipient velocity, all fine grained bottom sediment is removed and the inversely-proportional relationship breaks down.

Based on the correlation between modeled near bottom velocities and the bed sediment size distribution as determined from the videography and using the modeled 2-D near bottom flow fields over the whole model domain, the bed sediment size distribution over the White Sturgeon spawning and early larval rearing areas was then determined. The derivation is verified by comparing our analysis results with the sample data at sites 1-3 in Golder (2011) as shown in Figure 8-5.

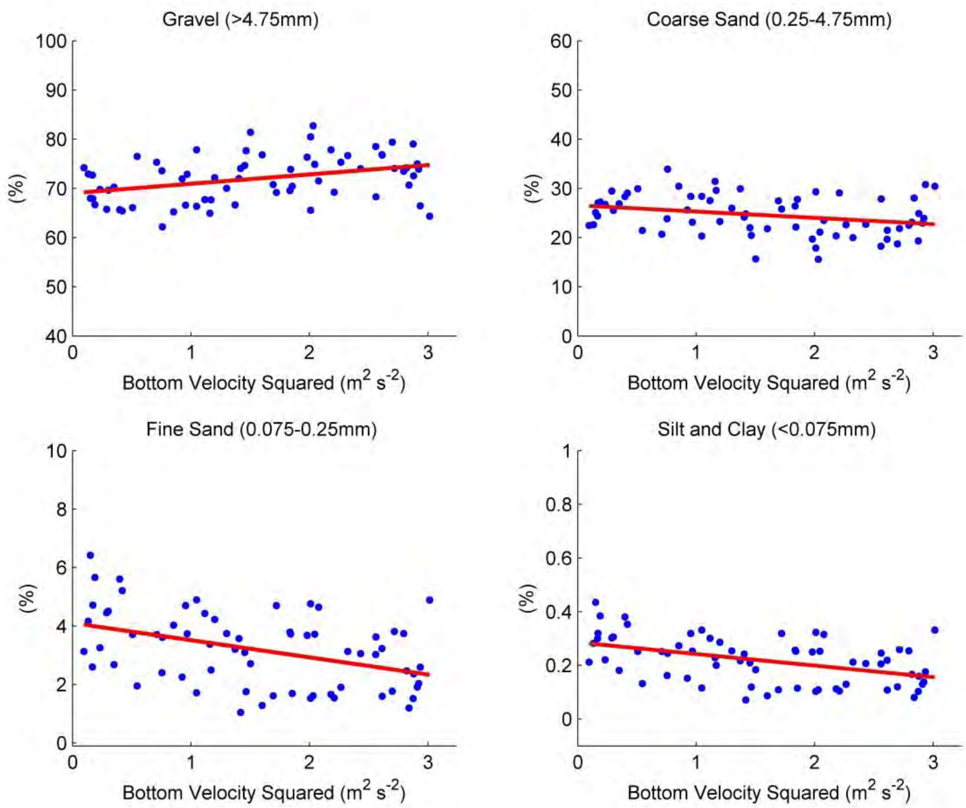


Figure 8-4. Regressive analysis between the bottom sediment size distribution and the modeled near bottom velocity squared (near bottom velocities less than 1.8 m/s).

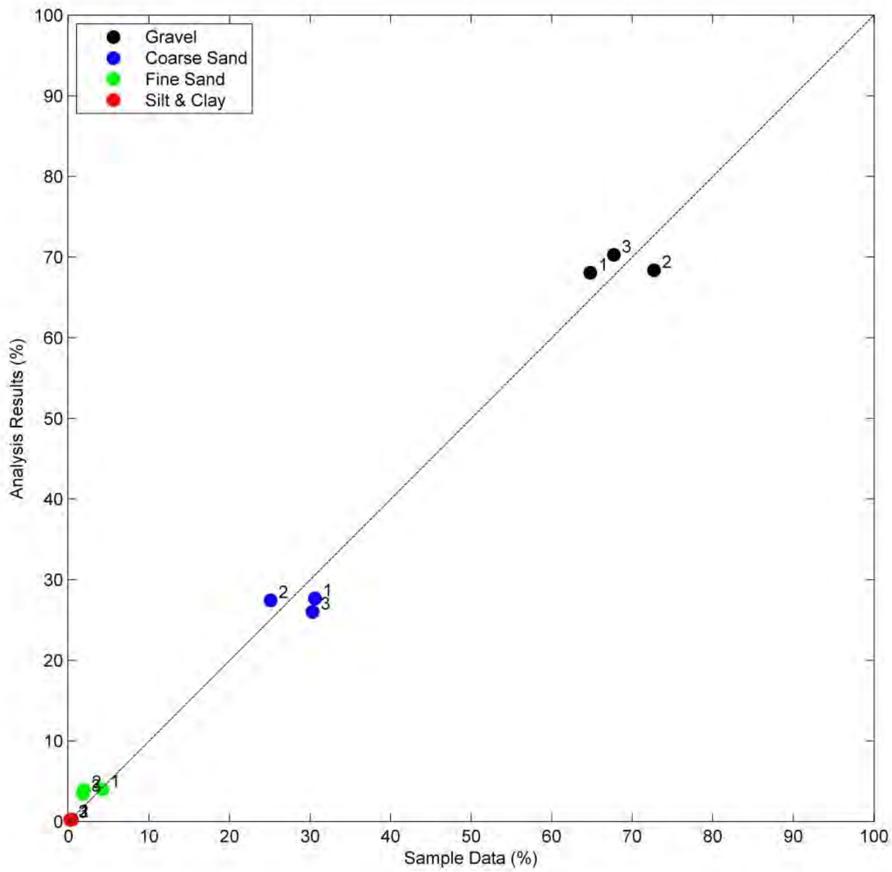


Figure 8-5. Comparison between the sample data at Sites 1-3 (Golder 2011) and the regression analysis results.

8.3 PRE REV5 Model Run

The input sediment distribution in the study area was determined based on the videography surveys and the analysis in Section 8.2. The distribution of sediment size varied within a small range in the model domain (gravel: 67.2-73.1%, coarse sand: 24.0-28.3%, fine sand: 2.8-4.2%, and silt and clay: 0.18-0.29%). An average distribution of the substrate material was then used in the sediment model which includes 70.5% gravels, 25.8% coarse sands, 3.4% fine sands, and 0.3% silts and clays.

The videography survey only provides a rough 2D distribution of the bottom sediment and there is no information available for the depth of the bottom sediment. In order to be conservative, the available thickness of total sediment was set to be 5 m (much thicker than in the actual river). As such, the modeled results of bottom erosion and deposition are qualitative.

First, the model was integrated to simulate the sediment transport process for 6 hours, with a Revelstoke Dam flow of 1699 m^3/s (60 kcfs) and a low (434 m) ALR level at Nakusp (Table 8-1).

The erosion and deposition distribution for the whole model domain is shown in Figure 8-6. Bottom sediment was suspended in the blue areas, transported by the flow, and redeposited in the negative red areas. Most suspended sediment was deposited in the following areas as shown in Figure 8-6:

A: upstream area to the Jordan River confluence,
B: downstream to the Jordan River confluence and upstream to the Big Eddy,
C: shallow areas in the wide downstream channel, and
D: downstream to the Big Eddy where the channel is getting wide.

Major erosion occurred in the adjacent areas upstream to A-D.

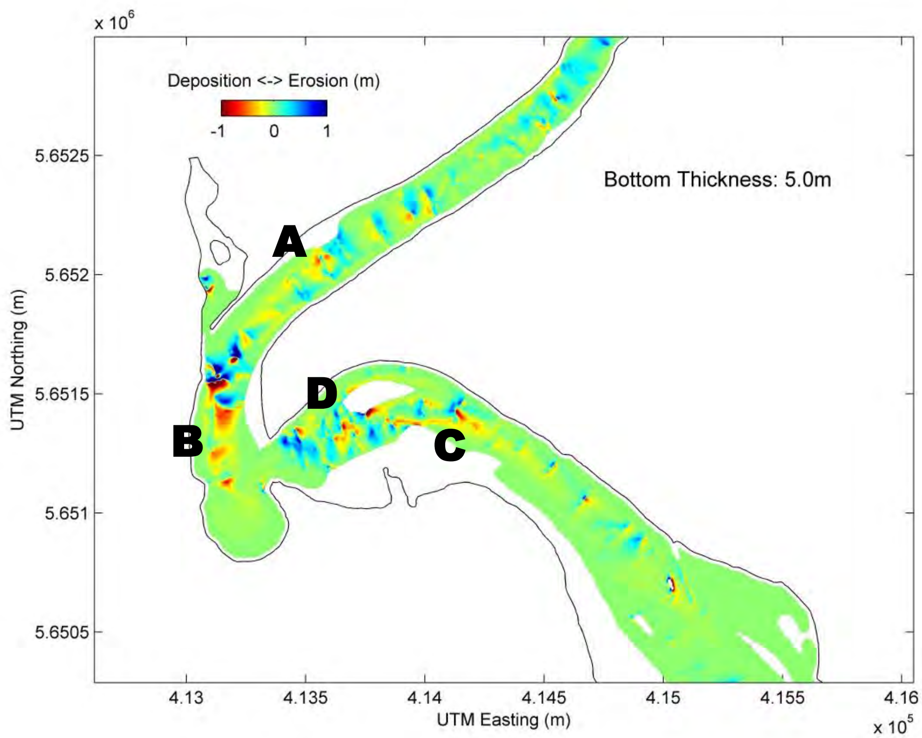


Figure 8-6. Erosion and deposition in the Model Run 1 PRE REV5).

8.4 POST REV5 Model Run

The same initial bottom sediment distribution and 434 m Arrow Lake level at Nakusp were applied in this model run. Revelstoke Dam discharge was increased to 2124 m^3/s (75 kcfs) equivalent to full generation capacity with five operational units (REV5). The difference between the results of this run and the PRE REV5 Model Run 1 indicates the effect of the POST REV5 flow on the substrate.

For total sediment, erosion and deposition were less than 0.5 meters in most areas as shown in Figure 8-7. The pattern is similar to the distribution found in the Model Run 1 (Figure 8-6). There was more deposition at the east bank near the Golf Course just before the water flows through the narrow channel downstream to the Big Eddy (area B marked in Figure 8-7).

Among the 4 sediment types, the effect of the POST REV5 flow on gravels and cobbles is negligible for the whole model domain (not shown). Difference of erosion and deposition between POST REV5 Model Run and PRE REV5 Model Run for fine-grained sediment, i.e. coarse sand, fine sand, and silt and clay, are shown in Figures 8-8 to 8-10. Although the initial thickness of total sediment is still 5 meters in the POST REV5 Model Run, each sediment type has its own initial bottom thickness (available for erosion) based on its fraction. The available thicknesses for erosion of coarse sand, fine sand, and silt and clay are 1.29 m, 0.17 m, and 0.01 m, respectively (and 3.53 m for gravel).

The greatest effect of the POST REV5 flow on riverbed substrates in the study area was the change of erosion and deposition for fine sand (Figure 8-9). Again, the notable area of deposition is at the east bank near the Golf Course to the north of the Big Eddy.

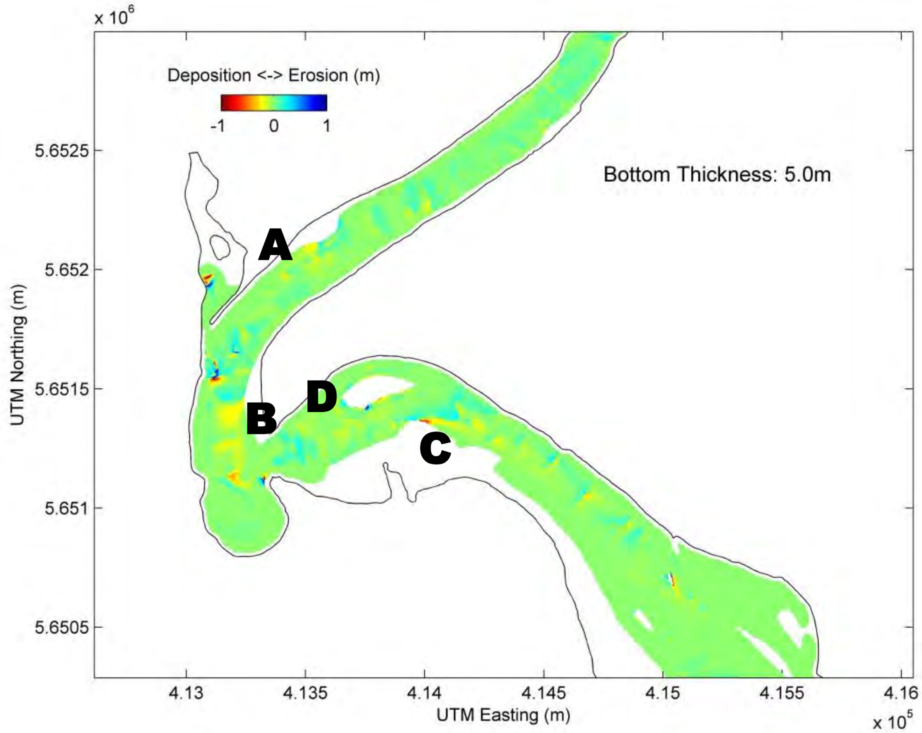


Figure 8-7. Difference between POST REV5 Model Run and PRE REV5 Model Run for total sediment.

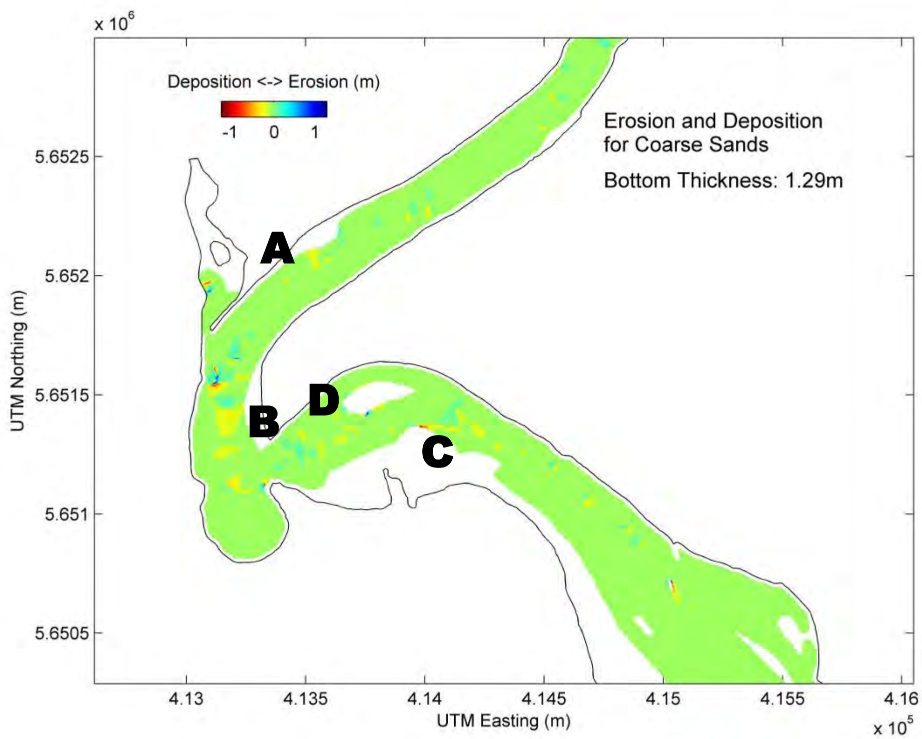


Figure 8-8. Difference between POST REV5 Model Run and PRE REV5 Model Run for coarse sand (0.25-4.75 mm).

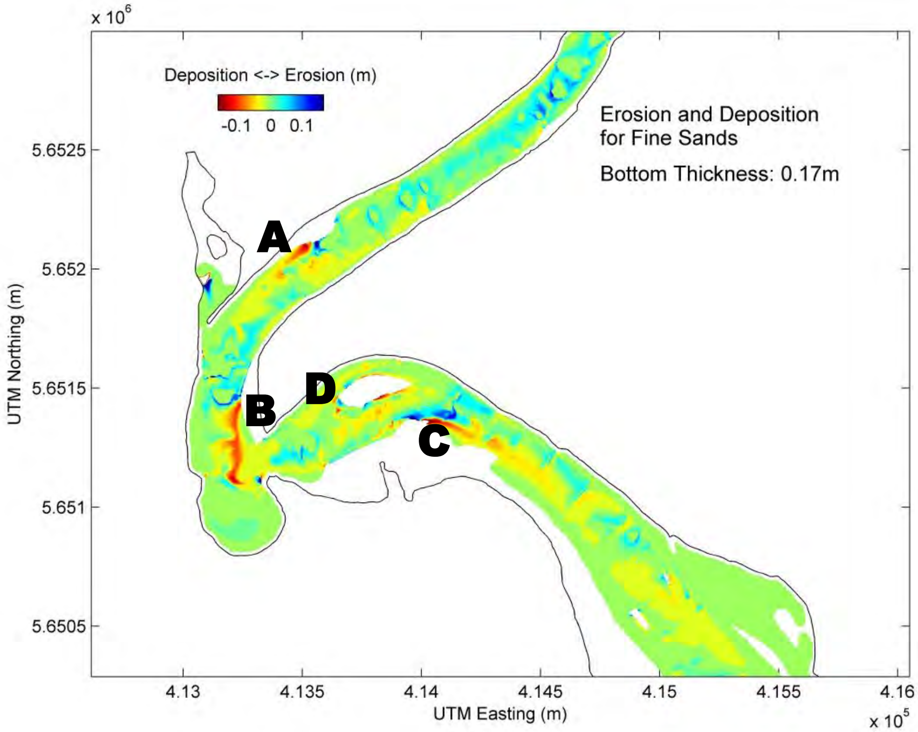


Figure 8-9. Difference of between POST REV5 Model Run and PRE REV5 Model Run for fine sand (0.075-0.25 mm).

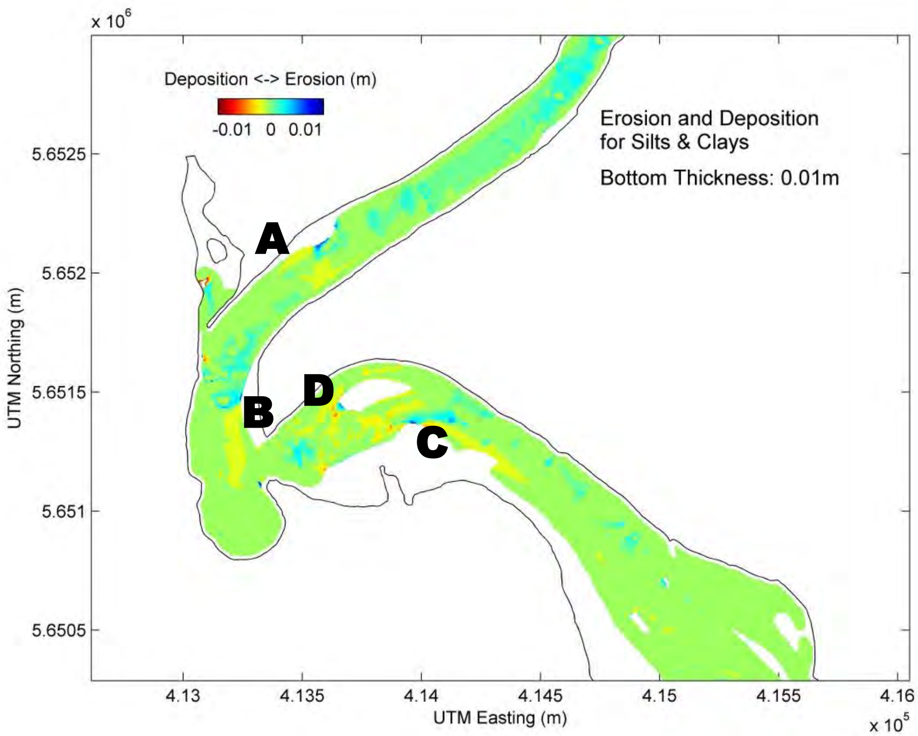


Figure 8-10. Difference between POST REV5 Model Run and PRE REV5 Model Run for silt and clay (<0.075 mm).

9. Larval Dispersal Patterns

In this section, model results of particle tracking were used to demonstrate effects of various REV flows on patterns of feeding larval dispersal. Larval “particle” characteristics were simulated based on data provided by James Crossman (BC Hydro): the grain size was set at 13.38 +/- 0.299 mm, granular density was slightly negatively buoyant (used neutral in the model), and the mass of each larvae was 0.024 +/- 0.001 g. The larvae were “released” at 0.5 m above the bottom at each of the 34 egg mat sites where eggs were captured (Table 3-2).

The 15 model runs with particle tracking module activated were summarized in Table 9-1. In association, Columbia River discharges equivalent to 5, 20, 30, 60, and 75 kcfs (142 m^3/s to 2124 m^3/s) with low, moderate, and high ALR levels (434, 437, and 441 m).

The simulated movement of released larvae is presented by time-lapse snapshots in Appendix C. The total 34 sites (sources) were separated to 6 groups based on the locations and the features of the larval dispersal tracks (fates).

Table 9-1: Summary of model cases to examine White Sturgeon larval dispersal patterns.

Model Cases	Revelstoke Dam Flow		Jordan River Flow (m3/s)	Arrow Lakes Reservoir Level at Nakusp (m)
	(m3/s)	(kcfs)		
$H_{ALR}5_{REVQ}$	142	5	19	441
$M_{ALR}5_{REVQ}$	142	5	19	437
$L_{ALR}5_{REVQ}$	142	5	19	434
$H_{ALR}20_{REVQ}$	566	20	19	441
$M_{ALR}20_{REVQ}$	566	20	19	437
$L_{ALR}20_{REVQ}$	566	20	19	434
$H_{ALR}30_{REVQ}$	850	30	19	441
$M_{ALR}30_{REVQ}$	850	30	19	437
$L_{ALR}30_{REVQ}$	850	30	19	434
$H_{ALR}60_{REVQ}$	1699	60	19	441
$M_{ALR}60_{REVQ}$	1699	60	19	437
$L_{ALR}60_{REVQ}$	1699	60	19	434
$H_{ALR}75_{REVQ}$ (Verification 6)	2124	75	19	441
$M_{ALR}75_{REVQ}$	2124	75	19	437
$L_{ALR}75_{REVQ}$	2124	75	19	434

10. Summary

High resolution (5m×5m horizontally, 12 sigma layers vertically) COCIRM-SED modelling was used to investigate the effects of flow alterations on velocities, temperatures, and sediments within the White Sturgeon spawning and larval rearing area downstream of Revelstoke Dam. Realistic values and variations of Columbia and Jordan river discharges, water temperatures, and ALR levels based on historical observations were used in the model runs.

The effect of differential water temperatures in the Columbia and Jordan rivers was studied in Section 2.

To assess near bottom flow conditions at the estimated time of spawning, the model was used to determine flows during each of the 13 spawning events and at each of the 34 locations where eggs were captured (Section 3). Near bottom flow conditions during the egg incubation period were determined hourly over the 15 day egg incubation periods following each spawning event and at each egg mat location where eggs were captured (Section 4).

The effects of REV5 minimum flow (5 kcfs; Section 5), the 15 kcfs increase in maximum REV5 flow (60 versus 75 kcfs; Section 6), and the proposed 20 and 30 kcfs White Sturgeon spawning enhancement flows (Section 7), on near-bottom velocities in the Revelstoke spawning area also were examined. The areal extent of near-bottom flow velocity increments in the White Sturgeon egg deposition/incubation area were analyzed and presented for each of these analyses.

In Section 8, the effects of the 75 kcfs (2124 m^3/s) REV5 flows at low ALR levels (434 m) on substrate size composition and distribution in the study area were examined. The model results of erosion and deposition were compared with the model results of the 60 kcfs (1699 m^3/s) REV4 discharge. Section 9 provides the model results of particle tracking to demonstrate effects of various Revelstoke discharges and ALR levels on patterns of White Sturgeon larval dispersal.

11. References

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