Columbia River Project Water Use Plan

Lower Columbia River

Reference: CLBMON #29 (Year 4 and Year 5)

Lower Columbia River Juvenile Sturgeon Detection Program: 2011 and 2012 Investigations Data Report

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BC Hydro and Power Authority

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EXECUTIVE SUMMARY

The population of White Sturgeon (*Acipenser transmontanus*) in the lower Columbia River (LCR) Canada was listed as one of four endangered populations under the Species at Risk Act (SARA) in 2006. Despite some evidence of limited natural recruitment in the LCR, the level of recruitment annually is considered insufficient to maintain a self-sustaining population, and the population was forecast to become functionally extinct by 2044 in the absence of effective recovery. Recovery was directly initiated in 2001 through the release of hatchery-reared juveniles as a stopgap measure until recruitment failure could be addressed. It was identified during the development of the Columba Water Use Plan (WUP) that direct management responses for White Sturgeon were limited to non-operational habitat improvements designed to improve spawning success and juvenile survival. However, life history data (e.g., abundance, growth, survival) were lacking, and habitat suitability and availability across larval and juvenile life stages were unknown. Accordingly, larval and juvenile monitoring in the LCR over a longer period was deemed critical to addressing management questions related to recruitment and success of the Conservation Aquaculture Program.

For early life stage monitoring, passive sampling was conducted using drift nets in order to determine the distribution of White Sturgeon yolk-sac larvae (YSL) in the LCR and assist in identifying spawning locations and identify areas of habitat use. Consistent with previous years, sampling was conducted at multiple locations (i.e., ALH/HLK, river kilometer (rkm) 0.1; Kootenay River, rkm 10.5; downstream Kinnaird, rkm 18.2; and Waneta, rkm 56.0) in an attempt to identify if spawning had occurred. In 2011, spawning was estimated to have occurred from June 30 to August 3 at Waneta, and from August 1 to August 5 at ALH. Spawning was documented downstream of Kinnaird, however, condition of egg and larval samples inhibited estimation of fertilization date due to the physical state of the samples which prevented developmental staging. No samples were collected at the Kootenay and HLK sites. In 2012, Spawning was estimated to have occurred between June 28 and July 22 at Waneta while no samples were collected at other monitoring locations despite effort. Larval samples collected at all locations over both years were at the yolk-sac stage suggesting habitat is not suitable for YSL burrowing behaviour causing early drift dispersal. Finally, a common garden experiment was designed and implemented to investigate the effects of temperature on development of larvae. Results from this experiment will improve confidence in the age of larvae collected in the wild, allowing for more accurate estimates of when spawning occurred.

An annual juvenile White Sturgeon program was initiated in 2008 to describe important parameters related to growth, survival, and distribution in the LCR. To determine distribution of fish throughout the LCR, sampling effort was randomly distributed with equal probability within and across each of 5 zones (11.2 rkm in length) ensuring a spatially balanced sampling design. Captures were predominantly hatchery-released juveniles with wild juveniles representing <1% of the total catch. High habitat use was documented in the Robson stretch, Kinnaird, and Waneta, with juveniles selecting primarily slow, deep sections of habitat (e.g., deep runs and eddy habitats). To further describe juvenile habitat,

data collection for the production of a detailed substrate habitat map for the entire LCR was initiated. Generally, older ages represented larger proportions of the total catch but all hatchery release ages were represented within the high use areas. Annual growth rates ranged 9.5 – 12.0 cm in fork length for younger fish (fish released from 2006 -2011) and 7.6 – 8.5 cm per year for older aged juveniles (fish released 2001-2005). Average annual weight increases were smaller for younger fish (fish released from 2006 -2011) and larger for older ones (fish released 2001-2005), suggesting that growth in total length is more important in the early years than weight.

Results from this long- term monitoring program will contribute to knowledge regarding larval and juvenile stages to better understand potential causes of recruitment failure and help inform recovery measures moving forward. The state of knowledge pertaining to the various management questions associated with this monitoring project are summarized in Table ES1.

Table ES1. CLBMON #29 Status of Lower Columbia River Juvenile White Sturgeon Monitoring Program Management Questions.

Management Question	Status
What are the relative abundance, survival rates, and distribution locations of larvae and juvenile White Sturgeon in the lower Columbia River under current operating parameters?	- Larval Stage: Additional data pertaining to timing, locations, and frequency of spawning in the lower Columbia River (LCR) are needed to address this question at the larval stage. Larvae have been collected near the HLK/ALH spawning area, downstream of Kinnaird, and from the Waneta spawning site downstream into the US portion of the LCR. Larval catch has predominantly consisted of young (1-3 days post hatch) individuals, suggesting early dispersal from spanwing locations possibly due to habitat suitability or other factors. - Juvenile Stage: Distribution of juveniles has been assessed throughout the LCR, and is restricted primarily to slower moving habitats like eddy's and deeper runs. While these habitats are available primarily in the upper (Robson to Genelle) or lower (Beaver Creek to Waneta) sections of the river, juveniles of hatchery origin are captured throughout the entire LCR. With continued sampling in the coming years, abundance and survival rates will be able to be estimated.
What are the physical and hydraulic properties of this habitat that define its suitability as juvenile sturgeon habitat?	- Juveniles are selecting deeper (>10 m), slow moving (< 1.0 m/s), habitats with smaller substrates (e.g., sand, small gravel). These habitats are widely distributed through the upper reaches (e.g., Robson) and are restricted to eddy habitats downstream of the Kootenay River confluence to the US border.
How do normal river operations affect larval habitat conditions in the lower Columbia River?	- At the present time more data are required to address this question. Spawning has been identified at several locations but the quantity and quality of spawning habitat is currently unknown. Based on the capture of primarily yolk-sac larvae within a few days of hatch, the spawning habitat throughout the LCR is presumed to be poor for hiding after hatching from the egg. Further work is needed to address current habitat conditions.

Management Question	Status
How do normal river operations affect juvenile habitat conditions in the lower Columbia River during dispersal and on a seasonal basis?	- The distribution of juvenile White Sturgeon in the LCR is restricted to deeper, slower moving, habitats. These habitats are currently not limited by the operational regime of the river, irrespective of the time of year. Additional data will help to further address this question over a longer time period that includes more operational scenarios.

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1 INTRODUCTION

The population of White Sturgeon (*Acipenser transmontanus*) in the lower Columbia River (LCR) Canada was listed as one of four endangered populations under the Species at Risk Act (SARA) in 2006. In Canada, the LCR is defined as the 57.0 km reach of the Columbia River downstream of Hugh L. Keenleyside Dam (HLK) to the United States border. An estimated 1,157 adult White Sturgeon (95% C.I. 414-1899; Irvine et al. 2007) reside within the Canadian reach, with an additional 2,003 individuals (95% C.I. 1093-3223) in the United States between the border and Grand Coulee Dam, WA (Howell and McLellan 2007). This transboundary population is suffering from recruitment failure similar to other populations of White Sturgeon residing in the Kootenay (Anders et al. 2002), Nechako (McAdam et al. 2005), and Snake (Jager et al. 2002) rivers. Despite some evidence of limited natural recruitment in the LCR, the level of recruitment annually is considered insufficient to maintain a self-sustaining population, and the population was forecast by the Upper Columbia White Sturgeon Recovery Initiative (UCWSRI) to become functionally extinct by 2044 in the absence of effective recovery measures (UCWSRI 2002).

The Columbia River Water Use Plan (WUP) Consultative Committee (CC; 2005) recommended giving priority to conservation and recovery of White Sturgeon. However, in recognition of its high value power generation, the Columbia River was designated to remain a working river. It was identified that direct management responses for White Sturgeon were limited to non-operational habitat improvements designed to improve spawning success and juvenile survival. In order to meet this goal, data are required to assess habitat use, suitability, and availability for all life stages of White Sturgeon residing in the LCR. These data include life history measures that are indicative of habitat quality including abundance, growth, development, condition, evidence of food availability, and survival rates. Furthermore, providing estimates of successful reproduction (e.g., egg and larval captures) at both known and suspected spawning locations in the LCR is critical to addressing management questions related to recruitment.

The WUP CC outlined a juvenile sturgeon program that would provide annual monitoring of the relative abundance and distribution of juvenile White Sturgeon in the LCR (CC 2005). The supporting rationale indicated monitoring was to provide information on the patterns of habitat use to better understand potential causes of recruitment failure and opportunities for feasible mitigative actions (CC 2005). The rationale assumed that, the probable bottleneck affecting juvenile survival could be determined with the release of hatchery-reared juvenile White Sturgeon into the system to help identify non-operational changes required for a positive effect on levels of natural recruitment of age 1+ sturgeon. As such, the B.C. Comptroller of Water Rights (CWR) issued a Water License Order directing operations of BC Hydro's projects on the Columbia River (Mattison 2007). The Order (Schedule F(1)(h)) specifies that the Juvenile Sturgeon Detection Program shall monitor the abundance, distribution, and patterns of habitat use in the LCR in relationship to discharges from HLK.

Outside of annual monitoring programs used to collect information to guide recovery, the sole conservation strategy implemented to date for this population has been restoration through a Conservation Aquaculture Program. The objective of this strategy is to supplement the population with hatchery reared juveniles until adequate levels of natural recruitment can be restored (UCSWRI 2012). Since 2001, an annual broodstock acquisition program has been conducted, with wild mature adults spawned in the hatchery to contribute progeny for stocking in the LCR (BC Hydro 2009). The Conservation Aquaculture Program has been successful in releasing 97,524 hatchery reared juvenile sturgeon into the Canadian section of the LCR (as of the spring of 2012).

Hatchery-reared juveniles released as part of the Conservation Aquaculture Program serve as an important learning tool as juvenile age classes are absent in many populations. Determining factors influencing growth and survival of these fish will not only contribute to refining the Aquaculture Program, but will provide critical insight into the ecology of this species which can be used to guide recovery efforts. In addition to growth and survival, it is important to track information on the diet of juvenile White Sturgeon in order to help identify what resources they are using as well as to determine when older juveniles might start switching to consuming other fish. An important objective of this monitoring program was to collect hatchery-reared juvenile White Sturgeon from a suite of ages, size classes, and habitat types to determine how variability in the diet is proportioned. Once complete, the results will expand our knowledge on the feeding ecology of juvenile White Sturgeon, and provide new information on how habitat use and site fidelity influence dietary overlap in a regulated river. Finally, it is important to be able to determine the age of any wild juveniles encountered with confidence, to determine the year they were born. This will allow the conditions present in those years with detectable recruitment to be evaluated. The presence of known-age juveniles in the LCR will help address uncertainties regarding ageing accuracy.

Work that has occurred over the past decade has identified that hatchery-reared juveniles have been successful in surviving after release from the hatchery (Golder 2009b). The survival of hatchery released age-0 juveniles combined with high survival at the older life stages (Golder 2009b; Irvine et al. 2007) suggests that the recruitment bottleneck is likely the result of poor survival during earlier life stages (Gregory and Long 2008; Golder 2009b), which is similar to other systems (Ireland et al. 2002; Gross et al. 2002). As a result, recent monitoring has focused on the potential causes of mortality at the yolk-sac larval (YSL) and young-of-year (YOY) life stages, and to understand underlying mechanisms resulting in recruitment failure.

Identification of critical rearing habitat within the LCR is an important component of recovery to allow for protection or enhancement as recovery moves forward. Monitoring White Sturgeon spawning activity determines the location of YSL rearing sites. Past studies have documented White Sturgeon spawning behavior immediately downstream of Arrow Lakes Generating Station (ALH, river kilometer (rkm) 0.1; BC Hydro 2013b), downstream of Kinnaird (rkm 13.0 to 19.0; Golder 2009a; BC Hydro 2013b), Pend d'Oreille River confluence (Waneta, rkm 56.0; UCWSRI 2012) and in the vicinity of Northport, WA (Howell and McLellan 2006). At the upstream locations of ALH and Kinnaird, exact locations of egg deposition remains unknown therefore continued monitoring is important to identify location of spawning and YSL rearing habitats.

Estimating the White Sturgeon spawning period within the LCR using staged eggs has been the primary measure of spawning activity for many years and the best available metric describing start and end dates of spawning activity. However, including staged YSL could improve estimates representing possible spawning days that were not represented by egg samples. However, while developmental stages are known (Dettlaff et al. 1993), their relation to rearing temperatures in the wild is uncertain. In order to improve our ability to stage YSL collected in the wild, a developmental key is required to quantify the developmental response of White Sturgeon YSL to different temperatures experienced during incubation and the time period leading up to first feeding. In addition to helping reduce uncertainty around spawning timing and frequency, describing thermal induced responses in the development of White Sturgeon YSL is important to understanding recruitment processes and natural adaptability in altered systems, and can be used as a management tool to increase understanding of White Sturgeon reproductive ecology.

This report describes the fourth (2011) and fifth (2012) years of ongoing monitoring in the LCR as a component of the WUP under the project: CLBMON-29 Lower Columbia River Juvenile Sturgeon Detection. Specific components of the study are to:

1. Monitor distribution and growth of early life stages.
2. Look at the distribution, growth, and survival of both wild and hatchery origin juvenile White Sturgeon.
3. Quantify developmental responses of YSL to different temperature regimes between incubation and first feeding.
4. Describe juvenile White Sturgeon diet including overall composition and prey selectivity.
5. Determine ageing accuracy using hatchery-reared juveniles of known age to help improve confidence when assigning year of birth to wild juveniles.

1.1 Management Questions

Key management uncertainties encountered during development of the WUP related to how operations of HLK may adversely affect habitat suitability and availability for juvenile sturgeon and thus potentially contribute to recruitment failure of White Sturgeon in the LCR (Columbia River WUP CC 2005). Fundamental management questions to be addressed through the Juvenile Sturgeon Detection Program include:

1. What are the relative abundance, survival rates, and distribution locations of larval and juvenile White Sturgeon in the LCR under current operating parameters?

2. What are the physical and hydraulic properties of this habitat that define its suitability as juvenile sturgeon habitat?

3. How do normal river operations affect larval habitat conditions in the LCR?

4. How do normal river operations affect juvenile habitat conditions in the LCR during dispersal and on a seasonal basis?

1.2 Management Hypothesis

While impoundments and water management at HLK and other dams in the Columbia watershed may be correlated with declines in White Sturgeon recruitment in the LCR, the precise mechanisms remain unclear. Early life stages appear to be most adversely affected and spawning site selection and timing may impact mortality rates experienced by these early life stages. The Juvenile Sturgeon Detection Program is designed to provide baseline information that may be used to evaluate recruitment failure hypotheses and can be used in design of future operational or physical mitigative approaches. Additionally, where feasible, the program is experimentally testing of research hypotheses to get at underlying mechanisms behind recruitment failure. This is the established process outlined at the Upper Columbia White Sturgeon Recovery Initiative Technical Working Group, and described in the groups operational plan which available at www.uppercolumbiasturgeon.org.

The following management hypotheses were used to guide the Juvenile Sturgeon Detection Program studies:

H_0: The operations of the Columbia River dams and reservoirs are not contributing to changes in survival among juvenile sturgeon in the lower Columbia reach.

H_1: Columbia River operations (HLK alone or the cumulative operations of dams affecting the LCR reach hydrograph) are affecting larval behaviour, development, growth, and habitat selection, which result in reduced survival of early life stages.

H_2: Columbia River operations (HLK alone or the cumulative operations of dams affecting the lower Columbia reach hydrograph) are affecting juvenile movements, growth, and selection of suitable rearing habitat, which result in reduced survival of juvenile life stages.

H_3: Columbia River operations (HLK alone or the cumulative operations of dams affecting the lower Columbia reach hydrograph) are affecting the suitability and availability of habitat parameters resulting in reduced survival of early life and juvenile stages of White Sturgeon.

1.3 Objectives and Scope

The LCR Juvenile Sturgeon Detection Program in 2011 and 2012 was designed to describe life history aspects of juvenile White Sturgeon, as well as provide input to the ongoing consideration of recruitment failure hypotheses, the evaluation of the effects of future management responses, and information to guide conservation culture stocking targets.

As stated in the terms of reference for the work, the objectives of this program will have been met when:

1. The development, condition, drift and movement behaviours, growth, and survival of YSL and juvenile sturgeon are assessed with sufficient consistency to describe annual trends.

2. Early life stage distributions over time, including location and parameters of YSL and Juvenile rearing habitats, are adequately defined.

3. Relationships between YSL and juvenile habitat quality and variations in discharge from upstream dams and water levels of Lake Roosevelt reservoir are quantified.

4. Assessment of the effects of current operations and determine feasibility of management responses are completed.

The scope of the juvenile program focuses on data collection to define YSL and juvenile habitat conditions, determine the effect of existing hydraulic conditions, and identify and assess the most suitable of several management responses to be considered in lieu of operational changes. The specific objectives related to the various components of this Juvenile Sturgeon Detection Program are summarized as follows:

1.3.1 Conservation Aquaculture Program

1. Adult Broodstock: Provide eight to ten late-vitellogenic female and eight to ten mature males for induced spawning at the Kootenay Sturgeon Hatchery (KSH) to provide offspring towards an annual objective of 8 genetically distinct families or secondary families.

2. Hatchery Rearing: The successful incubation and rearing of approximately equal numbers of healthy juveniles from each family or subfamily bred in a given year targeting an annual release of 12,000 sub-yearling sturgeon into both the LCR and Mid-Columbia Rivers.

1.3.2 Larval Stage

1.3.2.1 Yolk-sac Larval Assessment

1. Identify timing and frequency of annual spawning days at Waneta, ALH, and Kinnaird sites using drift nets to collect White Sturgeon YSL.

2. Identify specific locations of unknown spawning grounds and describe YSL rearing habitat.

3. Assess YSL development, condition, behaviour, and survival.

4. Determine effects of current operations on YSL survival and rearing habitats.

1.3.2.2 Larval Genetics

1. Assess the number, distribution, and timing of White Sturgeon spawning activity within the LCR.

2. Estimate the effective breeding number (N_b), number of adults contributing to offspring (N_s), and number of kin groups (N_k).

3. Assess reproductive ecology including reproductive success, spawning duration, and spawning group composition.

1.3.2.3 Larval Developmental Key

1. Quantify thermal induced responses of YSL reared at varying temperatures.

2. Provide an index of YSL development as a tool for estimating fertilization date of wild caught YSL.

3. Examine temperature effects on resource allocation and development of morphological traits.

1.3.3 Juvenile Stage

1.3.3.1 Juvenile Population Assessment

1. Assess juvenile population abundance, growth, age structure, annual survival rates, and population trajectories.

2. Provide relative abundance and periodic updates to population estimates of the LCR juvenile White Sturgeon populations.

3. Periodically compare new data describing length/weight relationships to monitor growth and conditions of all age classes.

Data from this program will be analyzed and evaluated on an ongoing basis to drive program decisions or to identify any emerging and imminent threats to the remaining population.

1.3.3.2 Ageing

1. Determine ageing accuracy using the pectoral fin ray from hatchery-reared juveniles of known age.

1.3.3.3 Diet Assessment

1. Evaluate and describe the composition and prey selectivity in the diet of juveniles of different habitats.

2. Determine if site fidelity is a function of food availability or composition.

3. Describe reliability of non-lethal gastric lavage compared to lethal sampling in describing the diet to increase confidence when assessing seasonal or annual diet trends.

1.3.4 Habitat Mapping

1. Assess availability and suitability of juvenile White Sturgeon habitat.

2. Quantify physical habitat that can be tied to early life stages and juvenile data collected as part of the Detection Program.

3. Describe and classify physical habitat in the LCR downstream of HLK to the Canada/US border.

1.4 Study Area and Study Period

The study area for the 2011/2012 monitoring program encompassed the 57 km stretch of the LCR from HLK to the Canada/US Border (Figure 1). The study area also included a small section (~2.5 km) of the Kootenay River below Brilliant Dam extending to its confluence with the LCR. Specific areas of the LCR sampled under the various components of the program are described below.

Figure 1. Overview of the study area between HLK (rkm 0.1) and the Canada/US border (rkm 57.0).

2 METHODOLGY

The monitoring study design follows the recommendations of the UCWSRI Technical Working Group (TWG) who provided an outline for what they viewed as the components of a LCR juvenile monitoring program (UCWSRI 2006) during the development of the Columbia WUP. Further, it incorporates the guidance of the WUP Fisheries Technical Committee (FTC). The program is divided into data collection during spawn monitoring, YSL and juvenile assessments, habitat mapping, and a suite of population characteristics including diet composition, age structure, population size estimation, and genetics assessments. These are described separately below.

2.1 Physical Parameters

2.1.1 Discharge

In 2011/2012, discharge records for the LCR at Arrow Reservoir (combined HLK and ALH discharges from Arrow Lakes Reservoir), the Kootenay River (combined discharge from Brilliant Dam and the Brilliant Expansion facility), the LCR at Birchbank (combine discharge from Arrow Lakes Reservoir and Kootenay River; rkm 29), and the LCR at the Canada/United States border (combined discharge from Birchbank and the Pend d’Oreille River; rkm 57.0) were obtained from BC Hydro power records. Discharge data were recorded at one-minute intervals and averaged hourly in cubic meters per second (cms), cubic feet per second (cfs), and in thousands of cubic feet per second (kcfs) of passage flow.

Typically, the metric discharge measurement (cms) is used to discuss and present results of volumetric flow rates in technical reports and scientific publications. However, water planners and biologists readily use the non-metric discharge measurement (cfs) to discuss flows from hydroelectric facilities. As such, both units of measure (cms and cfs) are presented and referenced within the results and discussion sections of this study report.

2.1.2 Water Temperature

For the 2011/2012 study period, water temperatures were collected at several locations on the LCR including HLK (rkm 0.1), Kootenay River (rkm 10.5), Kinnaird (rkm 13.4), Genelle (rkm 26.0), Rivervale (rkm 35.8), and Waneta (rkm 56.0). Water temperatures were recorded hourly at each location using thermographs (Vemco Minilogs, accurate to +0.1°C).

2.2 Conservation Aquaculture Program

Conservation aquaculture has become a critical component of the UCWSRI since 2001 and supports the work conducted under this program through the release of hatchery-reared juveniles. Adult White Sturgeon were acquired from the LCR for broodstock purposes through the Lower Columbia River Adult White Sturgeon

Monitoring Program (CLBMON 28). Specific capture, handling, induced spawning, and adult release methodology are described by BC Hydro (2013b, 2015). Offspring were reared at the KSH for approximately 9 months and released into the LCR during the following spring. Rearing conditions are provided by FFSBC (2013). Prior to release, fish were measured for fork length (FL; cm), and weight (g). All individuals were administered a Passive Integrated Transponder (PIT) tag from Biosonics Inc. (400 kHz PIT tag or 134.2 kHz ISO PIT tag). PIT tags were inserted into the dorsal musculature at the midpoint between the dorsal and lateral scute lines inferior to the anterior margin of the dorsal crest scute line. Each individual was also marked externally by removal of two left lateral scutes according to a prescribed coding formula corresponding to year class (see FFSBC 2011, 2013, for details). LCR release location was recorded for each individual.

2.3 Larval Stage

2.3.1 Yolk Sac Larval Assessment

2.3.1.1 Study Design

Sampling was conducted at several sites to determine the relative abundance and distribution of White Sturgeon YSL in the LCR. Sites were selected based on previous monitoring program data collection where White Sturgeon have been confirmed to have spawned, or have been suspected to spawn.

Within the Canadian portion of the LCR, White Sturgeon reproduction occurs from mid-June through August (BC Hydro 2013a, 2013b) at two known spawning sites of Waneta (rkm 56.0) and ALH (rkm 0.1) (Figure 2). Waneta sampling is located downstream of the Pend d'Oreille River confluence immediately upstream of the Canada/US border. This site has been monitored for spawning activity since 1993 and is the main area of White Sturgeon spawning activity within the LCR, Canada (Hildebrand et al. 1999; Irvine et al. 2007; Golder 2009a). Sampling occurred immediately downstream of ALH tailraces as described by Terraquatic Resource Management (2011). Sampling was also conducted downstream of Kinnaird (rkm 18.2) based on previous studies (Golder 2009a), however location of exact egg deposition remains unknown. Additional 2011 sampling sites included HLK (rkm 0.1; immediately downstream of spillways) and Kootenay River (rkm 10.5; downstream of Brilliant Dam and upstream of the Kootenay/LCR confluence) (Figure 2). These additional sampling sites were selected based on past spawn monitoring surveys and White Sturgeon movement studies (BC Hydro 2013b). HLK and Kootenay were not sampled in 2012 due to difficulties in sampling the areas efficiently given the hydrology (HLK) or amount of detritus collected (Kootenay).

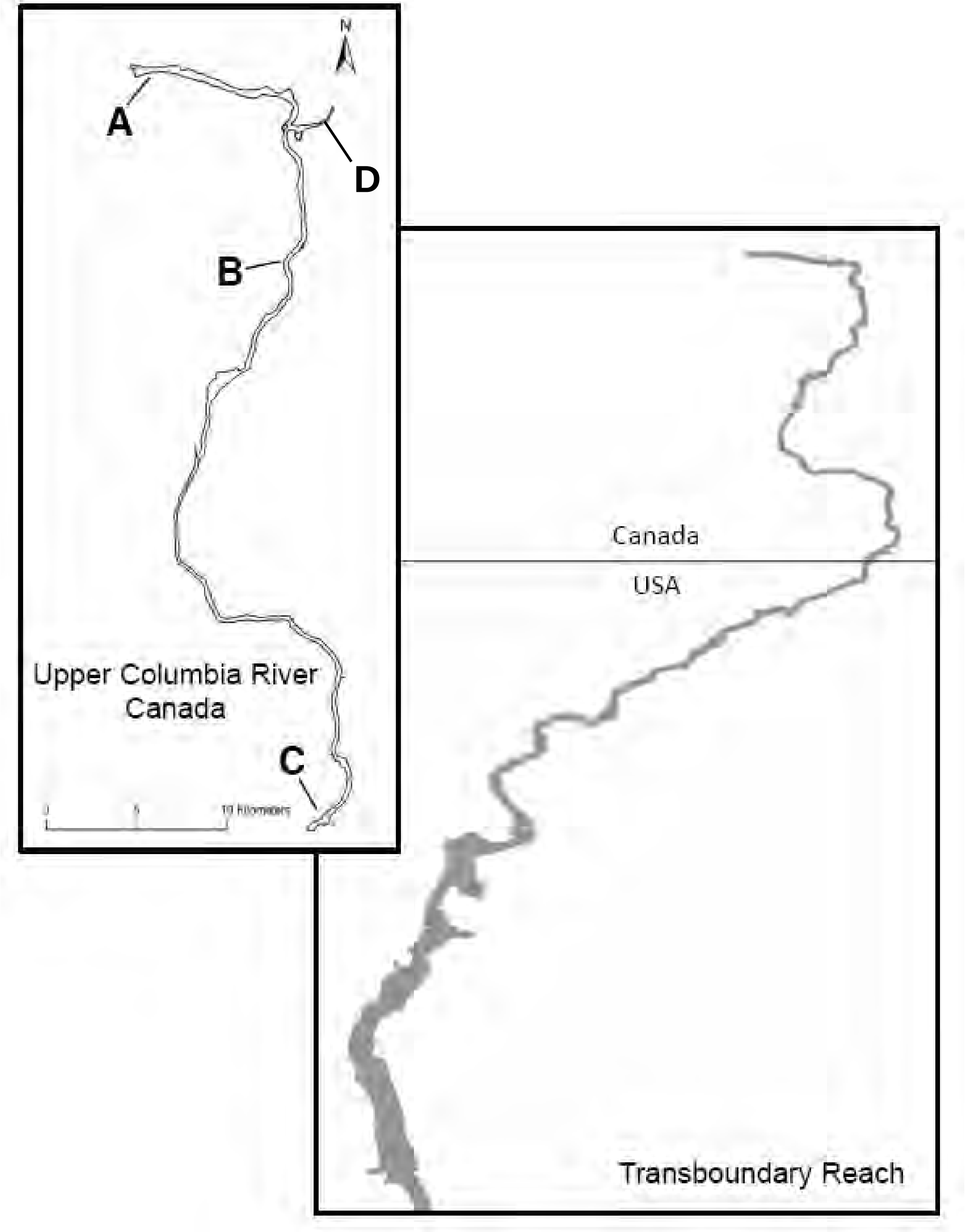

Figure 2. Drift net deployment sites in the LCR including: A) ALH and HLK (rkm 0.1), B) rkm 18.2 (downstream Kinnaird), C) Waneta (rkm 56.0), and D) Kootenay (rkm 10.5). All sites were included in the 2011 sampling methods; HLK and Kootenay sites were not sampled in 2012.

2.3.1.2 Drift Net Sampling Methods

Drift net sampling has been used successfully to capture passively dispersing YSL for many sturgeon species including White Sturgeon in the LCR (Golder 2009a), Lake Sturgeon (*A. fulvescens*; Auer and Baker 2002), and Shortnose Sturgeon (*A. brevirostrum*, Moser et al. 2000). Drift net sampling has been added to the spawn monitoring program in recent years and has proven to be successful at documenting spawning days and larval dispersal patterns (BC Hydro 2013b).

Drift nets used in this program consisted of a 1.3 cm rolled stainless steel frame (D shape) with a 0.6 m x 0.8 m opening that is trailed by a 4 m tapered plankton net (0.16 cm delta mesh size) with a collection cup device. Deployment and anchor system specifications were consistent between sampling locations in the LCR. A lead steel claw river anchor (30 kg) was used to hold the entire system to the river bottom. Approximately 6 m of 3/8 galvanized chain was attached to the main anchor and was preceded by a secondary steel anchor (30 kg) to ensure the anchor system remained in place on the river bottom. Two 30 m sections of 0.95 cm diameter braided rope were attached to the main anchor. The first rope was attached to a buoy at the surface of the river, which provided a means to remove the entire anchoring system. The second rope was attached directly to the front of the drift net. A third rope was attached to the top of the drift net frame to a second surface buoy for the purpose of both deployment and retrieval of the net.

When retrieving the drift net, the buoy attached directly to the net would be picked up from the boat and the net brought to the surface. The length of rope between drift net and main anchor was greater than the water depth allowing retrieval without dislodging the anchor system ensuring sampling sites were consistent throughout the sampling period. Typically, drift nets were deployed and retrieved from the bow of the boat using an electronic winch. Once at the surface, the drift net would be detached from the anchor system and brought into the boat for collection cup removal. Contents of drift nets and collection cups were thoroughly rinsed into 19 L buckets with river water before being reattached to the anchor system and redeployed. The collected contents were inspected in small aliquots using white trays that increased contrast when searching for White Sturgeon YSL. White Sturgeon YSL were enumerated by net for each sampling session. Deployment and retrieval times, water temperatures (°C), and water depths (m) for each net location were recorded.

Spawn-monitoring remained consistent with previously established locations of drift net sampling (see Golder 2009a, 2010, 2012, 2013, 2014, and Terraquatic Resource Management 2011 for details). In 2011, drift nets were deployed at Waneta (n=1), ALH (n=6), rkm 18.2 (n=4), HLK (n=2), and Kootenay (n=3). In 2012, drift nets were deployed at Waneta (n=2), ALH (n=8), and rkm 18.2 (n=2). Catch per unit effort (CPUE) was calculated for each site across years.

2.3.1.3 Larvae Preservation

In 2011 and 2012, a random subsample of YSL (~20%) collected at Waneta and all YSL collected at the upstream locations were preserved in 95% ethanol for developmental staging and genetic analysis. The disparity of sample preservation between locations is due to the large number of YSL collected at Waneta and relatively few samples obtained at the upstream locations. Samples were collected for developmental staging and estimation of fertilization date (see Section 2.3.1.4). Samples were also used for genetic analyses (see Section 2.3.2).

2.3.1.4 Developmental Staging and Estimation of Fertilization Date

Preserved YSL were randomly examined with respect to date, stage, and site (to reduce observer bias) using a digital compound microscope (Nikon SMZ-745t Stereo Microscope with 10X eyepiece) and assigned a developmental stage. Enumeration of stages corresponded to the YSL classification by Dettlaff et al. (1993), including stages 36 (hatch) through 45 (exogenous feeding). Each developmental stage was associated with the appearance of at least one new feature therefore stages were not determined strictly by quantitative changes. No preserved samples had developed beyond stage 45.

Fertilization dates for collected YSL were estimated by back-calculation from the recorded date and time of preservation based on developmental stage and mean incubation water temperature. The estimated age (hours; see Section 2.3.3) was subtracted from the preservation date and time to determine the estimated date and time of fertilization (i.e., spawning date). Calculated fertilization dates provided an estimation of spawning duration for each spawning site. However, the accuracy of developmental staging as a method to delineate spawning days and estimate time of spawning can be affected by individual White Sturgeon spawning behaviour, YSL maturation rates, and more importantly, the fluctuation in daily thermal regimes (Parsley et al. 2010).

2.3.2 Larval Genetics

YSL tissue samples used for genetic analysis were collected during the 2011 and 2012 spawn monitoring. Individuals were genotyped using 12 microsatellite loci and likelihood-based pedigree analyses were conducted to estimate number of adults contributing to offspring (N_s), effective breeding number (N_b), number of kin groups (N_k), and individual reproductive success of White Sturgeon contributing to viable eggs and YSL in the LCR. Detailed methods are available in Jay et al. (2014) and BC Hydro (2015).

2.3.3 Temperature Effects on Development

Estimates of White Sturgeon spawning duration and number of spawning events is possible by back calculating fertilization dates based on time and date of capture, developmental stages of eggs and mean water temperatures during incubation (Golder 2009a). Prior to 2011, estimating White Sturgeon spawning period within the LCR using developmentally staged eggs was the best available metric describing spawning duration and has been used as the primary measure of spawning activity for many years. These methods could also be applied to developmentally staged YSL to provide a better representation of all spawning days, however, data describing the effects of temperature on the development of YSL is required to ensure confidence in these estimates.

In 2012, experiments were conducted to identify thermal induced responses of White sturgeon YSL reared in varying temperatures. This data was applied to current methods of estimating spawning activity and understanding recruitment processes and reproductive ecology.

2.3.3.1 Gamete Collection and Fertilization

Mature adult White Sturgeon were captured from the LCR in June 2012, transported, and held at the KSH. Females (n=2) were held in tanks maintained at a constant temperature of 15°C throughout captivity. Males (n=2) were initially held at an ambient temperature of 10°C and temperature was increased to 15°C after administration of Luteinizing Hormone – Releasing Hormone analogue (LHRHa; des-Gly10, [D-Ala6] LH-RH Ethylamide). Changes in water temperature were made at 2°C hourly increments to improve acclimation. Females were injected intramuscularly with LHRHa dissolved saline to induce ovulation with a loading dose of 5 µg/kg (10%) and a resolving dose of 45 µg/kg (90%) administered 12 hours apart. Males were intramuscularly injected with a single bolus dose of LHRHa dissolved in saline (10 µg/kg) concurrently with the initial female injection. Females began ovulation and released eggs approximately 24 hours after the resolving injection. Approximately 12,000 eggs (estimated by subsampling a known volume of eggs) were collected from each female using manual expression through the uro-genital opening. Pressure was applied from the anterior section of the abdomen to the posterior in order to extrude eggs. Milt from each male was collected through the uro-genital opening by inserting tygon tubing attached to a 20-cc plastic syringe and applying pressure anterior to the uro-genital opening (Conte et al. 1988). Each female was crossed with one male to produce two full-sibling families (F1 and F2). Fertilization and de-adhesion of eggs were completed following methods as described by Conte et al. (1988). Adult fish were held for three days following spawning to assure they were in suitable condition before release into the LCR.

2.3.3.2 Experimental Treatments

The experimental treatments were constant water temperatures (± 0.2°C) held at 12.5°C, 14.0°C, 15.5°C and 17.0°C during the egg incubation and YSL stages. Temperature treatments were developed based on conditions during White Sturgeon spawning, egg incubation, and YSL stages within the Columbia River (AMEC 2014; Terraquatic 2011; Golder 2009a) and other White Sturgeon inhabited river systems (Fraser River, Perrin et al. 2003; Kootenai River, Paragamian et al. 2001). Both ambient (10.0°C) and heated (17.0°C) groundwater was supplied to each treatment with adjustable valves to maintain the aforementioned temperatures throughout the duration of the experiment. Temperatures were measured hourly (VEMCO Minilog-II-T, Bedford, Nova Scotia).

Using family as a replicate, 3000 eggs were incubated immediately after fertilization in a hatching jar (MacDonald Type; J30, Dynamic Aqua-Supply Ltd., Surrey, BC) for each temperature treatment. Eggs were acclimated to the temperatures treatments at a rate of 1°C h^{-1}. To ensure adequate egg separation and oxygenation, water flow was maintained at 5 L min^{-1} and raised to 15 L min^{-1} before and after neutralization, respectively. Survival to neutralization was estimated by randomly sampling 100 eggs in each hatching jar.

Upon hatching, YSL were flushed from the hatching jars directly into treatment and family specific rearing troughs (152.4 x 76.2 x 20.3 cm; L x W X H) with water levels of 10 cm depth. Following 100% hatch, water flows were reduced (10 L min^{-1}) to exchange water at least twice per hour but not disturb larvae causing them to swim. YSL exhibit negative phototaxis (Conte et al. 1988), therefore all rearing troughs were covered with dark plastic sheets to eliminate effects of overhead light. Additionally, troughs were supplied with artificial substrate (1" diameter sinking Bio-Spheres; Dynamic Aqua-Supply Ltd. Surrey, BC) allowing YSL to burrow into interstitial spaces preventing an increase in energy consumption among YSL searching for cover that can reduce growth (McAdam 2011; Boucher et al. 2014) or development. YSL were not provided a food source during the duration of the experiment to prevent confounding effects on development across the different temperature ranges.

2.3.3.3 Sampling and Developmental Staging

Ten YSL per treatment were sampled when observations of 50% of eggs had hatched within a hatching jar (time zero) and every 12 hours thereafter until complete yolk-sac absorption. Specimens were euthanized by an overdose of MS-222 (tricaine methanesulfonate) and preserved in Prefer buffer (solution of glyoxcal, buffer and alcohol). Preserved samples were examined using a digital compound microscope (Nikon SMZ-745t Stereo Microscope with 10X eyepiece) and assigned a developmental stage. Enumeration of stages corresponded to the classification by Dettlaff et al. (1993), as follows: stage 36 – hatch; 37 – pectoral fin rudiment, opening of mouth; 38 – gill filament rudiments; 39 – digestive system rudiment divides into stomach and intestine; 40 – ventral fin rudiment; 41 – liver subdivided; 42 – complete liver division, pyloric appendage rudiment; 43 – ventral fin extends to preanal fin fold margin; 44 – complete yolk-sac absorption, discharge of pigment plug from spiral valve. Based on previous studies (Wang et al. 1985; Beer 1981; Dettlaff et al. 1993), 12 hours was assumed to be sufficient sampling intervals to record all developmental stages.

Time (h) and accumulated thermal units (ATU; °C•d; Rombough 1985) were used to measure the initial occurrence of each developmental stage. One thermal unit is accumulated by a specimen held in water of 1°C for 24 h and is additive for every additional 24 h period. Both units were measured from 50% of observed hatching ($t_0 = 0$ h; $ATU_0 = 0$) specific for each temperature treatment. The relative time (RT_i) of each developmental stage was estimated following the formula (Klimogianni et al. 2004):

$$RT_i = (t_i/Tsd)*100\%$$

where RT_i is the relative time of developmental stage *i*, t_i is the time interval (h) from t_0 to developmental stage *i,* and Tsd is total duration of the YSL period (h; development from stage 36 to 44). Since RT_i is a proportional measurement, the same results are given when calculated using ATU.

2.3.3.4 Morphological Traits

Photographs of preserved YSL (n=10) were taken from the time of hatch to the end of the experiment at 24-hour intervals for analysis of seven morphological traits. Due to the volume of individual photographs required to assess multiple traits, we only included temperatures treatments of 12.5°C and 17.0°C in this part of the study. Additionally, there was uncertainty as not all measured traits have been compared for this species, and we expected an increased probability of finding differences in YSL development when comparing the upper and lower temperature treatments. Photographs were taken with a ruler (mm) placed in the field of view using a digital compound microscope of consistent magnification with camera adaptor (DS-2Mv colour non-cooled digital camera head). Morphological traits were measured to the nearest 0.01 mm using ImageJ (Rasband, 2010, version 1.43r, Bethesda) and included total length (TL; mm), body area (BA; mm^2), yolk sac area (YSA; mm^2), head area (HA; mm^2), mouth area (MA; mm^2), pectoral fin area (PFA; mm^2), and gill filament area (GFA; mm^2). TL, BA, and YSA are common traits measured for both sturgeon (*Acipenser transmontanus*, Boucher et al. 2014; *A. fulvescens*, Hastings et al. 2013; *A. brevirostrum*, *A. oxyrhynchus,* Hardy and Litvak 2004) and other fish species (*Danio rerio*, Jardine and Litvak 2003; *Pomacentrus amboinensis*, McCormick 1999; *Morone saxatillis,* Brown et al. 1988) during early life stages. HA was measured as the lateral area of the head from tip of snout to posterior margin of operculum. MA was measured following the inner margin of the mouth opening. PFA measured the ventral surface area of the right pectoral fin. GFA measured the lateral area of all developed gill filaments. Measurements of TL, BA, HA, PA, GFA and YSA were measured parallel to the sagittal (longitudinal) axis of the body, and MA was measured perpendicular to this axis. Each trait was measured twice for each specimen by a single technician and the mean was used. If the examined morphological trait was damaged, the photograph was discarded.

2.3.3.5 Statistical Analysis

All analyses were performed using the statistical software "R" (version 3.0.3, R Development Core Team 2012, http://www.r-project.org). As a function of temperature, the relationship between developmental stage *i* (y), and initial occurrence of developmental stage *i* (x), was fitted by a least squares regression following the model y = mx + b, where *m* is the developmental rate and *b* is the intercept. This relationship was calculated for time, ATU and RT_i. Analysis of variance (ANOVA) was used to test for differences in developmental rate among all temperature treatments measured in time, ATU and RT_i. A Student's T-test was applied to test for any difference in size of the morphological traits between the temperatures treatments of 12.5°C and 17.0°C at each 24-hour period, and each developmental stage. Morphological traits could not be compared using ATU since measurements were not recorded based on specific ATU values.

2.4 Juvenile Stage

2.4.1 Juvenile Population Assessment

2.4.1.1 Study Design

Identifying the distribution of juvenile White Sturgeon was an important component to this program as previous sampling efforts were limited to specific spatial areas of the LCR (Golder 2006). Therefore, the LCR study area was stratified into 5 equal zones (11.2 rkm in length), and during the first two years (2009 and 2010), all zones were sampled under a spatially balanced design. As expected, unequal capture rates were evident with lower rates occurring in zones 3 (rkm 22.4 to rkm 33.6) and 4 (rkm 33.6 to rkm 44.8; BC Hydro 2013b). This limited the number of recaptures needed for developing age specific survival estimates. Sampling efforts in 2011 and 2012 were adjusted, excluding zones 3 and 4, in efforts to increase number of recaptures available for estimating survival and evaluating success of the hatchery program, as conducted in other systems (Ireland et al. 2002; Justice et al. 2009). Of the remaining zones, sampling effort was randomly distributed with equal probability within zones and adjusted across zones depending on catch per unit effort (CPUE) of previous years captures. We used a generalized random-tessellation stratified (GRTS) design developed by Stevens and Olsen (2004) to assign sampling locations within each river zone. This was conducted with the statistical package R (Program R, version 2.9.0) using the library packages spsurvey and sp, provided by the United States Environmental Protection Agency (US EPA). The library package spsurvey allows a user to input data/criteria needed for a GRTS sampling design. We developed shapefiles (i.e. geo-referenced maps) for each river zone using ArcMap (version 10.0, Environmental Systems Research Institute, Inc. (ESRI)). Each river zone shapefile was imported into spsurvey and 50 sampling sites were randomly generated with equal probability and distribution for each of the gear types described below (section 2.2.2). The locations of each sampling site (1 through 50) were output as coordinates in Universal Transverse Mercator (UTM) format for visual display on maps and for importing into handheld global positioning system (GPS) devices used for field application. Sites were sampled in ascending order until the required effort had been expended (further detail provided below). Within each river zone, a proportion of the randomly generated sites could not be sampled. This occurred if the sampling site was generated in an area where sampling gear could not be deployed (e.g. water depth <1m) or where safety concerns were evident (e.g. high sustained river flows). If a site was omitted due to an inability to sample, the next site occurring on the list was sampled.

2.4.1.2 Juvenile Capture Techniques

Setlines, gill nets, and angling have been effective capture techniques in the LCR and were used to collect juvenile White Sturgeon for this program. Set lines have been demonstrated to provide higher catch-rates, be less size selective compared to other sampling gear (e.g., gill nets), and rarely capture non-target species (Elliot and Beamesderfer 1990). Gill nets have also been successful in juvenile White Sturgeon capture in the Columbia (Golder 2009a; Howell and McLellan, 2006, 2007), Kootenai/Kootenay (Ireland et al. 2002; Justice et al.

2009), and Fraser Rivers (Bennett et al. 2005). Set line and angling techniques were used in 2011 and 2012. Based on lower CPUE by gill nets, combined with the risk of mortality due to this sampling technique, gill nets were discontinued after 2011.

2.4.1.2.1 Set lines

A medium line configuration was the standard used for set lines, similar to that used by Oregon Department of Fish and Wildlife (ODFW) and the Washington Department of Fish and Wildlife (WDFW) to capture White Sturgeon in the United States portion of the Columbia River (Nigro et al. 1988). Medium lines measured 54.0 m in length and consisted of a 0.95 cm diameter nylon mainline with 10 to 12 circle halibut hooks (6/0) attached at 6.0 m intervals. Hooks were attached to the mainline using a 0.95 cm swivel snap and a 0.7 m long ganglion line tied between the swivel and the hook. Barbs on all hooks were removed to reduce the severity of hook-related injuries and to facilitate fish recovery and release. All set line hooks were baited with kokanee (*Oncorhynchus nerka*) obtained from the Meadow Creek Hatchery (Meadow Creek, BC) and earth worms (*Lumbricus terrestris*).

Set lines were deployed from a boat and set configuration was based on the physical parameters (depths and water flow) of the site. Set line configuration consisted of either deploying the line parallel to the shore in faster flowing water or perpendicular to the shore in slower moving water. This was conducted to ensure that fish were able to orientate themselves into the current and rest on the bottom of the river, minimizing stress. Prior to each set, water depth (m) was measured by an echo sounder, and this information was used to select a float line of appropriate length. The set line was secured to shore with a shore line of suitable length to ensure that the set line was deployed in water depths greater than 2 m. Anchors were attached to each end of the mainline and a float line was attached to the back anchor of the mainline. Set lines were deployed for 4 to 6 hours before being retrieved.

The set line retrieval procedure involved lifting the back anchor using the float line, until the mainline was retrieved. The boat was then propelled along the mainline and each hook line was removed. If a fish was captured on a hook, the boat was stopped while the fish was removed. All fish were removed from the set line and tethered between two anchor points to the port or starboard side of the boat. While tethered, the entire body of the fish was submerged. Once all fish were removed from the set line, fish were transferred into the boat and kept in a holding tank filled with ambient river water until biologically processed (Section 2.4.1.3). Recorded data included date and time of deployment and retrieval, weather, water depth, water temperature, and bait used.

2.4.1.2.2 Gill Nets

Gill nets consisted of a 5.1 cm stretched measure multi-filament mesh and measured 1.8 m deep by 30.5 m long (area of 54.9 m^2). Anchors and buoys were attached to both ends of the weighted and float lines, respectively. While reversing the boat, gill nets were slowly deployed ensuring no tangles were present and that the lead and floats lines separated. Gill nets were set in areas with lower velocities to prevent drifting or snagging on the bottom, and to minimize harm to any captured fish. GRTS sample sites that resulted in faster water were not used as the risk of mortality of a fish caught in a gill net set in moving water was not acceptable. All gill nets were set during day light hours for 4 to 6 hours. Upon retrieval, captured White Sturgeon were placed in a holding tank with ambient river water until they were processed (Section 2.4.1.3). Recorded data included date and time of deployment and retrieval, weather, water depth, and water temperature.

2.4.1.2.3 Angling

Angling was conducted between deployment and retrieval of both setlines and gillnets and was generally targeted for 2 hours of fishing time. Consistent with other sampling techniques, effort was randomly distributed with equal probability within and across each of the 5 zones in the study area. Three angling sites were sampled within the zone selected for a particular day. If no fish were captured after 30 minutes, sampling was moved to the next site. If White Sturgeon were being captured at an angling site, sampling remained at that site until a time where other fishing gear needed to be retrieved or fish captures were not occurring. Angling gear consisted of a fishing rod (Big Cat; n=3) with 120 monofilament line, a 12-24 oz. lead weight, and a size 6/0 or 8/0 barbless hook. Both kokanee (*Oncorhynchus nerka*) and earth worms (*Lumbricus terrestris*) were used for bait. Captured fish were placed in a holding tank of ambient water temperature until it could be processed and released (Section 2.4.1.3). Recorded data included date and time of deployment and retrieval, weather, water depth, water temperature, and bait used.

2.4.1.3 Fish Handling, Biological Processing and Release

All collected fish were enumerated by species. All captured White Sturgeon were assessed for external markings (removed scutes) and PIT tag. We followed the assumption that juvenile White Sturgeon captured without a PIT tag or external markings were of wild origin. If a wild sturgeon was caught, a tissue sample was removed from the dorsal fin and preserved dry in a scale envelope for future genetic analysis. All wild juvenile sturgeon that were captured were administered a PIT tag. Prior to insertion, both the tag and tagging syringe were immersed in an antiseptic solution (Germaphene). Care was taken to angle the syringe needle so the tag was deposited in the subcutaneous layer and not the muscle tissue. The second left lateral scute was removed using a sterilized scalpel to serve as an external marker.

White Sturgeon were measured for fork length (FL; ±0.5 cm) and weight (±0.1 kg). External examinations were conducted to identify deformities. All data were recorded in the field on standardized data forms and later entered into an electronic database.

2.4.1.4 Data Analysis

Catch per unit effort (CPUE) was calculated for each year, sampling method, and sampling zone as total White Sturgeon captures per effort hour. Proportion of total capture was calculated by means of brood year class, sampling method and sampling zone for each year. Spatial distribution of juvenile White Sturgeon in the LCR was assessed qualitatively by visual examination of capture locations and quantitatively by comparison of CPUE among sampling zones within each year.

Biological data collected and analyzed in this report included fork length (FL; cm), weight (kg), and relative weight (W_r). W_r is a measure of fish plumpness allowing comparison between fish of different lengths, inherent changes in body forms, and populations (Wege and Anderson 1978). W_r is calculated with the following formula:

$$(W_r) = (W/W_S)*100$$

where W is the actual fish weight (kg), and W_S is a standard weight for fish of the same length (Wege and Anderson 1978). We determined W_r for captured juveniles in 2011 and 2012, as well as previous years including 2009 and 2010 (BC Hydro 2013a), according to the White Sturgeon standard weight-length equation developed by Beamesderfer (1993):

$$W_S = 2.735E^{-6} * L^{3.232}$$

where W_S is standardized weight and L is fork length (FL; cm).

All data was calculated for mean (±SD) by sampling year, brood-year/age class, sampling method, and sampling zone. Analysis of variance (ANOVA) was used to test for differences in size (FL, weight) among sampling methods and sampling zones. Differences in W_r were tested for among age class and sampling zones. Sampling method was examined to determine if methodology tends to favour a certain size. Sampling zone was examined based on documentation of high site fidelity within the LCR and growth rates differing spatially (van Poorten and McAdam 2010). All analyses were performed using JMP (Version 12.0.1 (12.0); SAS Institute Inc. 2015). Data were tested for normality and homogeneity of variances and data transformations were conducted where required.

Total and annual growth was calculated for each age class. We used an allometric growth model ($W = \alpha L^{\beta}$) to predict juvenile sturgeon weight from length and to develop a relationship for use in further sampling efforts. Prior to fitting the model, the equation was log-transformed on both sides to achieve a linear relationship:

$$\ln W_i = \ln(\alpha) + \beta * \ln(L_i)$$

where W_i is the predicted weight and L_i is the fork length of the individual juvenile sturgeon used to predict W_i. We fit the model by minimizing the residual sum of squares using the solver tool in excel. After fitting the model the estimates were back transformed using the equation:

$$W_i = EXP(\alpha)*EXP(L_i)^{\beta}$$

A von Bertalanffy growth model (Equation 9.9, Ricker 1975) was used to predict juvenile White Sturgeon length-at- age from age using the solver tool in excel to predict model parameters. The equation used was:

$$l_t = L_\infty \left(1 - e^{\left(-K\left(t-t_0\right)\right)}\right)$$

where l is length at age t, L_∞ is the length that a fish would achieve if it continued to live and grow indefinitely, K is a constant determining the rate of increase or decrease in length, and t_0 is the age at which the fish would have been zero length if it grew according to the manner described in the equation (Ricker 1975).

2.4.2 Age Structuring

2.4.2.1 Study Design

Knowledge of the age of juvenile White Sturgeon collected in the wild is important when evaluating mechanisms influencing recruitment. However, few studies have quantified factors influencing the accuracy of ages estimated from pectoral fin ray sections. To determine the accuracy of age estimates for juvenile White Sturgeon, we collected both pectoral fin rays from equal numbers of known age hatchery released fish (ages 4-11) in the LCR. We selected 3 juveniles from each age classes (based on PIT tags and scute marks). Within each age class, we collected individuals from each of three size ranges (40-70 cm, 70-100 cm, >100 cm). This was done to acknowledge variability in length at age for this population. We then collected multiple sections from each fin ray following the methods below.

2.4.2.2 Fin Ray Collection and Analysis

The leading pectoral fin ray (including the knuckle) was removed from sacrificed juvenile White Sturgeon of known age (i.e. stocked, n=46) and wild fish (n=1) through the diet assessment experiment (Section 2.4.3). After drying, fin rays were dipped in epoxy resin (Cold Cure™) and allowed to harden.

To determine the optimal location on the pectoral fin ray for ageing interpretation, two structures (one large [127 mm] and the other small [80 mm]) were selected. Sections, 0.7 mm in width, were cut from each of the fin rays in succession, starting from the proximal end of the fin (defined as the base of the “knuckle”) using a Struers Minitom low speed, precision jewellers saw (Struers Inc., Cleveland, Ohio). Sectioning continued until the distal end of fin ray was reached. Fin ray sections were fixed on glass slides with Cytoseal-60 (Thermo Scientific, Waltham, Massachusetts) and examined under a dissecting microscope (30 – 40x magnification). Without prior knowledge of fish length, weight, capture date or true-age, sections were read in succession (from proximal to distal) by an ageing technician with 10 year’s experience to determine where:

i) the first annulus (nucleus) became visible;

ii) outer annuli became most defined (i.e. separation between growth and non-growth periods sequentially differentiated); and,

iii) where 1st annulus started to fade.

The optimal location (in terms of distance from the “knuckle”) for ageing was therefore defined by where both the 1st annulus was visible, and where outer annuli were well defined.

For the remainder of the fish, one section was cut from each of two fin rays collected for each fish, using the methodologies previously described. The section was cut at the location determined to be optimal for age interpretation. Sections were interpreted by four or more readers, without prior knowledge of fish length, weight, capture date, true-age, or ages assigned by other readers. All visible annuli were counted, and presence/absence of an outer annulus was explicitly noted so that that actual read age could be determined when capture date is taken into account.

2.4.3 Diet Assessment

Qualitative information on the diet of juvenile White Sturgeon is important to informing estimates of growth and survival that will be developed as part of this work. Reliable estimates of diet composition are important to identify changes in food availability (Correa and Winemiller 2014) and selection in aquatic systems where population sizes are changing (Schindler et al. 1997), or there are other changes at the community level that may influence how resources are partitioned (e.g., invasive species, Vander Zanden et al. 1999). Sacrificing individuals provide the most robust data in describing the diet or prey selection (Heupel and Simpfendorfer 2010). However, given the endangered status of LCR juvenile White Sturgeon, sacrificing individuals is not an annual option. Nonlethal methods to assess diet have been in use for decades and typically involve gut content analysis using stomach suction or flushing (e.g., gastric lavage; GL) techniques (Bowen 1996; Kamler and Pope 2001).

In 2012, a study was initiated to evaluate and describe overall composition and prey selectivity in the diets of juvenile White Sturgeon from a suite of ages, size classes, and habitat types to determine how variability in the diet is proportioned. Results of this two-year study (2012 and 2013) will improve knowledge of juvenile White Sturgeon feeding ecology and further support the use of non-lethal gastric lavage to assess diets when fish cannot be sacrificed. Additionally, it will provide new information on how habitat use and site fidelity influence dietary overlap in the regulated LCR.

2.4.3.1 Study Design

This study was initiated in 2012 and sampling was conducted within three river sections: (1) rkm 0.1 to 12.0 including the Kootenay/LCR confluence, (2) rkm 13.0 to 26.0, and (3) rkm 45.0 to 57.0 (Figure 3). The relative availability and suitability of juvenile White Sturgeon habitat components differed among river sections. River section 1 is a predominantly deep (up to 20 m in the thalweg), slow moving (<1 m/s) length of river, whereas the more downstream sections 2 and 3 are typified by shallower thalweg depths (<10 m) and faster flows (>1 m/s), with slow water habitats limited to occasional large, deep eddies. Juvenile White Sturgeon are distributed throughout all of river section 1 but tend to concentrate in eddy habitats in river sections 2 and 3.

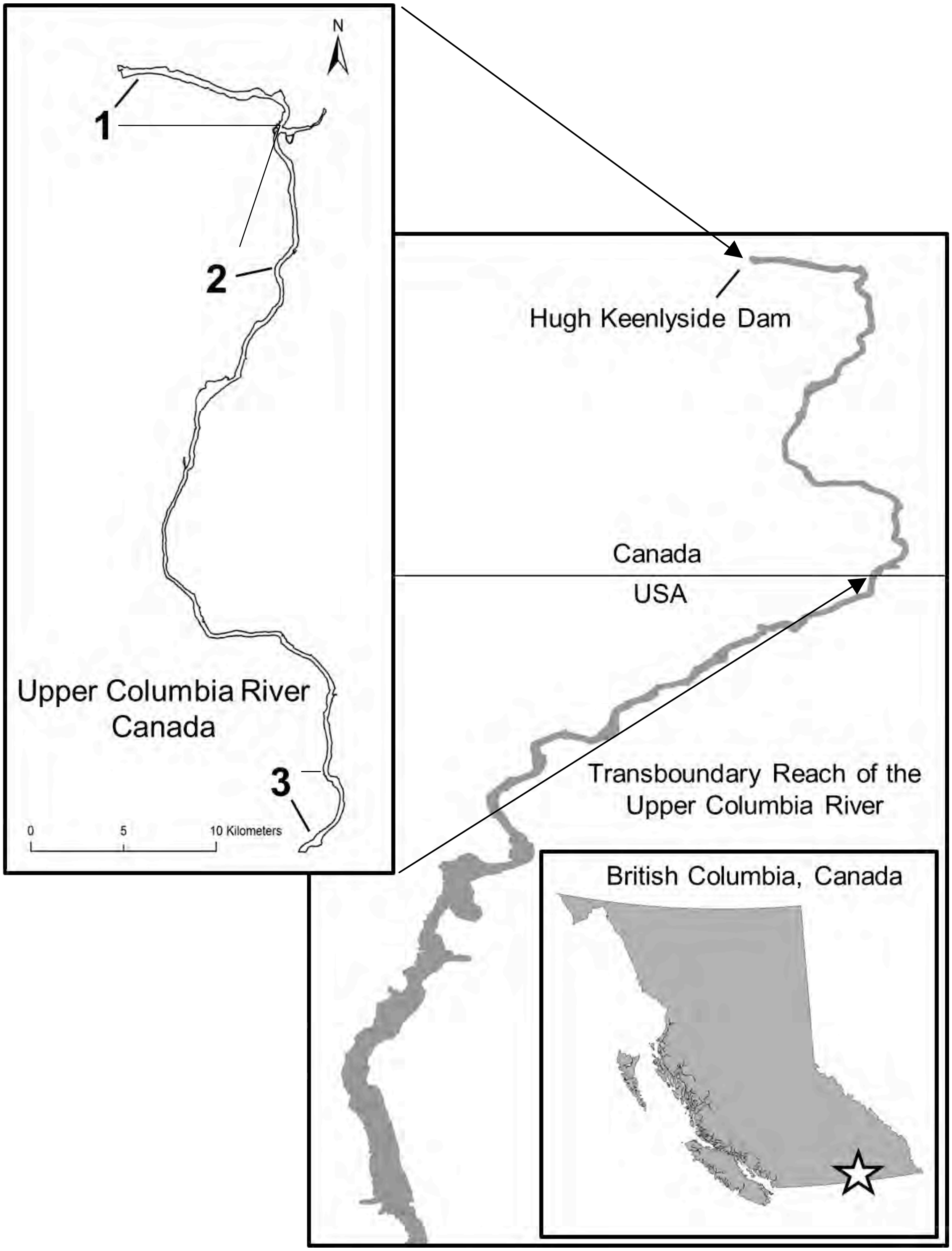

Figure 3. Tranboundary reach of the Columbia River showing sections of the lower Columbia River Canada where juvenile White Sturgeon were sampled from (1, 2, 3).

2.4.3.2 Experimental Design

As stated in the study objectives, we were interested in comparing different methods, both lethal and non-lethal, that can be used to describe the diet of juvenile White Sturgeon. Due to the species listed status in Canada, permitting restrictions resulted in the ability to only evaluate lethal methods in one of the two study years. In year one (2012), juvenile White Sturgeon of hatchery origin were collected from river sections 1 and 3 (Figure 3). We focused on the upstream and downstream most river sections because fidelity to these specific areas has been shown to be high and observed differences in growth rates (slower growth in river section 3) between the two areas is hypothesized as being a function of diet or resource availability (van Poorten and McAdam 2010; Hildebrand and Parsley 2013). Three juveniles of hatchery origin from each of eight age classes (ages 4-11) were selected in each river section for diet analysis. Further, in an attempt to acknowledge the documented variability in juvenile length at age as described in Hildebrand and Parsley (2013), we collected individuals within each age class from each of three size classes (fork length (FL); 40-70 cm, 70-100 cm, >100 cm). All fish captured in 2012 were sacrificed and sampling continued until juveniles from all age and size class criteria were sampled in both river sections.

In order to characterize the diet of juvenile White Sturgeon in relation to available prey items in the river, benthic grabs of the substrate were collected only at locations where fish were captured. Our objective was to accurately reflect the available food in the locations being selected by juvenile White Sturgeon at the time of capture, with comparisons of prey availability limited to the river sections only, rather than to specific meso or macro habitat types.

We used a generalized random-tessellation stratified (GRTS) sample design developed by Stevens and Olsen (2004) to randomly assign sampling locations with equal probability within each river section. This was conducted with the statistical package R (Program R, version 3.03, R Development Core Team 2014, http://www.r-project.org) using the library packages spsurvey and sp, provided by the United States Environmental Protection Agency (US EPA).

2.4.3.3 Fish Capture

Angling was the sole method used to capture juvenile White Sturgeon and was conducted in the month of October. This method allowed the rapid collection of fish, which limited digestion and potential regurgitation of prey items. At each sampling location, angling was conducted from an anchored boat for a minimum of 0.5 hours. If no juvenile White Sturgeon were captured, sampling moved to the next predetermined location. At locations where fish were captured, sampling continued for a maximum of 3 hours. Angling gear consisted of a heavy action rod spooled with 45 to 58 kg test braided nylon line. Hooks were barbless, j-shaped (size 8/0), and baited with earthworms. A lead weight (350-700 g) was attached approximately 0.3 m above the hook to ensure the bait remained on the river bottom. The time each juvenile was hooked and landed was recorded. Additionally, water depth and temperature were recorded at each sampling location.

At capture, fish were immediately measured for fork length (FL; ± 0.5 cm) and weight (± 0.1 kg) and scanned for the presence of a PIT tag to determine origin, and if hatchery origin, age. Juveniles that matched the origin, age and size class criteria described above had gastric lavage performed immediately after landing. In 2012, the fish were euthanized after gastric lavage and the stomach contents removed. Methods for both procedures are described in detail in the diet analysis section below. We recorded the time following landing of the fish that gastric lavage was performed, when the fish was immersed in anesthetic, and when the stomach contents were removed.

2.4.3.4 Diet Analysis

Different methods of describing the diet of sturgeon are available, though their efficiency in describing the diversity in identified prey taxa among individuals, life stages, or across years is uncertain. Data collected in this study allow for direct comparisons between methods to describe diet within and across two sampling years.

2.4.3.4.1 Gastric Lavage

Modified gastric lavage (GL; Haley 1998; Brosse et al. 2002; Kamler and Pope 2001; Barth et al. 2013) was performed on all juvenile White Sturgeon immediately following capture to halt digestion of prey items. Individuals were held ventral side up, with the snout pointing downwards at a 45° angle. A small plastic tube (3.0 mm external diameter), connected to a pressurized container (4 L) with regulated flow, was inserted through the mouth and into the esophagus as far as the first stomach loop following methods described by Wanner (2006). The appropriate distal location of the tubing was felt by hand through the ventral surface. Water was injected in a pulsed manner into the stomach while slowly withdrawing the tube. While the water was being flushed into the stomach, the ventral surface of the abdomen wall was massaged by hand to facilitate dislodging stomach contents. All regurgitated water was sieved through a 100 µm mesh screen and all stomach contents were preserved in 10% formalin solution. If there were no prey items recovered after administering 4 L of water, lavage was stopped. The time GL started and ended was recorded. Prey from all GL samples were classified to the lowest taxonomic level practical (usually order) and enumerated.

2.4.3.4.2 Stomach Contents

In 2012, complete stomach contents (SC) were taken from 50 juveniles to quantify individual diet composition and determine the efficiency of GL. Immediately following GL, juveniles were euthanized with an overdose of tricaine methanesulfonate (MS-222; 500 mg/ml solution) and the entire digestive system (esophagus, stomach, intestinal track) was surgically removed and preserved in 10% formalin solution. Prior to preservation, the stomach was punctured with a scalpel to ensure preservative entry into the gut. For each juvenile White Sturgeon, time immersed in MS-222, and time from capture to preservation of digestive system was recorded. Upon examination in the laboratory, contents of the fore- (esophagus) and mid-gut (stomach) sections were initially separated for taxonomic identification. The data were then pooled for analysis. Due to partial digestion, prey items in the hind-gut were not included in the analysis. However, to verify that the hind-gut did not contain prey taxa that were not present in the fore- and mid-guts, five randomly selected hind-gut samples were examined and all possible prey were identified. Prey were classified to the lowest taxonomic level practical (usually order) and enumerated.

2.4.3.4.3 Benthic Grabs

Sturgeon, while opportunistic, are primarily benthic feeders that prefer small, soft bodied, benthic prey organisms (Miller 2004). We collected a minimum of 2 benthic grabs (BG; 1 L containers) at all locations of fish capture using a Ponar sampler (15 x 20 cm). All substrate collected in each BG was preserved in 10% formalin solution and transported to the laboratory where the samples were transferred to a 70% ethyl-alcohol solution. The total volume of the sampled sediment was calculated using the depth of sediment in the sample containers and the diameter of the container. The sediments were separated from the potential food items by stirring the sample in a bucket and quickly decanting off the suspended prey items and other organic matter onto a 100 µm sieve. This was repeated until only mineral substrate remained.

2.4.3.5 Data Analysis

All statistical analyses will be performed using R (Program R, version 3.03, R Development Core Team 2014, http://www.r-project.org). The numeric abundance of each prey taxon will be tabulated for each juvenile sturgeon and method (GL, SC, and BG). To standardize across prey taxa and method, the percent frequency of occurrence (%F) of prey taxa will be calculated for each method (GL, SC, and BG) as the number of samples that contained a prey taxon divided by total number of samples collected. Percent frequency of occurrence will also be calculated for each method (GL, SC, and BG) by river section and year for the combined prey taxa comprising >95% of total prey abundance in the diet. Individual fish that did not have prey identified (e.g., empty stomach) will not be included in calculations of %F.

The relationship between the number of unique prey taxon identified in SC samples and data on length, weight, and age will each be tested using a linear regression to determine if larger or older individuals had a more diverse diet or were feeding on specific prey taxa. Additionally, a Student’s t-test will be used to examine the influence of river section on prey diversity.

To determine the efficiency of GL in describing the diets of individual juvenile White Sturgeon, we will compare the percent of total unique prey taxa identified in the GL and SC samples. Further, we will qualitatively compare the abundance of total prey items collected using both GL and SC methods.

To further evaluate the use of GL to describe the diet at the population level, we will develop a resampling procedure in R to determine the mean number of unique prey taxa identified as sequential juveniles had GL performed. We will use a dataset that includes each unique prey taxa identified for each sturgeon that had prey items successfully removed during GL. The list of prey taxa will be resampled for 100 iterations without replacement. We will plot the means and

95% confidence intervals to examine the accumulation of unique prey taxa captured by the incremental addition of juvenile White Sturgeon in the dataset.

Many species of fish are selective foragers, with preference for specific prey types that may not be in the highest abundance (Mittelbach 2002). Using both data for prey taxa identified in the diet (GL and SC) and those identified in the BG collected from the river, we will determine preferences for the dominant prey taxa in juvenile White Sturgeon diets by calculating selectivity according to the linear food selection index (*L*) developed by Strauss (1979):

$$L = r_i - p_i$$

where r_i represents the relative proportion of the *ith* prey taxon in the diet (GL and SC samples) and p_i is the relative proportion of the *ith* prey taxon in the river (BG). The linear food index ranges between -1 (complete avoidance) and +1 (strong selection), with $L = 0$ suggesting that fish are selecting prey *i* in proportion to its abundance in the river. This method has been used with confidence to describe the selectivity of prey taxa in other species (e.g. Guppies *Poecilia reticulate*, Zandona et al. 2011; Coho Salmon *Oncorhynchus kisutch*, Kiffney et al. 2014).

In addition, we will also determine the amount of overlap in the diets of juvenile White Sturgeon between collection years (2012 versus 2013) and between river sections within each year. The proportion of dietary overlap will be estimated using Schoener's (1970) similarity index,

$$\alpha = 1 - 0.5\left(\sum | p_{ij} - p_{ik} |\right)$$

where α is the degree of overlap, p_{ij} is the proportion of the *ith* prey taxon used by group *j*, and p_{ik} is the proportion of the *ith* prey taxon used by group *k*. Schoener's similarity index values range from 0 to 1, where a value of $\alpha = 0$ is interpreted as the two groups sharing no prey taxa and a value of $\alpha = 1$ indicates completely identical prey selection. When overlap values exceed 0.6, they are considered to represent a biologically significant overlap in resource use (Wallace 1981). This index is typically used to compare the diets of two species that overlap in distribution but can also provide a sense of how resource use may differ between fish residing in different habitats. Juvenile White Sturgeon fidelity is known to be high to specific habitats (Hildebrand and Parsley 2013), allowing comparison between the different river sections with the assumption that movement during this study was low.

2.5 Habitat Mapping

To address questions regarding the use and availability of suitable habitat for larval or juvenile stages of White Sturgeon in the LCR, it is important to quantify physical habitat that can be tied to data collected as part of this program. It is believed that small substrate (e.g., gravel) with interstitial spacing is important for survival of YSL by providing hiding habitat that they can use to avoid predators (McAdam 2011) while age-0 and older juvenile White Sturgeon tend to prefer substrates of hard clay, mud, silt, and sand (Parsley et al. 1993). Uncertainties exist in the LCR as to how the quality and quantity of such habitat changes across different sections of the river. As such, physical habitat data are required to assess habitat use and suitability/availability for both wild and hatchery released juvenile sturgeon found in the LCR.

As part of this monitoring program, a habitat mapping program was developed for the LCR to describe and classify physical habitat in the LCR between HLK and the US border. Riverbed images were acquired in 2010 and 2011 with a Tritech Starfish sidescan sonar. Appendix 1 provides detailed methodology for image collection, editing, processing, assignment of acoustic classes, and mapping.

3 MONITORING RESULTS

It is intended that the long term results of all White Sturgeon monitoring programs will be used to characterize movements and redistribution patterns, spawning behavior and frequency, relative abundance, habitat preferences, growth rates, survival, provide information on potential new hypotheses and physical works options, and provide baseline information necessary to evaluate physical works experiments and effects of opportunistic flows.

3.1 Physical Parameters

3.1.1 Discharge

Mean daily discharge (cms; cfs) measured from Arrow Reservoir, Kootenay River, Birchbank, and Canada/U.S. International Border for the 2011 and 2012 study periods are presented Figure 4 and Figure 5, respectively. Minimum and maximum discharge (cms; cfs) for each location and year is given in Table 1.

Table 1. Minimum and maximum discharge (cubic meters per second, cms; cubic feet per second, cfs) at four locations on the LCR in 2011 and 2012.

Location (Year)	Minimum Discharge	Maximum Discharge
Arrow Reservoir (2011)	897 cms (31,689 cfs)	1,814 cms (64,043 cfs)
Arrow Reservoir (2012)	568 cms (20,065 cfs)	3,258 cms (115,056 cfs)
Kootenay River (2011)	806 cms (28,482 cfs)	2,906 cms (102,637 cfs)
Kootenay River (2012)	230 cms (8,130 cfs)	3,424 cms (120,930 cfs)
Birchbank (2011)	1,551 cms (54,755cfs)	4,155 cms (146,746 cfs)
Birchbank (2012)	1,078 cms (38,093 cfs)	6,043 cms (213,410 cfs)
Border (2011)	2,687 cms (94,900cfs)	7,561 cms (181,245 cfs)
Border (2012)	1,407 cms (49,720 cfs)	7,940 cms (280,400 cfs)

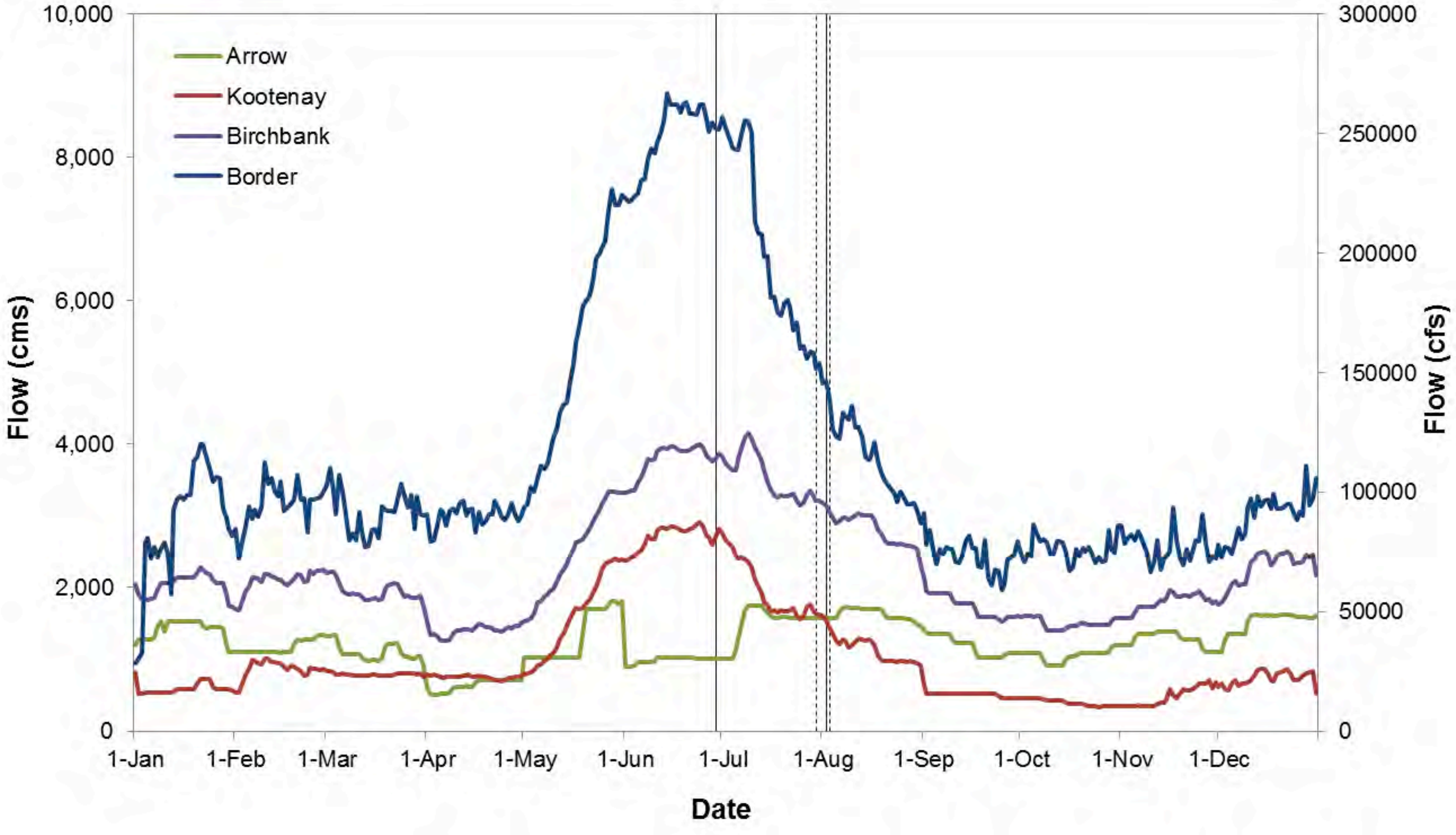

Figure 4. Mean daily discharge measured from Arrow Reservoir, Kootenay River, Birchbank, and the Canada/U.S. International Border on the LCR from January 01, 2011 – December 31, 2011. The solid vertical bars represent the first and last estimated spawning dates at Waneta in 2011, either based on the collection of fertilized eggs (BC Hydro 2013b) or YSL. Vertical dashed bars represent the first and last estimated spawning dates at ALH.

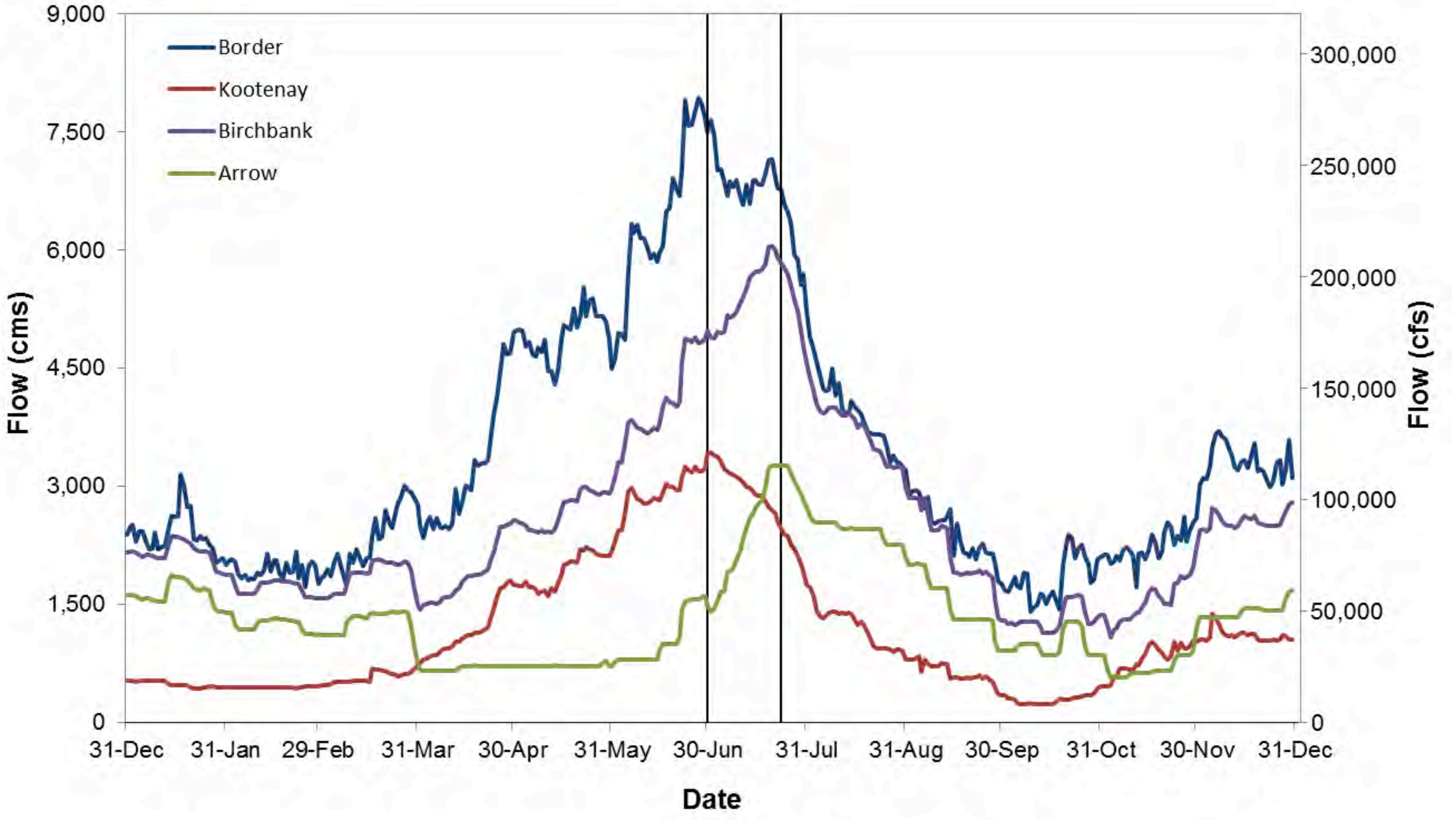

Figure 5. Mean daily discharge measured from Arrow Reservoir, Kootenay River, Birchbank, and the Canada/U.S. International Border on the LCR from January 01, 2012 – December 31, 2012. The solid vertical bars represent the first and last estimated spawning dates at Waneta in 2012, either based on the collection of fertilized eggs (BC Hydro 2015) or YSL. Despite sampling effort, estimated spawning dates were not calculated for the upstream locations.

3.1.2 Water Temperature

Mean daily river temperatures (°C) during 2011 and 2012 are illustrated in Figure 6 and Figure 7, respectively. Annual mean (± SD), minimum, and maximum water temperatures (°C) at locations HLK (rkm 0.1), Kootenay Eddy (rkm 10.5), Kinnaird (rkm 13.4), Genelle Eddy (rkm 26.0), Rivervale (rkm 35.8), and Waneta Eddy (rkm 56.0) for 2011 and 2012 are summarized in Table 2. Variations in water temperatures experienced during the study period can be attributed to warm/cold water influences caused in the Arrow Reservoir system (i.e., combined HLK and ALH discharges from Arrow Lakes Reservoir), and other cold-water tributary influences.

Table 2. Mean (± SD) daily, minimum, and maximum water temperatures (^{o}C) recorded within the LCR during 2011 and 2012. Data was recorded at locations of HLK (rkm 0.1), Kootenay Eddy (rkm 10.5), Kinnaird (rkm 13.4), Genelle Eddy (rkm 26.0), Rivervale (rkm 35.8) and Waneta Eddy (rkm 56.0).

			Temperature (°C)		
Location	RKM	Year	Mean ± SD	Minimum	Maximum
HLK	0.1	2011	N/A	4.9	18.3
Kootenay	10.5	2011	8.8 ± 5.2	2.3	18.3
Kinnaird	13.4	2011	9.2 ± 5	2.8	18.4
Genelle	26.0	2011	8.7 ± 5.1	2.3	18.3
Rivervale	35.8	2011	9 ± 5.1	2.7	18.4
Waneta	56.0	2011	9.3 ± 5	2.7	18.2
HLK	0.1	2012	10 ± 5.1	4.0	19.0
Kootenay	10.5	2012	N/A	3.4	N/A
Kinnaird	13.4	2012	9.8 ± 5.1	3.9	19.6
Genelle	26.0	2012	9.8 ± 5.1	3.8	19.3
Rivervale	35.8	2012	N/A	3.9	N/A
Waneta	56.0	2012	10.1 ± 6	2.3	20.8

*****N/A: data unavailable due to lost or damaged temperature loggers

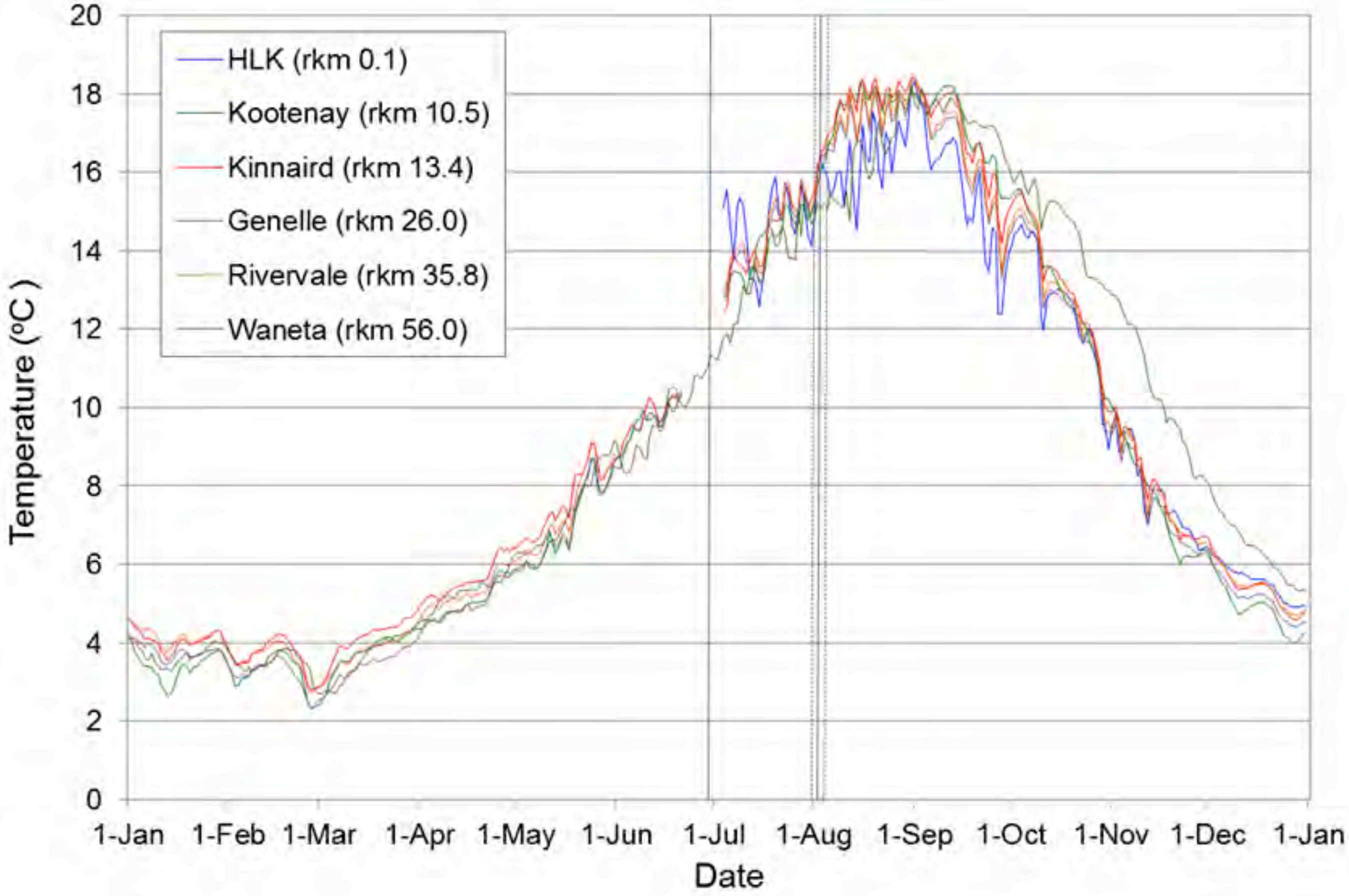

Figure 6. Mean daily water temperature (^{o}C) of the LCR in 2011. Data was recorded at locations of HLK (rkm 0.1), Kootenay (rkm 10.5), Kinnaird (rkm 13.4), Genelle (rkm 26.0), Rivervale (rkm 35.8) and Waneta (rkm 56.0). Missing data is due to lost or damaged temperature loggers. Vertical solid lines represent estimated first and last spawning dates at the Waneta spawning area while vertical dashed lines represent estimated first and last spawning dates at the ALH spawning area. Estimated spawning days were either based on the collection of fertilized eggs (BC Hydro 2013b) or YSL.

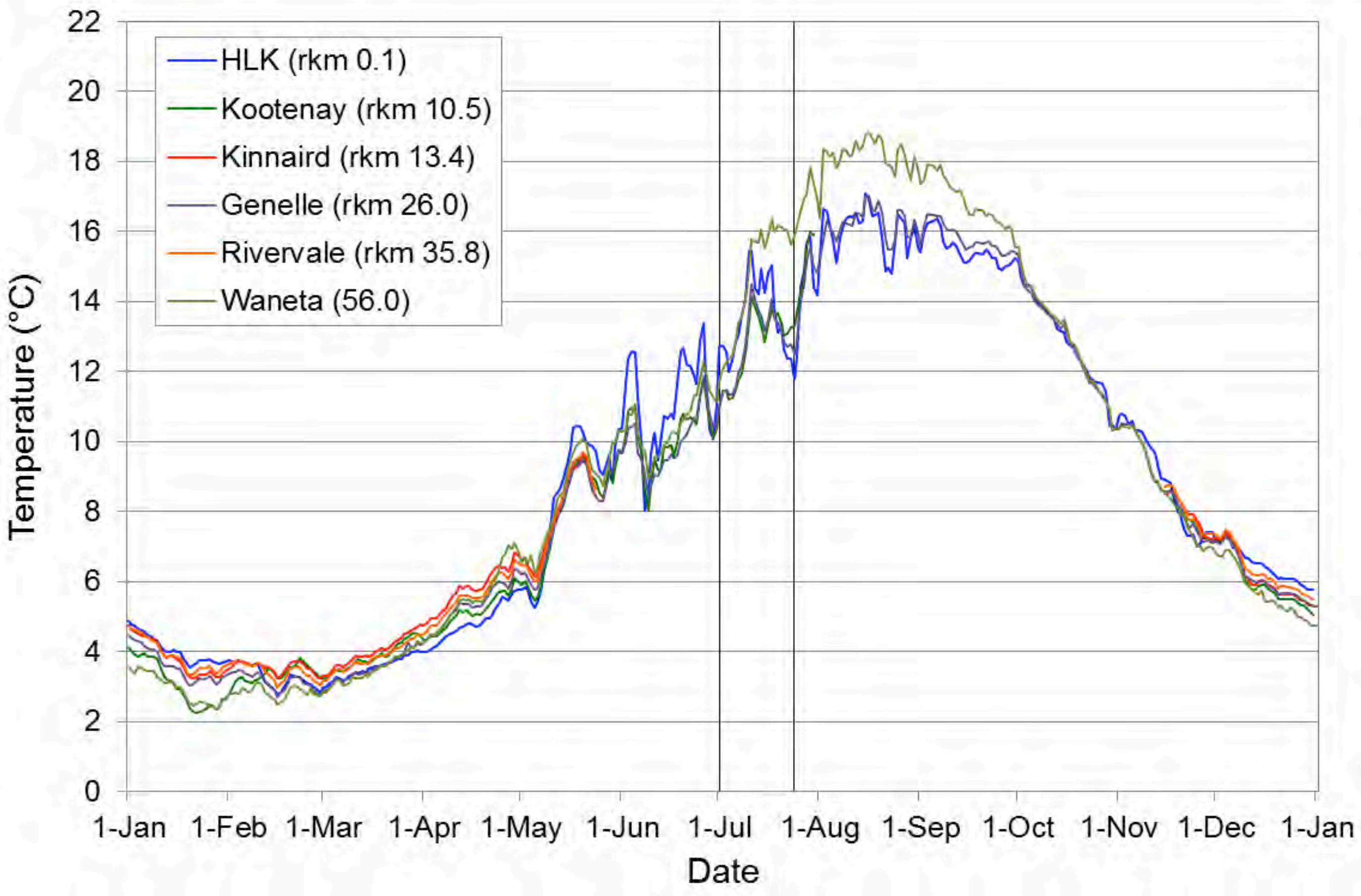

Figure 7. Mean daily water temperature (^{o}C) of the LCR in 2012. Data was recorded at locations of HLK (rkm 0.1), Kootenay (rkm 10.5), Kinnaird (rkm 13.4), Genelle (rkm 26.0), Rivervale (rkm 35.8) and Waneta (rkm 56.0). Missing data is due to lost or damaged temperature loggers. Vertical solid lines represent estimated first and last spawning dates at the Waneta spawning area, either based on the collection of fertilized eggs (BC Hydro 2015) or YSL. Despite sampling effort, estimated spawning dates were not calculated for the upstream locations.

3.2 Conservation Aquaculture Program

The total number of juvenile White Sturgeon released through the entire duration of the Conservation Aquaculture Program (Spring 2002 to Spring 2012) is provided in Table 3. In 2011, 4,010 hatchery-reared juveniles (year class 2010) from six maternal families were released into the LCR at locations of HLK (rkm 0.1; n=1,500), Kootenay Eddy (rkm 10.5; n=1,000), Genelle (rkm 24.0; n=1,000), and Beaver Creek (rkm 49.0; n=510) (Table 4; FFSBC 2011). FL (cm) and weight (kg) (mean ± SD) for released White Sturgeon was 19.8 ± 2.1 cm and 57.2 ± 20.8 g, respectively (Figure 8 and 9). In 2012, 4,189 hatchery-reared juveniles (year class 2011) were released into the LCR at locations of HLK (n=2,196), Kootenay (n=993), and Genelle (n=1,000) (Table 4; FFSBC 2012). FL and weight for released White Sturgeon was 22.6 ± 2.7 cm and 85.8 ± 35.1 g, respectively (Figure 8 and 9).

Table 3. Numbers of hatchery reared juvenile White Sturgeon released annually into both the LCR, Canada, and Lake Roosevelt, USA. Release numbers are presented by release year and indicated whether they occurred in the fall or spring.

Release Year	Canada		USA		Total
	Fall	Spring	Fall	Spring	
2002		8,671			8,671
2003		11,803			11,803
2004		9,695		1,881	11,576
2005	5,039	12,748		3,755	21,542
2006	4,042	10,828		4,351	19,221
2007	4,029	8,123		3,422	15,574
2008		6,448		3,821	10,269
2009		4,141		3,537	7,678
2010		3,947	522	3,873	8,342
2011		4,010	3,590	3,869	11,469
2012		4,189	302		4,302
	13,110	84,603	4,414	28,509	130,636

Table 4. Number of hatchery reared juvenile White Sturgeon released for year classes 2010 and 2011. Release numbers are presented by release location and family.

Year Class	Family	rkm 0.1	rkm 10.5	rkm 24.0	rkm 49.0	Total
2010	A	462	200	200	110	972
2010	B	238	200	200	100	738
2010	CD	400	300	300	150	1150
2010	EF	400	300	300	150	1150
2010	All	1500	1000	1000	510	4010
2011	G	448	200	200	0	848
2011	I	452	200	200	0	852
2011	J	456	193	200	0	849
2011	K	423	200	200	0	823
2011	L	417	200	200	0	817
2011	All	2196	993	1000	0	4189

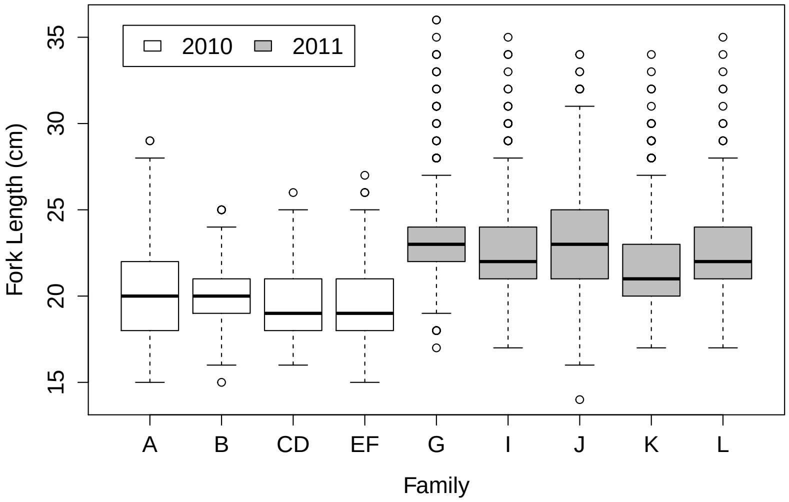

Figure 8. Fork length (cm) at release (approximately 9 months of age) of juvenile White Sturgeon year classes 2010 and 2011 by family.

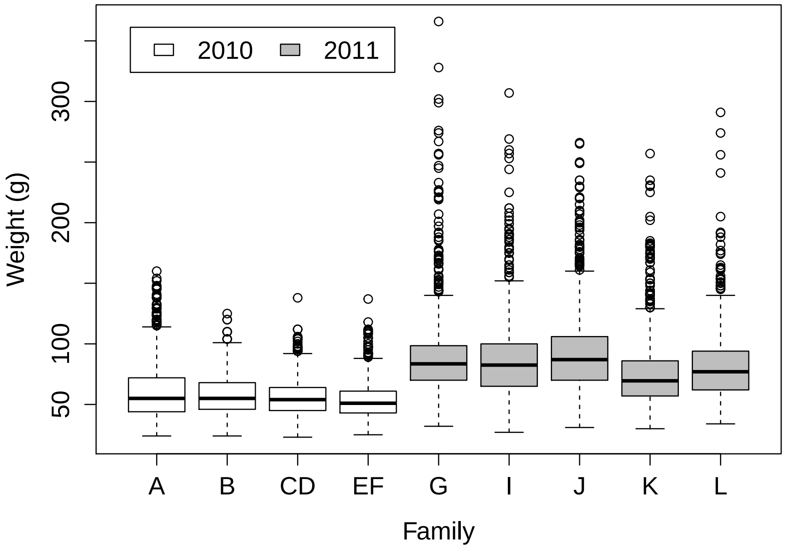

Figure 9. Weight (g) at release (approximately 9 months of age) of juvenile White Sturgeon year classes 2010 and 2011 by family.

3.3 Larval Stage

3.3.1 Yolk Sac Larval Assessment

3.3.1.1 Larval Sampling: Sampling Effort and Sample Preservation

3.3.1.1.1 2011

Downstream Location – Waneta (rkm 56.0)

Drift nets (n=1; 2 hour sets) were deployed on June 13 and sampling continued until August 12 with water temperatures ranging from 9.8 to 17.8°C (Figure 6). Total sampling effort was 50 hours (2.1 days; Table 5). The mean (± SD) daily effort was 1.9 ± 0.9 hours.

A total of 234 eggs and 15 YSL were collected between the dates of July 4 and August 6 (CPUE = 4.98; Table 5). A sub-sample of eggs (n=44) were incubated *in situ* (BC Hydro 2013b), successfully hatched, and preserved for use of genetic tissue (see Section 3.3.2). All YSL collected were preserved.

Upstream location – ALH (rkm 0.1)

Drift nets (n=6; 24 hour sets) were deployed on July 1 and sampling continued until August 19 with water temperatures ranging from 11.4 to 20.1°C (Figure 6). Total sampling effort was 2,538 hours (105.8 days; Table 5). Mean (± SD) daily effort and mean water depth was 22.6 ± 0.1 hours and 5.6 ± 2.8 m, respectively.

A total of 183 eggs and 305 YSL were collected between the dates of August 2 and August 12 (CPUE = 0.19; Table 5). Dead eggs were discarded (n=15). Live eggs were incubated and hatched YSL (n=112; 67% hatch rate; BC Hydro

2013b) were preserved for genetic tissue. All captured YSL were preserved. The day with the most samples collected was August (n=221) representing 53% of total collection. The next largest sampling collection date was August 10 (n=53) representing 13% of total collection.

Upstream location –HLK (rkm 0.1), Kootenay (rkm 10.5)

Drift nets were deployed at HLK (n=2; 24 hour sets) and Kootenay (n-3; 24 hour sets) on July 1 and sampling continued until August 12 with water temperatures ranging from 12.1 to 16.9°C and 11.4 to 18.1°C, respectively (Figure 6). Total sampling effort was 461 hours (19.2 days) and 993 hours (41.4 days) at HLK and Kootenay, respectively (Table 5). The mean (± SD) daily effort and mean water depth at HLK and Kootenay was 23.0 ± 0.2 hours and 7.6 ± 0.1 m and 23.6 ± 0.1 hours and 5.0 ± 1.4 m, respectively.

There was no documentation of spawning at either the Kootenay or HLK sites (CPUE = 0.00; Table 5). However, with the limited number of drift nets, limited sampling effort, and large sampling area, either site should not be ruled out as a possible White Sturgeon spawning site in years when conditions are suitable.

Upstream location – downstream of Kinnaird (rkm 18.2)

Drift nets (n=4; 24 hour sets) were deployed on July 1 and sampling continued until August 12 with water temperatures ranging from 12.1 to 18.3 °C (Figure 6). Total sampling effort was 1,413 hours (58.9 days; Table 5). The mean (± SD) daily effort was 23.3 ± 0.1 hours and mean water depth was 8.2 ± 2.8 m.

A total of 2 eggs and 33 YSL were captured between the dates of July 26 and August 9 (CPUE = 0.02; Table 5). Hatch rate of incubated eggs was 0% therefore no genetic tissue from captured eggs was preserved (BC Hydro 2013b). All YSL were preserved. The day of largest collection was July 27 (n=9) representing 27% of the total collection. The next largest sampling collection date was July 28 (n=6) representing 18% of the total collection.

3.3.1.1.2 2012

Downstream Location – Waneta (rkm 56.0)

Drift nets (n=2; 3 hour sets) were deployed on June 11 and sampling continued until August 3 with water temperatures ranging from 9.6 to 18.3°C (Figure 7). Total sampling effort was 48.2 hours (2.0 days; Table 5). The mean (± SD) daily effort was 2.3 ± 0.8 hours and mean water depth was 7.1 ± 1.8 m.

A total of 134 eggs and 15 YSL were captured at Waneta between the dates of July 4 and July 27 (CPUE = 3.10; Table 5). Of the total egg capture, a subsample (n=28) were incubated, successfully hatched and preserved for genetic analysis (BC Hydro 2015). All YSL collected were preserved.

Upstream locations – ALH (rkm 0.1) and downstream of Kinnaird (rkm 18.2)

Sampling at the upstream locations was delayed until July 26 due to high water flows (50 year flood level; see Section 3.1.1) that prevented gear deployment. Once permitted, drift nets were deployed for 24-hour sets at ALH (n=8) on July 26 and on August 12 at rkm 18.2 (n=2) with water temperatures ranging from 13.1 to 16.7 °C (Figure 7). Sampling was terminated at both sites on August 16. Across all sites, the cumulative effort for entire study period was 3,126.0 hours (130.3 days; Table 5). Total sampling effort completed at ALH and rkm 18.2 was 2,929.2 hours (122.1 days) and 196.8 hours (8.2 days), respectively. The mean (± SD) daily effort at ALH and rkm 18.2 was 21.2 ± 7.2 and 24.6 ± 2.5 hours, respectively. Mean (±SD) water depth was 8.9 ± 4.8 m at ALH and 7.4 m ± 0.7 m at rkm 18.2.

Six dead eggs were captured at ALH, however, there were no live eggs or YSL collected and preserved at ALH or rkm 18.2 (CPUE = 0.00; Table 5). This is expected to be a result of the hydrology of the spawning areas in 2012 (see Section 3.1.1). Both temperature and flow have been shown as important environmental predictors of White Sturgeon spawning. Hildebrand et al. (1999) found that spawning primarily occurred at the Waneta area following temperatures exceeding the 14°C threshold. In 2012, water temperatures at ALH and rkm 18.2 rarely rose above this threshold (14.3 ± 1.0°C; mean ± SD) and did not remain above 14°C for extended periods of time during the sampling period. Further, high flows increasing the riverbed area could have potentially provided additional spawning areas that were not sampled. Due to high flows (50 year flood level; Figure 5), nets were deployed three weeks later in 2012 compared to the 2011 spawn-monitoring program. However, it is believed spawning activity did not occur prior to deployment, as drift nets were set while water temperatures were below optimal spawning temperatures.

Table 5. White Sturgeon egg and YSL collection and sampling effort at LCR monitoring locations of Waneta (rkm 56.0), downstream of Kinnaird (rkm 18.2, rkm 14.5), Kootenay (rkm 10.5), downstream ALH (rkm 6.0), ALH (rkm 0.1), and HLK (rkm 0.1) for years 2008 through 2012.

Year	Location	Eggs	Larvae	Effort (hrs)	CPUE
2008	Waneta	494	220	72	9.92
	rkm 18.2	0	1	164	0.01
2009	Waneta	77	39	90	1.29
	rkm 18.2	0	5	976	0.01
	rkm 6.0	0	0	3,091	0.00
2010	Waneta	888	89	113	8.65
	rkm 18.2	1	8	2,104	0.00
	ALH	30	115	2,084	0.07
2011	Waneta	234	15	50	4.98
	rkm 18.2	2	33	1,413	0.02
	rkm 14.5	0	0	154	0.00
	rkm 10.5	0	0	993	0.00
	HLK	0	0	461	0.00
	ALH	183	308	2,538	0.19
2012	Waneta	134	15	48	3.10
	rkm 18.2	0	0	197	0.00
	ALH	6	0	2,979	0.00

3.3.1.2 Developmental Staging and Estimated Spawning Dates

All preserved YSL were assigned a developmental stage based on Dettlaff et al. (1993) to calculate an estimated date of fertilization. The majority proportion of samples was of newly hatched YSL (stage 36; ALH 2011, 0.5; Waneta 2011, 0.62; Waneta 2012, 0.63) or approximately 1-day post hatch (stage 37; ALH 2011, 0.46; Waneta 2011, 0.24; Waneta 2012, 0.25; Table 6).

Table 6. Proportion of White Sturgeon YSL collected across different developmental stages from spawn monitoring locations of Waneta and ALH in 2011 and 2012. YSL samples collected downstream of Kinnaird in 2011 were not developmentally staged due to poor condition. No YSL samples were collected at ALH or downstream of Kinnaird in 2012.

Stage	Development	ALH (2011)		Waneta (2011)		Waneta (2012)	
		n	*Prop.*	*n*	*Prop.*	*n*	*Prop.*
36	Hatch	63	0.50	13	0.62	5	0.63
37	Pectoral fin rudiment	58	0.46	5	0.24	2	0.25
38	Gill filament rudiments	4	0.03	0	0.00	0	0.00
39	Digestive system rudiment divides into stomach and intestine	0	0.00	0	0.00	0	0.00
40	Ventral fin rudiment	0	0.00	0	0.00	0	0.00
41	Liver subdivided	0	0.00	0	0.00	0	0.00
42	Complete liver division, pyloric fin rudiment	0	0.00	0	0.00	0	0.00
43	Ventral fin extends to preanal fin fold margin	0	0.00	1	0.05	1	0.13
44	Complete yolk-sac absorption, discharge of pigment plug	0	0.00	2	0.10	0	0.00
45	Exogenous feeding	0	0.00	0	0.00	0	0.00

3.3.1.2.1 2011

Downstream Location – Waneta (rkm 56.0)

Twelve distinct fertilization days between the dates of July 2 and July 28 were calculated for all preserved YSL. Two peaks in fertilization dates were observed as a reflection of the LCR discharge with estimations occurring on the descending limbs of each freshet peak (Figure 10)

Upstream locations – ALH (rkm 0.1)

Five distinct fertilization days between the dates of August 1 and August 5 were calculated for all preserved YSL.

Upstream locations –downstream of Kinnaird (rkm 18.2)

No preserved YSL could be developmentally staged due to poor condition and therefore fertilization date could not be calculated.

3.3.1.2.2 2012

Downstream Location – Waneta (rkm 56.0)

Ten distinct fertilization days between the dates of July 1 and July 21 were calculated for all preserved YSL. Three peaks of fertilization occurred in early July, mid-July and late-July.

Upstream locations – ALH (rkm 0.1) and downstream of Kinnaird (rkm 18.2)

Estimated fertilization dates were not calculated for ALH or rkm 18.2 since there were no YSL collected.

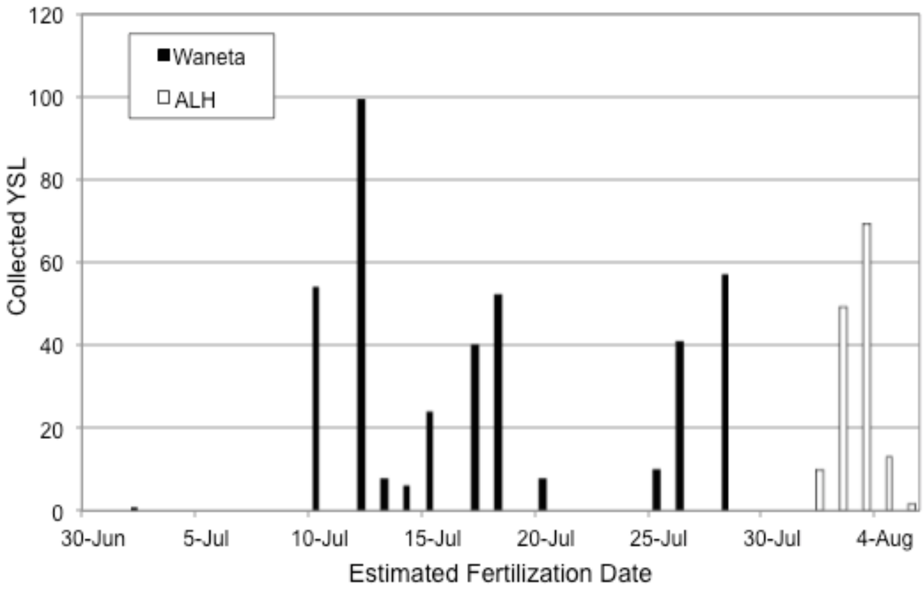

Figure 10. Estimated spawning dates based on YSL samples collected in the LCR during 2011 at locations of Waneta and ALH. Spawning dates are determined through back calculation from date of capture based on developmental stage of each sample and water temperatures. YSL collected at rkm 18.2 could not be developmentally staged due to poor condition. No YSL were collected at HLK or Kootenay.

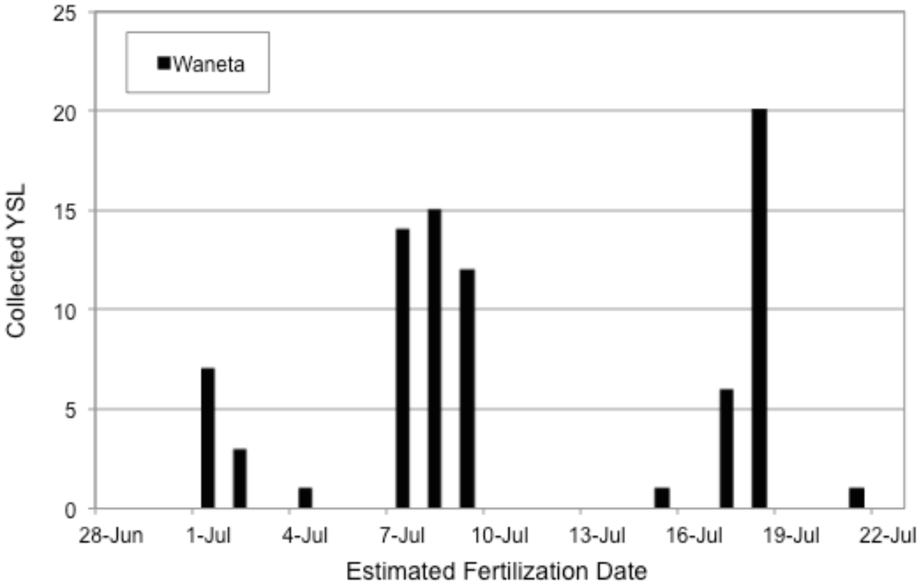

Figure 11. Estimated spawning dates based on YSL samples collected in the LCR during 2012 at location of Waneta. Spawning dates are determined through back calculation from date of capture based on developmental stage of each sample and water temperatures. No YSL were collected at ALH or rkm 18.2.

3.3.2 Larval Genetics

All preserved larvae in 2011 and 2012 were genotyped and pedigree analysis was used to quantify the effective number of breeding adults (N_b), number of adults contributing progeny (N_s), number of kin groups (N_k), and individual reproductive success of White Sturgeon in the LCR. Since these results focus on adult White Sturgeon spawning population and reproductive ecology results are not provided in this report. See Jay et al. (2014) and BC Hydro (2015) for detailed results.

3.3.3 Temperature Effects on Development

3.3.3.1 Experimental Sampling

Of the 24,000 fertilized eggs, 83.5 ± 14.4% (mean ± SD) reached neurulation within each hatching jar. The number of YSL hatched was not counted, as survival across treatments was not evaluated in this study. Duration to complete yolk-sac absorption, marking the termination of the experiment, varied between treatments resulting in different total YSL samples collected by the end of the experiment to examine developmental differences between the temperature treatments of 12.5°C (F1 n = 280, F2 n = 290), 14°C (F1 n = 230, F2 n = 230), 15.5°C (F1 n = 170, F2 n = 170), and 17°C (F1 n = 150, F2 n = 140). Similarly, cold temperatures delayed development and more photographs were required at the 12.5^{o}C treatment for the morphological traits analysis of BA (12.5°C n = 255, 17°C n = 186), GFA (12.5°C n = 206, 17°C n = 98), HA (12.5°C n = 254, 17°C n

= 189), TL (12.5°C n = 255, 17°C n = 186), MA (12.5°C n = 253, 17°C n = 189), PFA (12.5°C n = 240, 17°C n = 176), and YSA (12.5°C n = 255, 17°C n = 180).

3.3.3.2 Developmental Staging

Temperature affected the chronology of development in YSL as a function of both time (h) and ATU (Table 7; Figure 12). For example, time to attain stage 44 was 324 - 336 h (169 - 175 ATU) at 12.5°C, 264 h (154 ATU) at 14.0°C, 192 h (124 ATU) at 15.5°C, and 156 - 168 h (111 - 119 ATU) at 17.0°C. In terms of RT_i, chronology of development was relatively independent of temperature treatments (Table 8). The regression analyses showed a good fit for developmental rate for each temperature treatment (17.0°C, $R^2 = 0.960$; 15.5°C, $R^2 = 0.938$; 14.0°C, $R^2 = 0.940$; 12.5°C, $R^2 = 0.916$; Table 9). The developmental rate (m) significantly increased with increased temperatures as a function of time (17.0°C, m = 0.046; 15.5°C, m = 0.038; 14.0°C, m = 0.027; 12.5°C, m = 0.02; Tukey's HSD, $P < 0.02$; Table 9), with the exception of the 14.0°C and 12.5°C comparison (Tukey's HSD, P = 0.08). As a function of ATU, the developmental rate was significantly greater at higher temperatures (17.0°C, m = 0.065; 15.5°C, m = 0.059; 14.0°C, m = 0.047; 12.5°C, m = 0.040; Tukey's HSD, $P < 0.05$; Table 9), however no difference was found between 17.0°C and 15.5°C (Tukey's HSD, P = 0.322), or between 14.0°C and 12.5°C (Tukey's HSD, P = 0.228). In terms of RT_i, developmental rate was not significantly different between the temperature conditions applied (17.0°C, m = 7.471; 15.5°C, m = 7.337; 14.0°C, m = 7.184; 12.5°C, m = 6.790; Tukey's HSD, $P > 0.05$; Table 9).

Table 7. Mean time (hours) and accumulated thermal units (ATU) required to reach developmental stages of White Sturgeon YSL from time of hatch at experimental temperature regimes of 12.5°C, 14.0°C, 15.5°C, and 17.0°C.

	12.5°C	14°C	15.5°C	17°C
Stage	Hours Post Hatch			
36	0	0	0	0
37	24 - 36	12	12 - 24	12
38	48	48 - 60	36	36
39	72	72	48	48
40	96	84	60	60
41	156	120 - 132	84 - 96	84
42	228 - 252	180 - 192	144	108
43	288 - 300	228 - 240	168	132 - 144
44	324 - 336	264	192	156 - 168
	ATU Post Hatch			
36	0	0	0	0
37	13 - 19	7	8 - 16	9
38	25	28 - 35	23	26
39	38	42	31	34
40	50	49	39	43
41	81	70 - 77	54-62	60
42	119 - 131	105 - 112	93	77
43	150 - 156	133 - 140	109	94-102
44	169 - 175	154	124	111-119

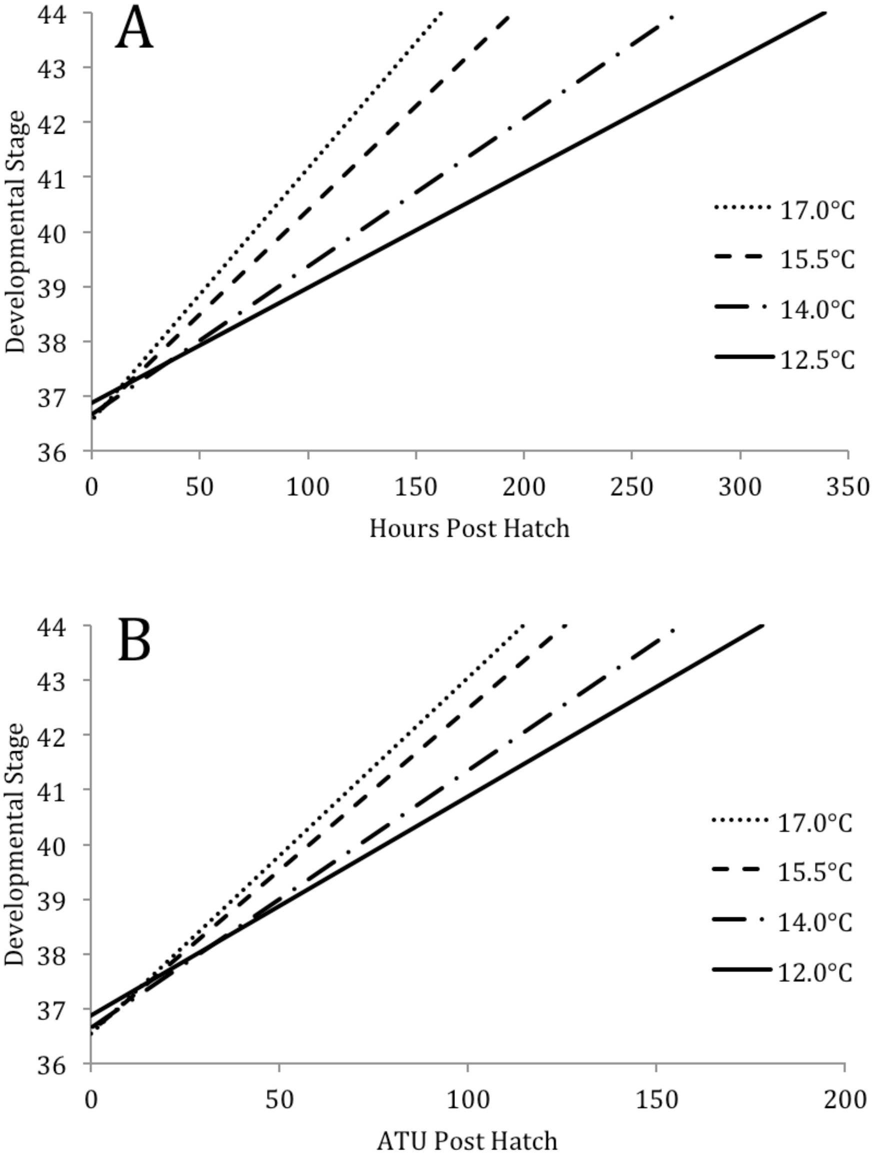

Figure 12. Relationship between developmental stage i (y), and initial occurrence of developmental stage i (x), fitted by a least squares regression following the model y = mx + b, where m is the developmental rate and b is the intercept. Occurrence of developmental stage was measured in time (hours; A) and accumulated thermal units (ATU; B) post hatch.

Table 8. White Sturgeon YSL development at conditions of 12.5°C, 14.0°C, 15.5°C, and 17.0°C. Time (h) is given as RT_i (relative measure of developmental stage *i*, as a proportion of the total duration of the YSL period).

Stage	RT_i			
	12.5°C	14°C	15.5°C	17°C
36	0.00	0.00	0.00	0.00
37	0.09	0.05	0.09	0.07
38	0.15	0.20	0.19	0.22
39	0.22	0.27	0.25	0.30
40	0.29	0.32	0.31	0.37
41	0.47	0.48	0.47	0.52
42	0.73	0.70	0.75	0.67
43	0.89	0.89	0.88	0.85
44	1.00	1.00	1.00	1.00

Table 9. Relationship between developmental stage (y) and transition measurement (hours, ATU and RT_i; x) as a function of temperature following the model $y = mx+b$, where m is the slope and *b* is the intercept. Differing superscripts within a parameter signifies differences at $P < 0.05$.

	m_{hours}	m_{ATU}	m_{RTi}	b	R^2
12.5°C	0.021^a	0.040^a	6.790^a	36.882	0.916
14.0°C	0.027^a	0.047^a	7.184^a	36.663	0.940
15.5°C	0.038^b	0.059^b	7.337^a	36.590	0.938
17.0°C	0.046^c	0.065^b	7.471^a	36.558	0.960

3.3.3.3 Morphological Traits

All measurements of morphological traits have been completed; however, further analyses are required to determine the effects of temperature on morphological trait size.

3.4 Juvenile Stage

3.4.1 Juvenile Population Assessment

3.4.1.1 Juvenile Captures and Sampling Effort

Total juvenile White Sturgeon capture was 1,061 and 602 in 2011 and 2012, respectively (Table 10). In 2011, set line (n=156), gill net (n=62), and angling (n=53) sampling was conducted between September 26 and October 28. Total sampling effort was 1,260.2 hours (set line, 888.2 hours; gill net, 288.5 hours; angling, 83.5 hours) for a CPUE of 0.84 captures per effort hours (set line, 0.35 CPUE; gill net, 0.31 CPUE; angling, 7.95 CPUE; Table 10). Mean (± SD) daily effort for setline, gill net, and angling sampling was 5.7 ± 0.9, 4.7 ± 1.7, and 1.6 ± 1.0 hours, respectively (Table 10). In 2012, set line (n=59), and angling (n=56) sampling was conducted between October 1 and October 31. Total sampling effort was 536.1 hours (set line, 371.2 hours; angling, 164.9 hours) for a CPUE of 1.12 (set line, 0.40 CPUE; angling, 2.76 CPUE; Table 10). Mean (± SD) daily effort for set line and angling sampling was 6.3 ± 1.6 and 2.9 ± 2.2 hours, respectively (Table 10). Gill net sampling was not conducted in 2012 due to the high potential for adult by-catch and potential mortality as habitat use of juveniles overlaps with that of adults. Total effort (hours), mean (± SD) daily effort (hours), mean sampling depth (m), mean daily water temperature (°C), total capture, and CPUE as a function of sampling method and sampling zone for 2011 and 2012 is provided in Table 10.

Total capture by brood year class (YrC) for sampling years 2009 through 2012 is provided in Table 11 (see BC Hydro 2013a for 2009 and 2010 methods and full results). Over the 4-year sampling period, 16 wild fish were captured representing a proportion ≤0.01 of the total capture across all sampling years (0.007) and within each year (2009, 0.005; 2010, 0.003; 2011, 0.006; 2012, 0.013) (Figure 13). YrC 2001 represented the largest proportion of total capture across all years (0.26) and within each year (2009, 0.23; 2010, 0.27; 2011, 0.26; 2012, 0.27) followed by YrC 2005 across all years (0.15), YrC 2004 in 2009 (0.18), YrC 2002 in 2010 (0.16), YrC 2005 in 2011 (0.14), and equal representation of YrC 2005 and 2006 in 2012 (0.14) (Figure 13).

Juvenile White Sturgeon capture summary for each sampling method is provided in Table 12 and illustrated in Figure 14. Angling resulted in the majority of total captures across both years (n=1,119; 0.67) despite a 10-fold decrease in sampling effort hours compared to set line effort (Table 10). The YrC most represented using angling techniques was 2001 across years (0.18) and within years (2011, 0.11; 2012, 0.07), followed by YrC 2006 across years (0.09) and within years (2011, 0.06; 2012, 0.04). YrC most represented using set line techniques was 2001 across years (0.08) and within years (2011, 0.05; 2012, 0.03), followed by 2002 across years (0.05) and within years (2011, 0.03; 2012, 0.01). Captures as a result of gill net sampling was 0.05 of total capture in 2011 where YrC 2005 and 2006 were the majority of the captures (0.01). Gill net sampling was not conducted in 2012.

Total capture across 2011 and 2012 within sampling zones 1, 2, and 5 was 910, 75, and 678 representing 0.55, 0.05, and 0.41 of total capture, respectively (Table 13). The majority of unmarked wild fish were captured in zone 1 (n=13) representing 0.93 of all wild fish captured over the two years. The highest proportions of fish captured in zone 1 were YrC 2001 (0.32) and 2002 (0.18); in zone 2 were YrC 2005 and 2006 (0.17); in zone 5 were YrC 2001 and 2005 (0.20) (Figure 15). Juveniles were distributed widely throughout zone 1 (Figure 16), and were caught in specific habitat types (e.g. eddies) in zone 2 (Figure 17) and zone 5 (Figure 18).

Table 10. Total effort (hours), mean (± SD) daily effort (hours), mean sampling depth (m), mean daily water temperature (°C), total juvenile White Sturgeon capture and catch per unit effort (CPUE; number of fish captured per hour of effort), for the LCR as an entirety as well as each sampling method (set line, gill net, and angling) and sampling zone (1, 2, and 5) in 2011 and 2012.

	Set line		Gill Net		Angling		LCR	
	2011	2012	2011	2012	2011	2012	2011	2012
Total Effort (hrs)	888.2	371.2	288.5	-	83.5	164.9	1260.2	536.1
Zone 1	328.9	196.5	85.4	-	29.1	103.1	443.4	299.6
Zone 2	92.5	39.2	56.3	-	10.4	4.29	159.2	43.49
Zone 5	466.8	135.4	146.8	-	44.1	57.5	657.7	192.9
Daily Effort (hrs)	5.7 ± 0.9	6.3 ± 1.6	4.7 ± 1.7	-	1.6 ± 1.0	2.9 ± 2.2	-	-
Zone 1	5.7 ± 0.9	6.1 ± 2.0	4.3 ± 2.1	-	1.4 ± 0.8	2.6 ± 1.8	-	-
Zone 2	5.4 ± 0.9	6.5 ± 0.9	5.6 ± 0.7	-	1.0 ± 0.7	1.4 ± 1.0	-	-
Zone 5	5.8 ± 0.9	6.4 ± 0.8	4.6 ± 1.4	-	2.0 ± 1.1	4.1 ± 3.0	-	-
Depth (m)	11.2 ± 3.2	12.7 ± 3.4	11.1 ± 3.9	-	18.9 ± 8.2	17.2 ± 6.6	-	-
Zone 1	12.2 ± 3.0	13.8 ± 2.0	13.0 ± 3.4	-	16.8 ± 2.1	15.4 ± 2.9	-	-
Zone 2	9.9 ± 2.3	7.4 ± 1.3	9.9 ± 2.4	-	11.0 ± 2.7	7.5 ± 1.2	-	-
Zone 5	10.8 ± 3.2	12.6 ± 4.0	10.2 ± 4.2	-	24.5 ± 1.3	24.1 ± 8.9	-	-
Water Temperature (°C)	13.0 ± 1.2	13.3 ± 1.5	13.6 ± 1.3	-	13.0 ± 1.3	13.0 ± 1.4	-	-
Zone 1	12.8 ± 1.1	13.0 ± 3.1	12.7 ± 1.1	-	12.3 ± 1.1	12.6 ± 1.4	-	-
Zone 2	14.3 ± 1.2	15.5 ± 0.9	15.3 ± 0.3	-	13.9 ± 1.2	15.7 ± 0.4	-	-
Zone 5	12.9 ± 3.2	13.1 ± 3.4	13.7 ± 4.2	-	13.2 ± 1.3	13.4 ± 1.0	-	-
Total Capture	307	147	90	-	664	455	1061	602
Zone 1	201	117	50	-	251	291	502	408
Zone 2	32	11	2	-	29	1	63	12
Zone 5	74	19	38	-	384	163	496	182
CPUE	0.35	0.40	0.31	-	7.95	2.76	0.84	1.12
Zone 1	0.61	0.60	0.59	-	8.63	2.82	1.13	1.36
Zone 2	0.35	0.28	0.04	-	2.79	0.23	0.40	0.28
Zone 5	0.16	0.14	0.26	-	8.71	2.83	0.75	0.94

Table 11. Total juvenile White Sturgeon captured by brood year class within the LCR during sampling years 2009 through 2012. Year class of hatchery origin fish was determined by external mark of removed lateral scutes and PIT tag. Wild fish are naturally produced individuals of unknown age.

Year Class	2009	2010	2011	2012	Total
2011	-	-	-	3	3
2010	-	-	2	0	2
2009	-	2	10	12	24
2008	2	2	34	9	47
2007	7	17	70	20	114
2006	27	39	139	82	287
2005	29	51	152	87	319
2004	33	49	136	80	298
2003	23	34	123	63	243
2002	23	53	115	74	265
2001	43	90	274	164	571
Wild	1	1	6	8	16
Total	188	338	1061	602	2189

Table 12. Total juvenile White Sturgeon captured by brood year class within the LCR for each sampling method (set line, gill net, and angling) during sampling years 2011 and 2012. Year class of hatchery origin fish was determined by external mark of removed lateral scutes and PIT tag. Wild fish are naturally produced individuals of unknown age. Gill nets were not used in 2012.

Year Class	Set line		Gill Net		Angling		LCR	
	2011	2012	2011	2012	2011	2012	2011	2012
2011	-	0	-	-	-	3	-	3
2010	1	0	1	-	0	0	2	0
2009	3	2	1	-	6	10	10	12
2008	7	0	4	-	23	9	34	9
2007	14	5	18	-	38	15	70	20
2006	26	20	22	-	91	62	139	82
2005	34	18	21	-	97	69	152	87
2004	34	18	17	-	85	62	136	80
2003	39	18	1	-	83	45	123	63
2002	57	21	2	-	56	53	115	74
2001	89	42	3	-	182	122	274	164
Wild	3	3	0	-	3	5	6	8
Total	307	147	90	-	664	455	1061	602

Table 13. Total juvenile White Sturgeon captured by brood year class within the LCR for each sampling zone (1, 2, and 5) during sampling years 2011 and 2012. Year class of hatchery origin fish was determined by external mark of removed lateral scutes and PIT tag. Wild fish are naturally produced individuals of unknown age.

Year Class	Zone 1		Zone 2		Zone 5		LCR	
	2011	2012	2011	2012	2011	2012	2011	2012
2011	-	0	-	0	-	3	-	3
2010	0	0	0	0	2	0	2	0
2009	1	0	1	0	8	12	10	12
2008	3	1	2	0	29	8	34	9
2007	18	7	3	1	49	12	70	20
2006	51	56	10	3	78	23	139	82
2005	45	44	11	2	96	41	152	87
2004	62	56	10	0	64	24	136	80
2003	54	45	9	2	60	16	123	63
2002	96	65	7	4	12	5	115	74
2001	166	127	10	0	98	37	274	164
Wild	6	7	0	0	0	1	6	8
Total	502	408	63	12	496	182	1061	602

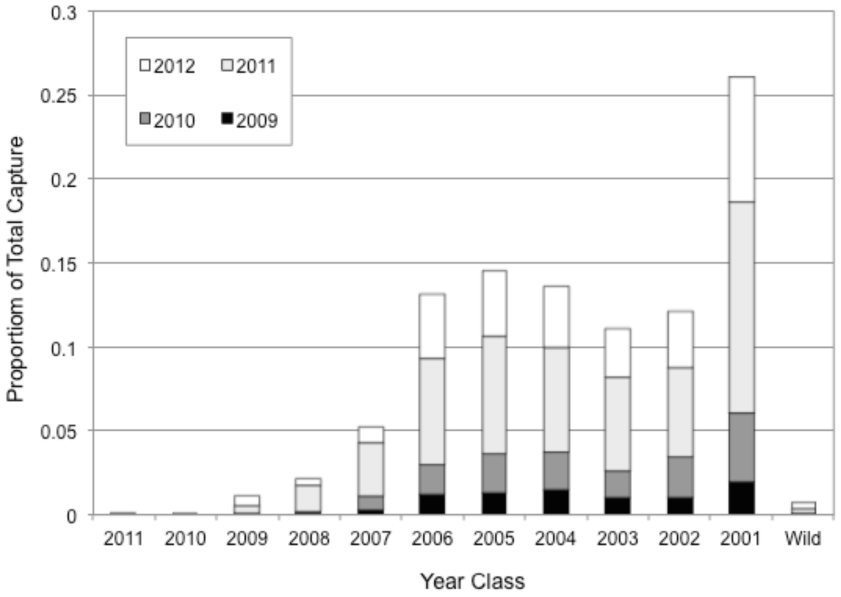

Figure 13. Proportion of total juvenile White Sturgeon capture by brood year class within the LCR across the years of 2009 through 2012. Year class of hatchery origin fish was determined by external mark of removed lateral scutes and PIT tag. Wild fish are of natural reproduction and unknown age.

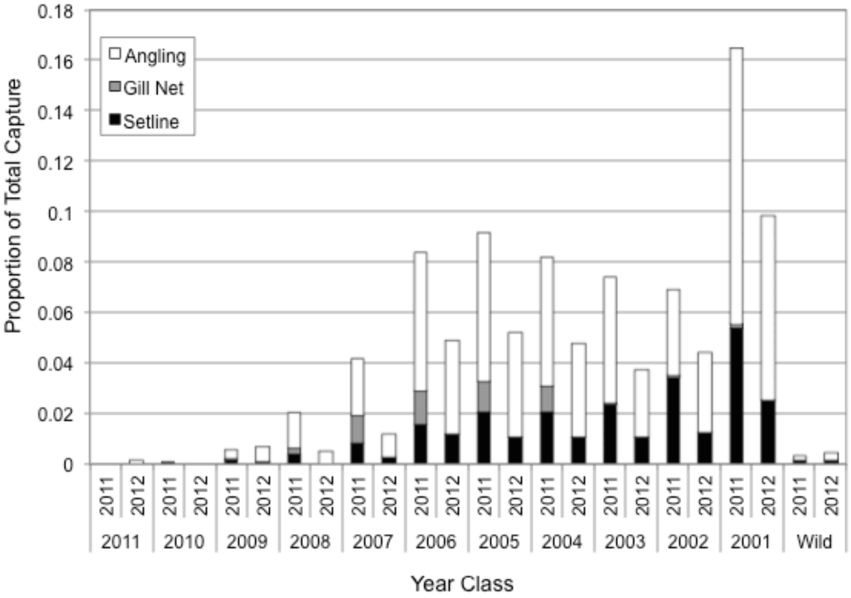

Figure 14. Proportion of total juvenile White Sturgeon capture by brood year class within the LCR for each sampling method (set line, angling, and gill net) across the years of 2011 and 2012. Year class of hatchery origin fish was determined by external mark of removed lateral scutes and PIT tag. Wild fish are of natural reproduction and unknown age. Gill nets were not used in 2012.

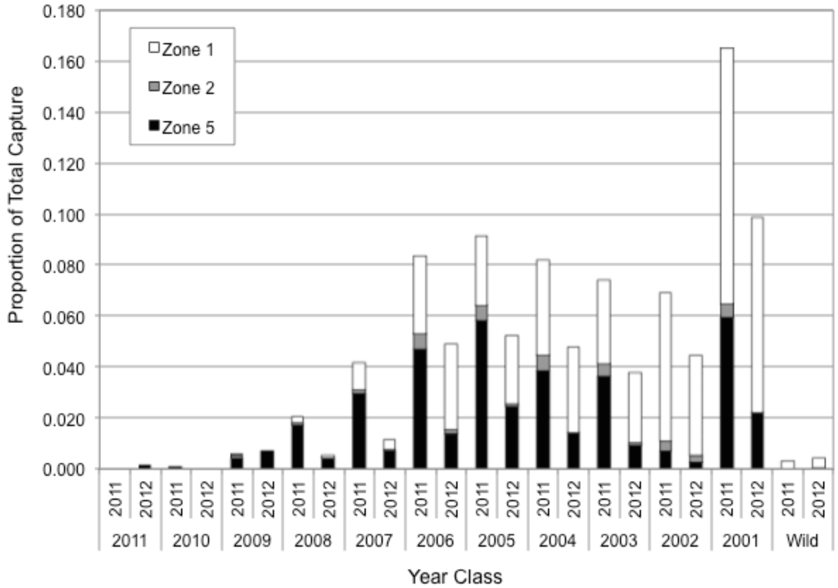

Figure 15. Proportion of total juvenile White Sturgeon capture by brood year class within the LCR for each sampling zone (1, 2, and 5) across the years of 2011 and 2012. Year class of hatchery origin fish was determined by external mark of removed lateral scutes and PIT tag. Wild fish are of natural reproduction and unknown age.

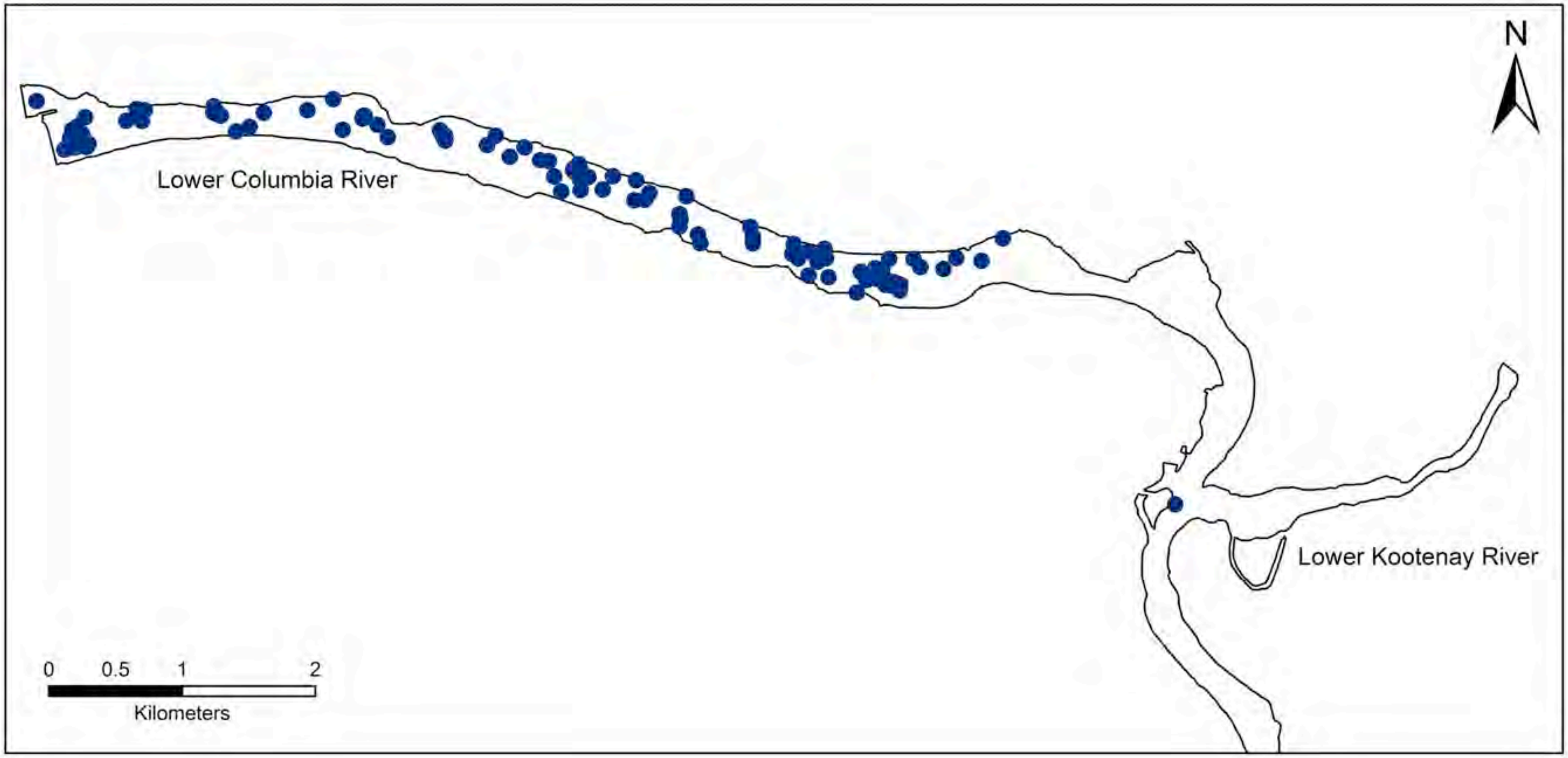

Figure 16. Juvenile White Sturgeon distribution in zone 1 based on locations of sampling effort and fish capture during 2011 and 2012.

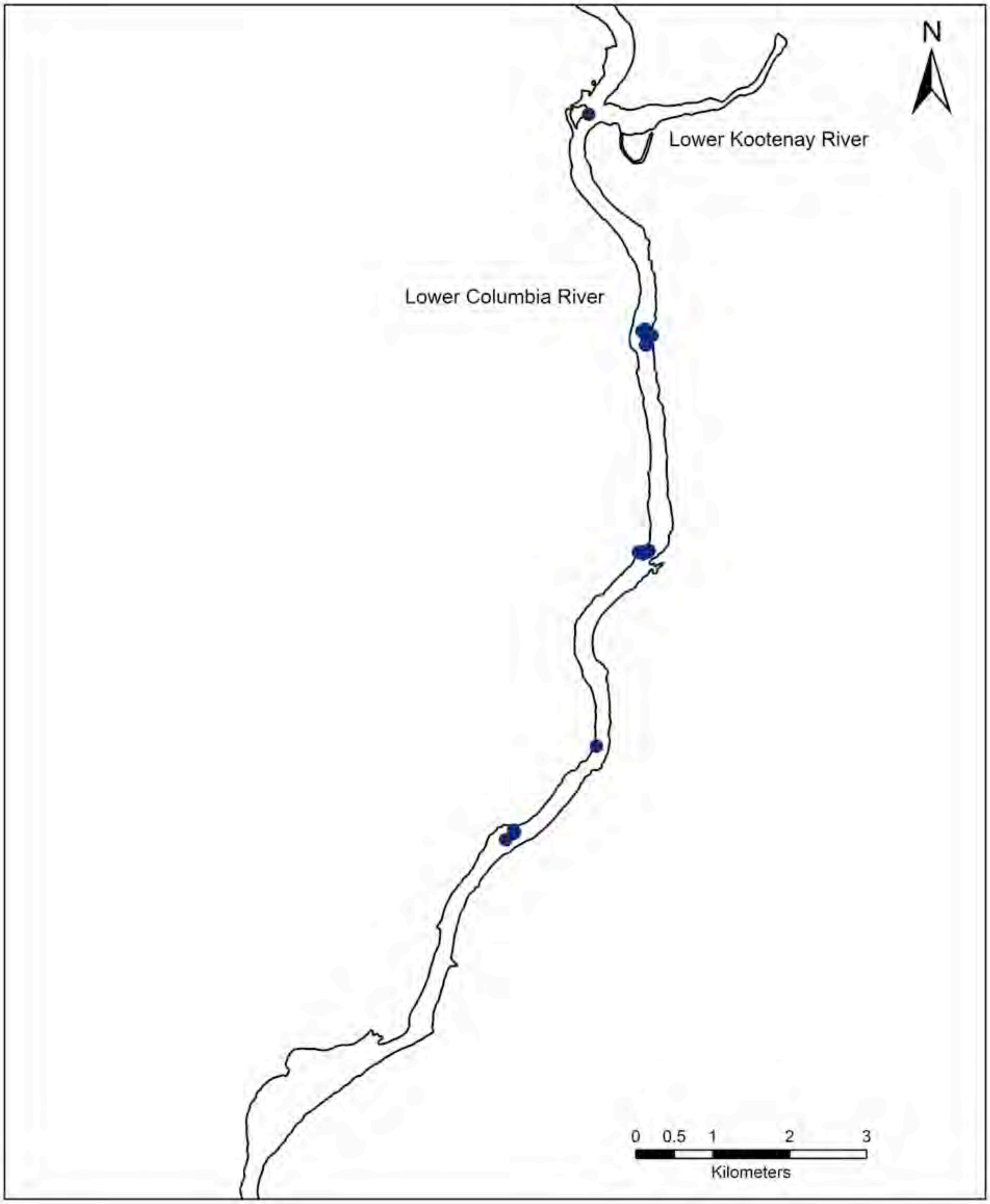

Figure 17. Juvenile White Sturgeon distribution in zone 2 based on locations of sampling effort and fish capture during 2011 and 2012.

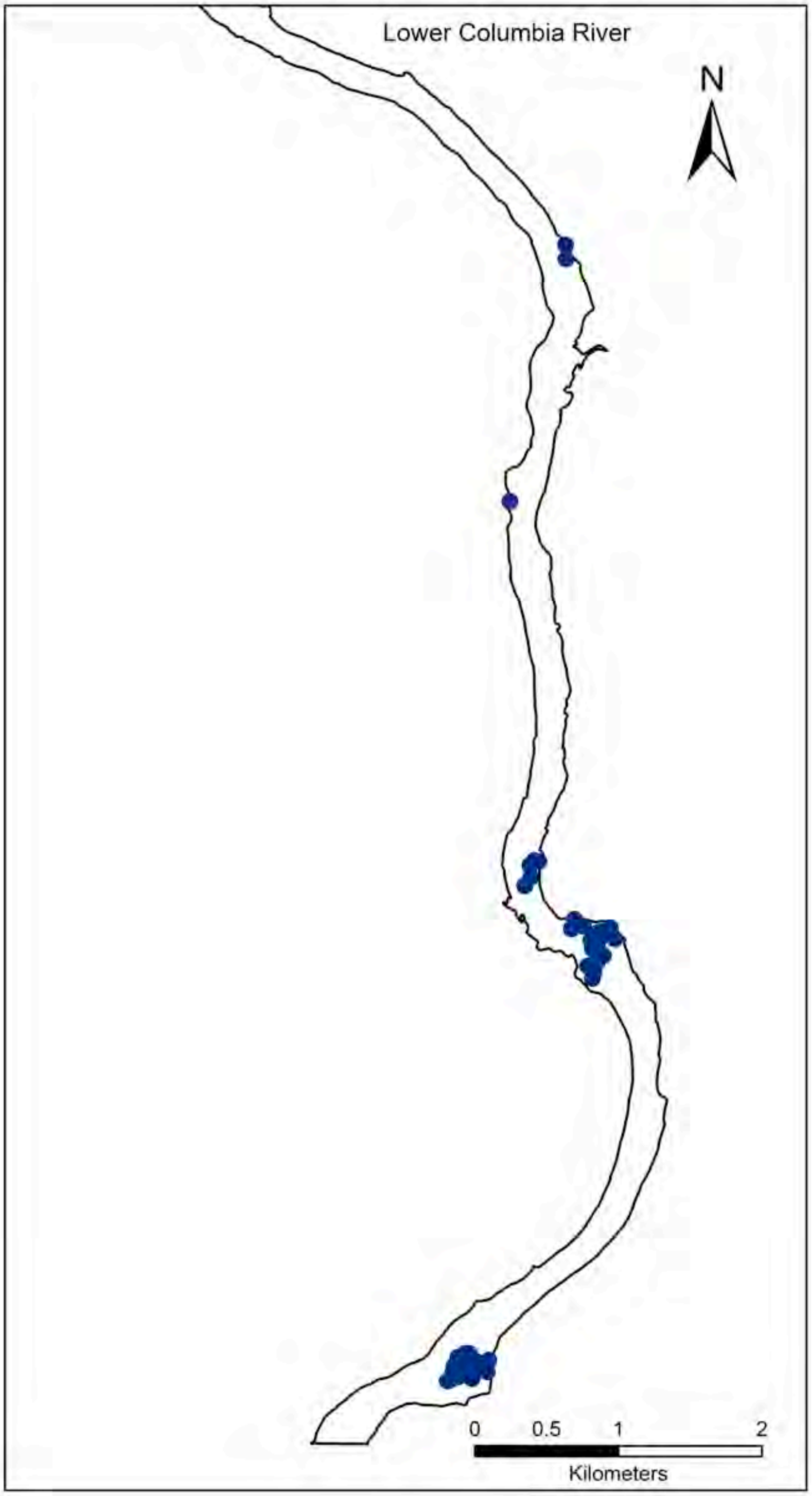

Figure 18. Juvenile White Sturgeon distribution in zone 5 based on locations of sampling effort and fish capture during 2011 and 2012.

3.4.1.2 Fork Length, Weight, Relative Weight, and Growth

3.4.1.2.1 Fork Length

Mean (±SD) fork length (FL; cm) of juveniles collected in 2011 and 2012 was 81.0 ± 17.3 cm and 87.5 ± 16.8 cm, respectively (Table 14). FL for each year class (Table 14), age class (Figure 19), capture method (Figure 20) and capture zone (Figure 21) is provided below. FL of fish captured on set lines were significantly larger than fish captured by means of angling and gill nets ($F_{2,\ 1631}$ = 39.56, $P<0.0001$; Table 15). FL of fish captured in sampling zone 1 was significantly larger than fish captured in zones 2 and 5 ($F_{2,\ 1631}$ = 548.5357, $P<0.0001$; Table 15).

Table 14. Mean (±SD) fork length (cm) by brood year class of juvenile White Sturgeon captured in the LCR during 2009 through 2012. Year class of hatchery origin fish was determined by external mark of removed lateral scutes and PIT tag. Wild fish are of natural reproduction and unknown age.

Year Class	2009	2010	2011	2012
2011	-	-	-	46.5 ± 13.6
2010	-	-	48.0 ± 0.7	-
2009	-	66.5 ± 13.5	49.3 ± 6.4	55.7 ± 3.5
2008	46.0 ± 11.3	37.5 ± 6.4	58.3 ± 7.0	66.9 ± 5.1
2007	45.9 ± 4.3	51.5 ± 2.1	63.4 ± 7.3	65.2 ± 7.4
2006	54.7 ± 7.1	52.5 ± 3.4	69.5 ± 9.5	77.5 ± 7.7
2005	59.0 ± 5.8	59.1 ± 8.2	71.8 ± 9.2	78.7 ± 8.6
2004	67.8 ± 8.8	63.0 ± 8.1	82.1 ± 10.7	85.1 ± 8.0
2003	67.2 ± 6.5	73.2 ± 14.5	83.5 ± 12.2	89.8 ± 11.6
2002	79.3 ± 14.1	95.5 ± 13.9	95.9 ± 12.0	101.2 ± 11.4
2001	75.9 ± 12.6	87.6 ± 17.9	91.6 ± 17.5	96.9 ± 15.9
Wild	-	91.5 ± 3.5	131.7 ± 6.1	113.5 ± 21.8
All	66.5 ± 13.5	76.2 ± 19.0	81.0 ± 17.3	87.5 ± 16.8

Table 15. Mean (±SD) fork length (FL; cm) of juvenile White Sturgeon captured in the LCR in both 2011 and 2012 by sampling method (set line, angling, and gillnet) and sampling zone (1, 2, and 5). Factors not connected by the same letter are significantly different.

Method	FL (cm)	
Set line	88.2 ± 17.75	A
Angling	81.7 ± 16.85	B
Gill Net	73.9 ± 12.08	C
Zone	**FL (cm)**	
1	92.7 ± 14.00	A
2	76.5 ± 12.91	B
5	70.9 ± 12.83	C

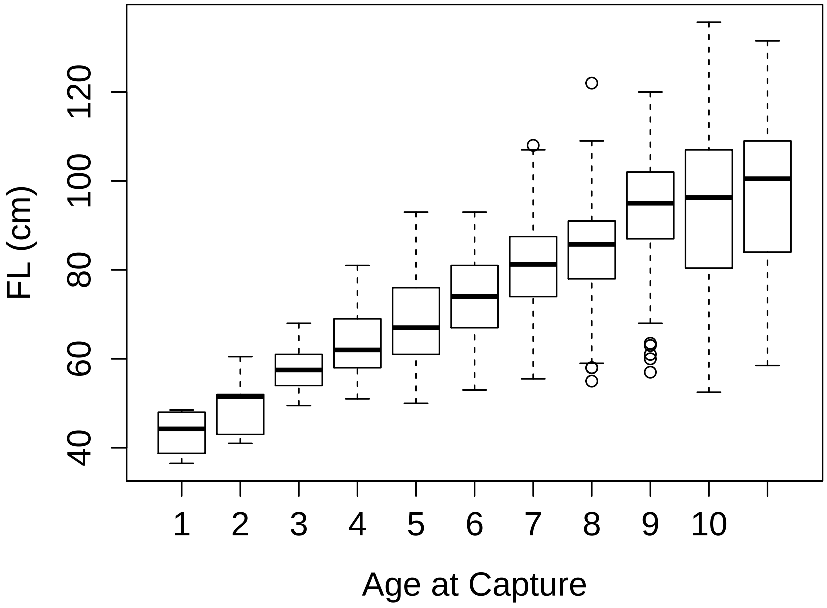

Figure 19. Fork length (cm) of juvenile White Sturgeon by age class captured in the LCR during 2011 and 2012. Year class of hatchery origin fish was determined by external mark of removed lateral scute and PIT tag.

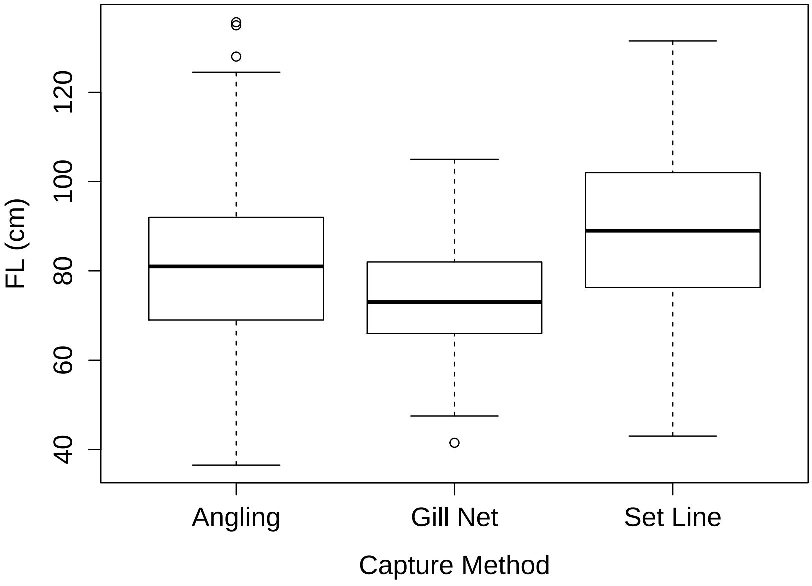

Figure 20. Fork length (FL, cm) of juvenile White Sturgeon captured in the LCR by capture method (angling, gill net, and set line) during 2011 and 2012. Gill net sampling was not conducted in 2012.

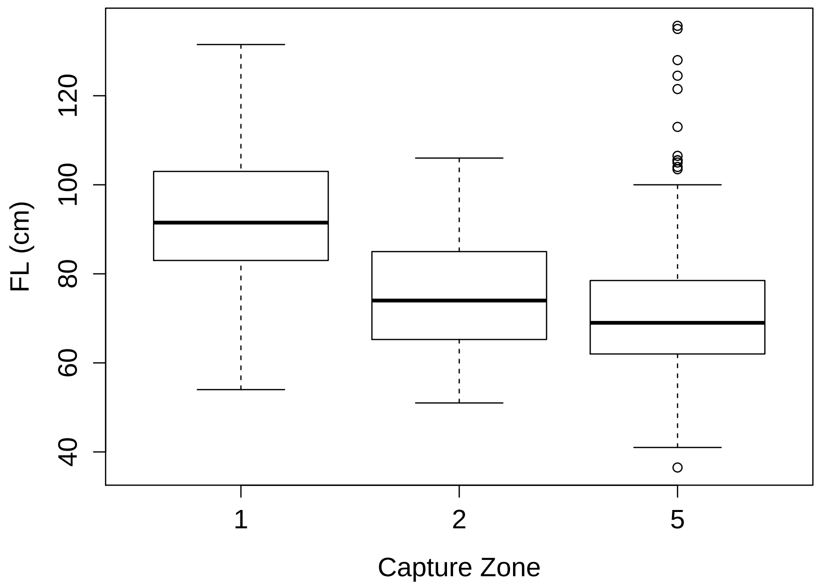

Figure 21. Fork length (cm) of juvenile White Sturgeon captured in the LCR by sampling zone (1, 2, and 5) during 2011 and 2012.

3.4.1.2.2 Weight

Mean weight (kg) of juveniles collected in 2011 and 2012 was 4.05 ± 2.76 and 4.72 ± 2.77 kg, respectively (Table 16). Weight of juveniles by each year class (Table 16), age class (Figure 22), capture zone (Figure 23), and capture method (Figure 24) is provided below. Weight of fish captured on set lines were significantly larger than fish captured by means of angling and gill nets ($F_{2, 1631}$ = 37.7857, $P<0.0001$; Table 17). Weight of fish captured in sampling zone 1 was significantly larger than fish captured in zones 2 and 5 ($F_{2, 1631}$ = 385.9517, $P<0.0001$; Table 17).

Table 16. Mean (±SD) weight (kg) of juvenile White Sturgeon captured in the LCR during 2009 through 2012 by brood year class. Year class of hatchery origin fish was determined by external mark of removed lateral scutes and PIT tag. Wild fish are of natural reproduction and unknown age.

Year Class	2009	2010	2011	2012
2011	-	-	-	0.72 ± 0.71
2010	-	-	0.58 ± 0.04	-
2009	-	0.35 ± 0.00	0.73 ± 0.26	1.15 ± 0.22
2008	0.63 ± 0.46	0.80 ± 0.07	1.21 ± 0.38	1.77 ± 0.41
2007	0.50 ± 0.21	0.81 ± 0.20	1.60 ± 0.67	2.22 ± 0.63
2006	1.01 ± 0.40	1.43 ± 0.68	2.31 ± 1.08	3.21 ± 0.92
2005	1.28 ± 0.40	1.66 ± 0.75	2.52 ± 1.04	3.13 ± 1.09
2004	1.83 ± 0.94	2.65 ± 1.13	3.80 ± 1.62	3.94 ± 1.18
2003	1.95 ± 0.65	3.18 ± 2.15	4.12 ± 1.84	5.06 ± 1.86
2002	3.41 ± 2.08	6.28 ± 2.39	6.24 ± 2.20	6.85 ± 2.32
2001	3.24 ± 1.90	5.19 ± 2.95	5.91 ± 3.13	6.26 ± 2.84
Wild	-	5.30 ± 0.64	14.89 ± 2.60	6.41 ± 5.98
All	2.09 ± 1.58	3.55 ± 2.74	4.05 ± 2.76	4.72 ± 2.77

Table 17. Mean (±SD) weight (kg) of juvenile White Sturgeon captured in the LCR in both 2011 and 2012 by sampling method (set line, angling, and gillnet) and sampling zone (1, 2, and 5). Factors not connected by the same letter are significantly different.

Method	Weight (kg)	
Set line	5.03 ± 2.93	A
Angling	4.03 ± 2.71	B
Gill Net	2.86 ± 1.51	C
Zone	**Weight (kg)**	
1	5.59 ± 2.62	A
2	3.14 ± 1.79	B
5	2.56 ± 1.82	B

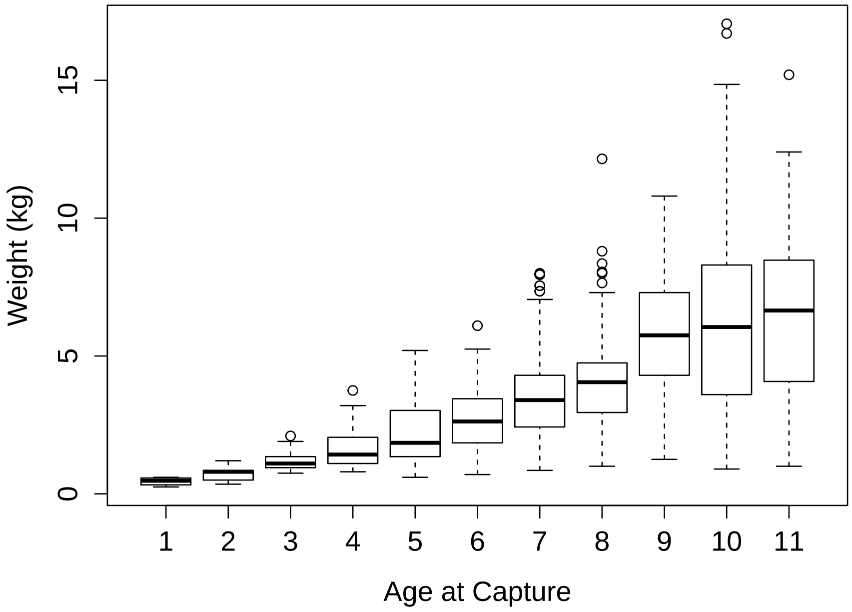

Figure 22. Weight (kg) of juvenile White Sturgeon by age class captured in the LCR during 2011 and 2012. Year class of hatchery origin fish was determined by external mark of removed lateral scute and PIT tag.

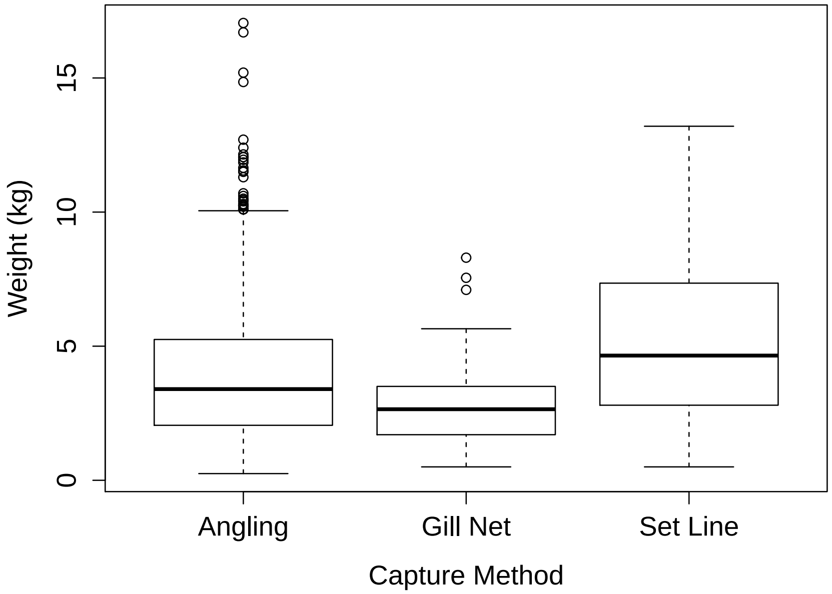

Figure 23. Weight (kg) of juvenile White Sturgeon captured in the LCR by capture method (angling, gill net, and set line) during 2011 and 2012. Gill net sampling was not conducted in 2012.

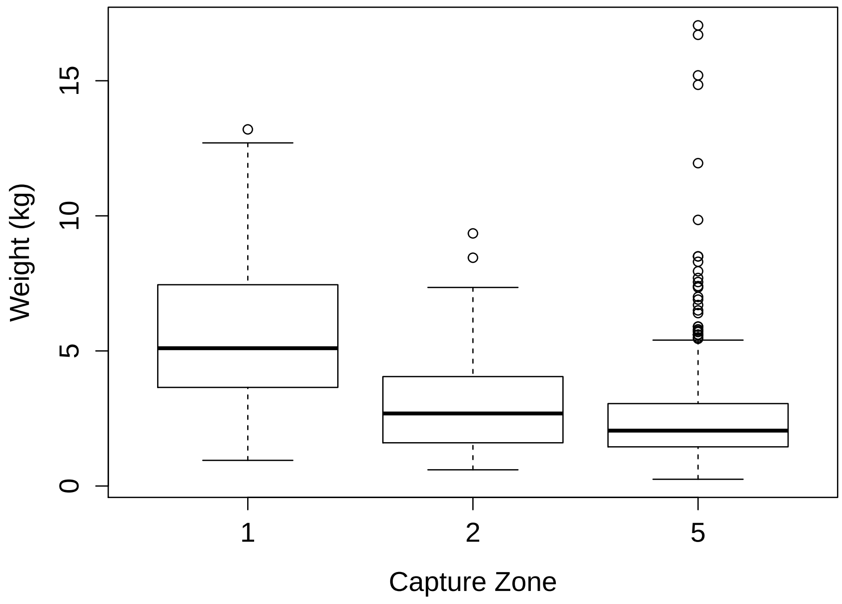

Figure 24. Weight (kg) of juvenile White Sturgeon captured in the LCR by sampling zone (1, 2, and 5) during 2011 and 2012.

3.4.1.2.3 Relative Weight

Mean relative weight (W_r) for juveniles captured in 2011 and 2012 was 86.63 ± 8.50 and 82.15 ± 8.47 (Table 18; Figure 25). Mean W_r for juveniles captured in zones 1, 2, and 5 was 85.14 ± 8.14, 83.88 ± 11.92 and 85.14 ± 9.16 (Figure 26). W_r was significantly different between age class ($F_{10, 1623}$ = 4.7842, P<0.0001; Table 19) and not significantly different between sampling zones ($F_{2,1631}$ = 0.5439, P = 0.5806; Table 19).

Table 18. Mean (±SD) relative weight (W_r) of juvenile White Sturgeon by brood year class captured in the LCR during 2009 through 2012. Year class of hatchery origin fish was determined by external mark of removed lateral scutes and PIT tag. Wild fish are of natural reproduction and unknown age.

Year Class	2009	2010	2011	2012
2011	-	-	-	87.51 ± 5.19
2010	-	-	77.61 ± 8.45	-
2009	-	115.40 ± 60.57	87.18 ± 9.11	90.20 ± 12.98
2008	86.70 ± 1.04	85.81 ± 3.83	84.57 ± 9.14	75.71 ± 5.80
2007	75.08 ± 12.87	81.62 ± 16.21	84.12 ± 9.70	81.43 ± 5.51
2006	89.69 ± 29.04	91.91 ± 9.02	87.42 ± 9.54	83.53 ± 9.77
2005	87.58 ± 15.96	87.54 ± 9.16	86.78 ± 8.01	81.17 ± 8.93
2004	75.83 ± 12.60	86.69 ± 90.14	84.11 ± 8.94	80.31 ± 7.24
2003	86.01 ± 16.14	86.34 ± 8.69	86.23 ± 7.82	81.87 ± 9.50
2002	82.41 ± 9.81	86.34 ± 8.69	87.05 ± 7.25	80.41 ± 6.54
2001	90.29 ± 23.69	89.30 ± 11.83	88.52 ± 7.81	83.85 ± 7.82
Wild	-	88.50 ± 0.40	75.57 ± 1.55	76.25 ± 5.48
All	85.22 ± 19.69	88.32 ± 11.22	86.63. ± 8.50	82.15 ± 8.47

Table 19. Mean relative weight (W_r) of juvenile White Sturgeon by age class captured in the LCR in both 2011 and 2012. Age class of hatchery origin fish was determined by external mark of removed lateral scute and PIT tag. Factors not connected by the same letter are significantly different.

Age	W_r			
1	83.50	A	B	C
2	87.26	A	B	C
3	86.04	A	B	C
4	83.09		B	C
5	86.71	A	B	
6	85.62	A	B	
7	82.99			C
8	83.89		B	C
9	85.22	A	B	C
10	86.81	A		
11	83.82		B	C
Zone	W_r			
1	85.14	A		
2	85.13	A		
5	84.05	A		

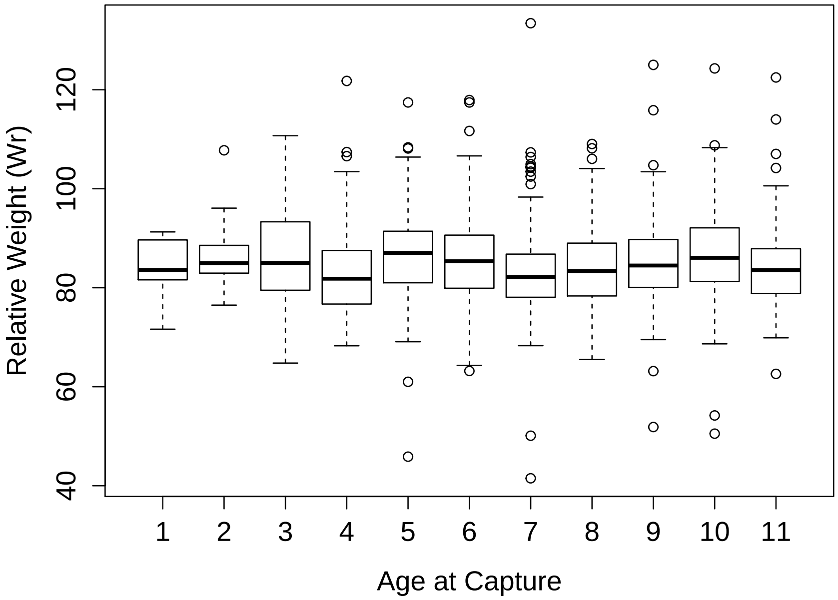

Figure 25. Relative weight (W_r) of juvenile White Sturgeon captured in the LCR by sampling zone (1, 2, and 5) during 2011 and 2012. Year class of hatchery origin fish was determined by external mark of removed lateral scute and PIT tag.

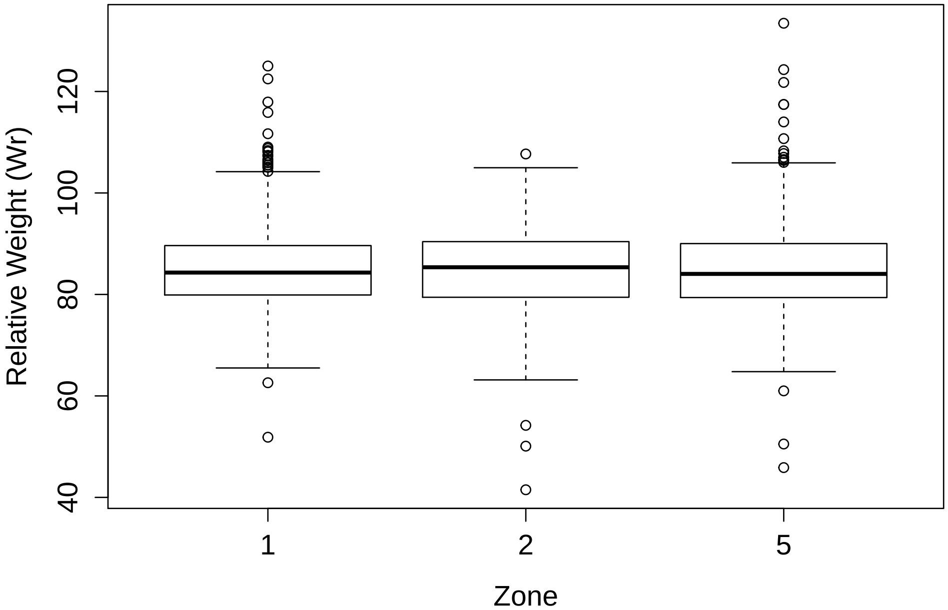

Figure 26. Relative weight (W_r) of juvenile White Sturgeon captured in the LCR by sampling zone (1, 2, and 5) during 2011 and 2012.

3.4.1.2.4 Growth

The relationship that best described juvenile White Sturgeon length-at-age was the von Bertalanffy growth equation (Figure 27):

$$L_t = 142.97\left(1 - e^{-0.084(t-2.68)}\right)$$

The length-weight relationship was described by the model (Figure 28):

$$W = 2.96e^{-6} \times TL^{(3.176)}$$

As with the length-at-age relationship, this weight-length relationship predicted faster growth in length at younger ages (Figure 29) and faster growth in weight at later ages (Figure 30). The model results are similar to relationships present for the LCR in 2009/2010 (BC Hydro 2013a) and other White Sturgeon populations (Beamesderfer 1993).

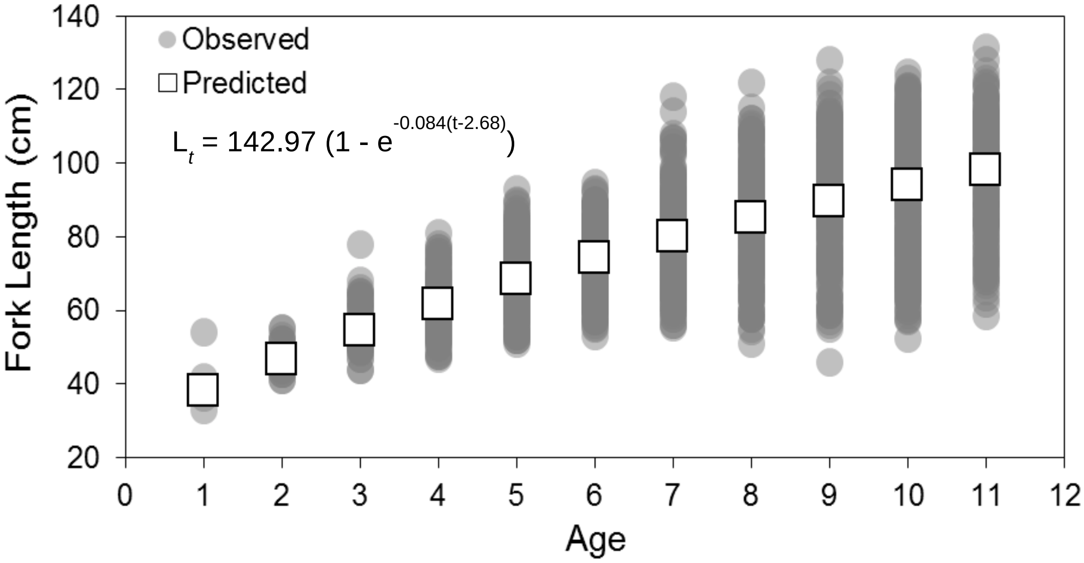

Figure 27. Length-at-age relationship and von Bertalanffy growth equation for juvenile White Sturgeon captured in the LCR during 2011 and 2012.

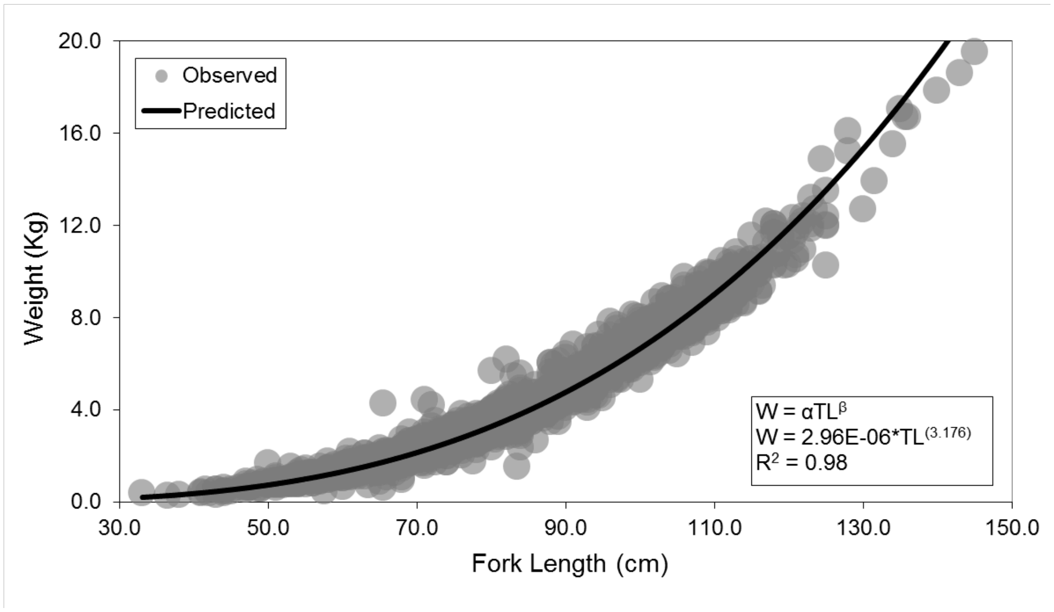

Figure 28. Observed and predicted length-weight relationship and equation for juvenile White Sturgeon captured in the LCR in 2011 and 2012.

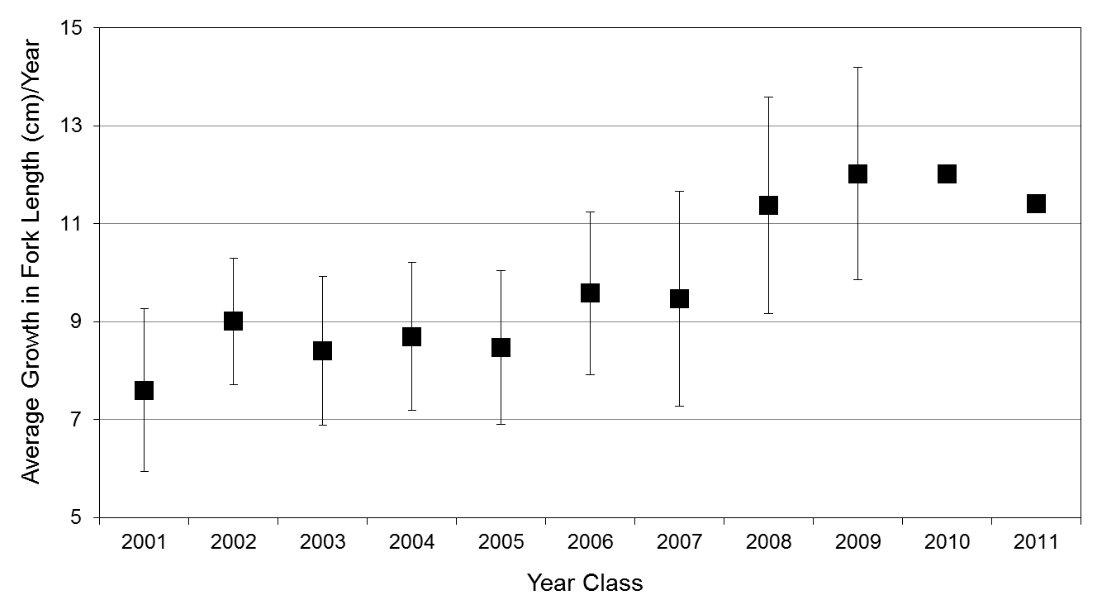

Figure 29. Fork length growth (cm/year) since release by brood year class for juvenile White Sturgeon captured in the LCR in 2011 and 2012. Year class of hatchery origin fish was determined by external mark of removed lateral scute and PIT tag.

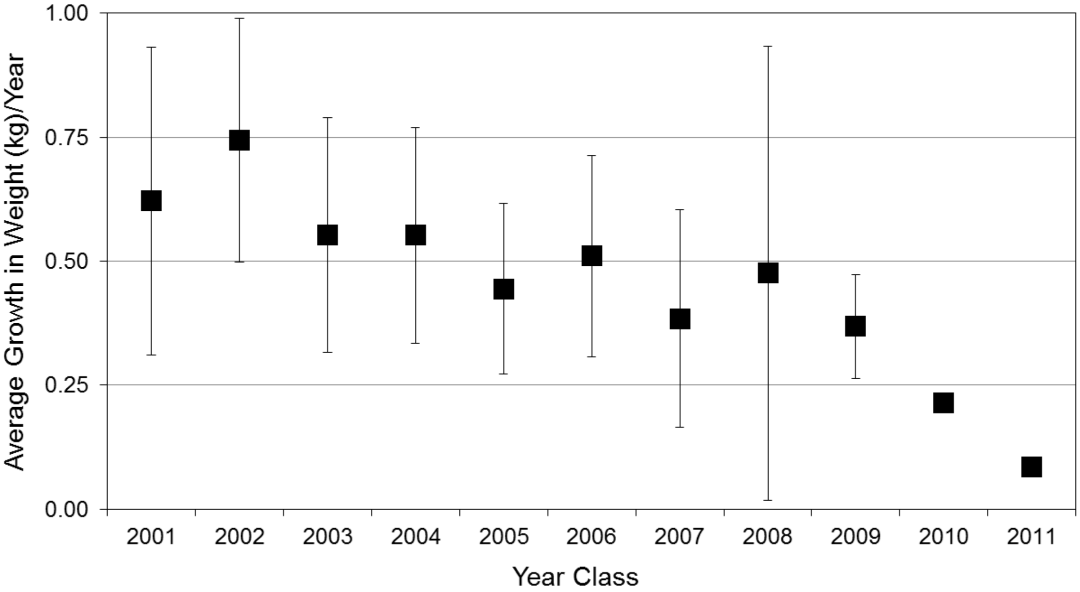

Figure 30. Growth (kg/year) in weight since release by brood year class for juvenile White Sturgeon captured in the LCR in 2011 and 2012. Year class of hatchery origin fish was determined by external mark of removed lateral scute and PIT tag.

3.4.2 Age Structuring

We evaluated where sections should be removed from pectoral fin rays to determine the optimal location for future ageing studies and to examine the potential for introducing additional error into the estimated age. We evaluated fin rays from large and small individuals. On the larger (127 mm) fin ray, the first annulus (nucleus) was visible 11 mm from the base. However, the outer annuli were crowded and hard to distinguish. By 18 mm from the base, the first annuli was still well defined, and outside annuli were easy to distinguish. By 25 mm from the base, the first annuli could not be seen. By 43 mm from the base, the second annuli also began to fade. By 61 mm from the base, sections were entirely unreadable. On the smaller (80 mm) fin ray, the first annuli became visible 11 mm from the base. The first annulus was lost 20 mm from the base. The notable optimal location on both fin rays was ~2 mm distal from the curvature inflection point (where the fin ray “straightens”, ~18 mm from the knuckle). Because fin ray size varies between fish, we used the curvature inflection point as a marker (instead of distance from the base) location going forward with mass ageing.

We found that mean (± 1 SD) aging error across all age classes evaluated overestimated true age by 1.09 ± 0.81 years since hatch (Table 20). Ageing error decreased with increasing age and was highest at the youngest ages examined (3-6 years; Figure 31). Error was explained significantly by reader, with the mean difference in age estimates between readers being 1.39 years (range 0 to 3.5 years). Fish size only explained a marginal amount of the variation observed and while growth rate is known to differ by habitats used, ageing error did not reflect this (Figure 32). Low confidence in ages estimated from pectoral fin rays of White Sturgeon continues to complicate recovery as this structure represents the only nonlethal method to age sturgeon.

Table 20. Mean (±1 SD) difference (years) in the assigned age based on pectoral fin ray sections from the true age of hatchery-reared juvenile White Sturgeon. Assigned age is compared to known age from the general year class marking, the age since hatch, and age since release from the hatchery.

	Year Class	Since Hatch	Since Release
Mean (±1 SD)	+1.20 (0.91)	+1.09 (0.81)	+1.57 (1.10)

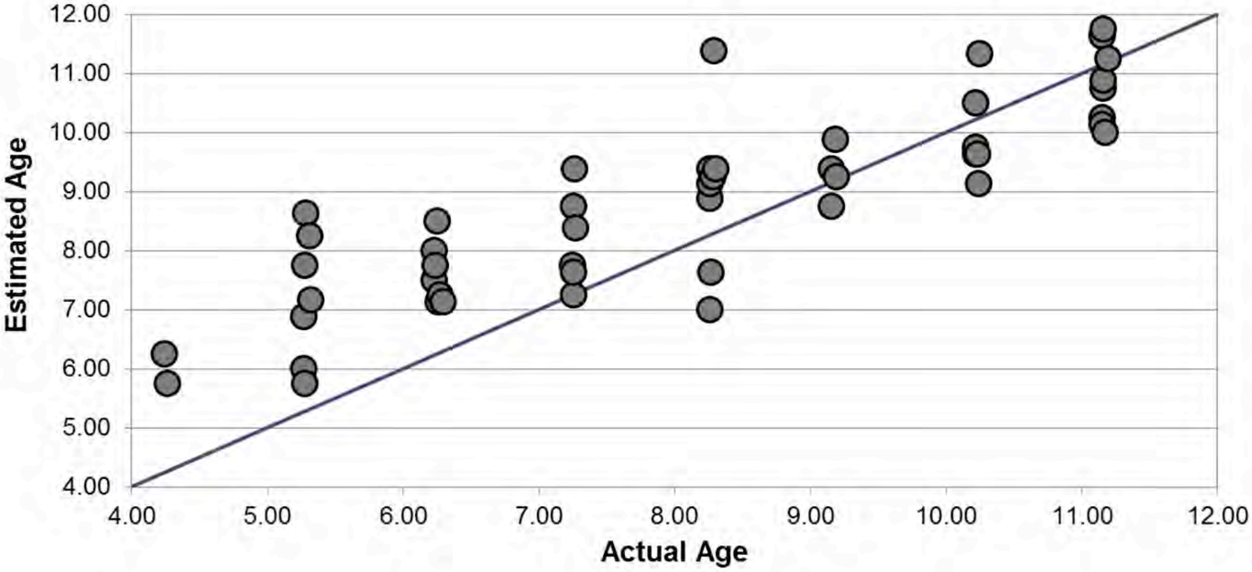

Figure 31. Estimated age from pectoral fin ray sections compared to the actual age for known age hatchery-reared juvenile White Sturgeon captured in the LCR in 2012.

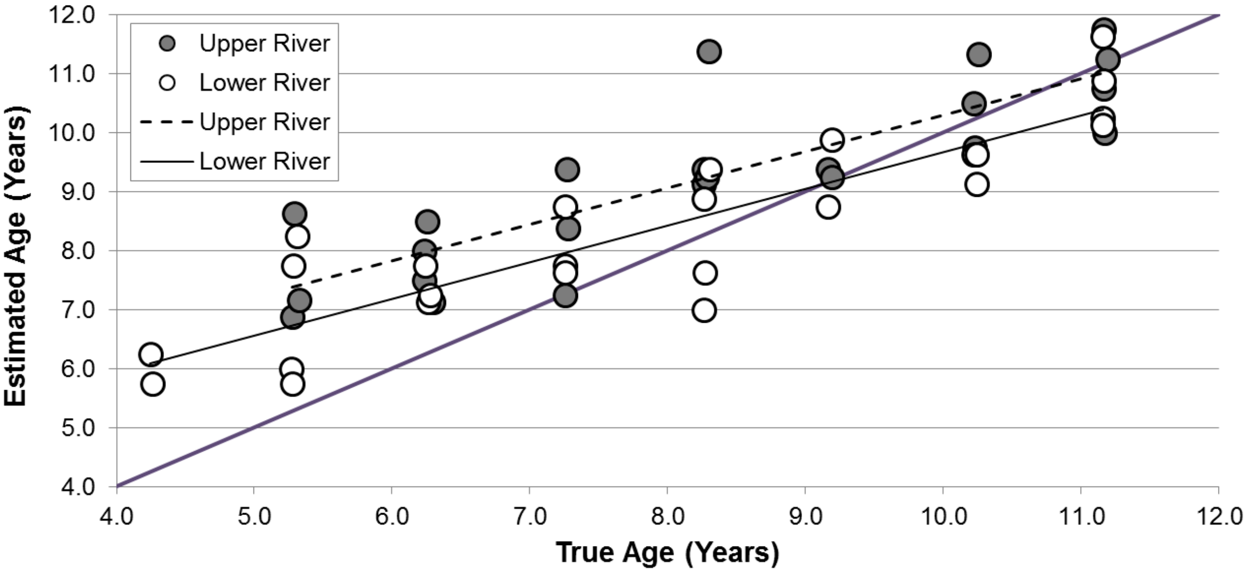

Figure 32. Estimated age from pectoral fin ray sections compared to the actual age for known age hatchery-reared juvenile White Sturgeon caught in upper (Zone 1) and lower (Zone 5) sections of the LCR in 2012.

3.4.3 Diet Assessment

Evaluation of the composition and prey selection in the diet of juveniles are currently being completed. Once all data analyses are complete, we will have compared the reliability of non-lethal gastric lavage to lethal sampling and determine level of confidence when assessing seasonal or annual diet trends. We will also attempt to describe how variability in the diet is proportioned, whether a function of food availability or habitat choice.

3.5 Habitat Mapping

Recorded images have been edited and processed identifying ten acoustic substrate classes. Detailed results of analyses are provided in Appendix 1. Image processing identified ten acoustic substrate classes. Ground truthing will be required to identify specific riverbed sediment types (e.g., cobble, gravel, sand) represented by each acoustic class.

4 DISCUSSION

While this report is primarily a data report, general discussion points are provided for each of the main areas of this monitoring program. Results are discussed in the context of the monitoring program objectives, however they should be interpreted with caution as they represent only the early years of this program. While this monitoring program has contributed significant knowledge pertaining to larval and juvenile White Sturgeon ecology and the overall success of the

Conservation Aquaculture Program, additional years of data are required to assess trends and answer the management questions of this program.

4.1 Yolk Sac Larval Assessment

For White Sturgeon throughout their range, it has generally been observed that the spawning period is protracted and occurs in the late spring and early summer months (May through early August) with specific timing dependent on environmental cues (e.g., temperature, flows; Parsley and Beckman 1994). Based on developmental stages of collected YSL, spawning was estimated to have occurred from early to late July at the downstream location of Waneta and early August at the upstream location of ALH in 2011 (Figure 10). In 2012, spawning was estimated to have occurred from early to mid July at the downstream site of Waneta (Figure 11). Despite sampling effort consistent with previous years, no YSL were collected upstream therefore spawning duration could not be estimated. The timing and duration of spawning activity for both years is similar to past years, with the majority of estimated spawning days occurring on the descending limb of the hydrograph and at water temperatures above 14ºC (Golder 2012).

In 2011, dispersing larvae were again collected within the vicinity of Kinnaird, which has now had spawning documented annually since 2007. However, the exact location of the spawning area (egg deposition) remains unknown and should be of focus in the next several years of this program. For spawning areas where the exact geographical location is uncertain, drift nets are the most effective tool to collect larval White Sturgeon as they can represent all areas upstream of the sampling location. While egg mats are used once the main areas of egg deposition have been identified, drift nets should be used primarily when attempting to assign a general location where spawning may be occurring. To address the objectives of this program as it relates to describing new spawning areas or determine the distribution of larvae, it is recommended that use of egg mats be restricted to Waneta, and that drift nets are the primary technique used in areas where spawning locations are uncertain (e.g., Kinnaird). Once geographical boundaries of the spawning location can be described, a monitoring program that includes the use of egg mats should be developed consistent with other locations (e.g., Waneta (Golder 2013) or Revelstoke (AMEC 2014)).

Reduced quality of early life stage habitat used for egg incubation and early rearing of larvae is one of the recruitment failure hypotheses for this population. Larvae that are young in development have dominated the collections to date across all spawning locations in Canada, suggesting the substrates at the spawning locations are not adequate for hiding until they reach feeding age. Describing spawning and early life stage habitat at known (e.g., Waneta, ALH) and suspected (e.g., Kinnaird) spawning locations is important to determine habitat suitability for YSL burrowing behaviour and young-of-year rearing conditions and the potential effects of habitat on recruitment. Further, it will be important to incorporate results from larval monitoring programs in the US section of the TRA, as captures of larvae at feeding stages occur annually (Hildebrand and Parsley 2013). These results suggest that hiding habitat is present between the Waneta spawning location and the capture location downstream of Northport WA. Possible genetic analyses could determine the proportion of larvae that originated from the Waneta location and should be considered if data are available in future years.

4.2 Temperature Effects on Development

While results of this work are preliminary, describing thermal induced responses in the development of White Sturgeon YSL is important to understanding recruitment processes and natural adaptability in altered systems, and can be used as a management tool to increase understanding of White Sturgeon reproductive ecology. Data from this study will provide a tool to more confidently assign developmental stage and estimate age of larvae collected in the wild. This will help describe the timing of spawning for areas where larvae are primarily collected (e.g., Kinnaird area) and add an additional level of detail for other spawning locations (e.g., Waneta). Results from this study will also serve as a useful management tool providing insight into YSL behaviour and White Sturgeon reproductive ecology, enhancing recovery planning and Conservation Aquaculture Programs.

4.3 Juvenile Population Assessment

For approximately the last 40 years, recruitment of White Sturgeon in the Transboundary Recovery Area (TRA) of the Columbia River (Hugh L. Keenleyside Dam (HLK) to Grand Coulee Dam (GCD) in WA, USA) has not occurred at a rate sufficient to maintain the population. In response to this, the Upper Columbia White Sturgeon Recovery Initiative (UCWSRI) was formed in 2000, and developed a Recovery Plan, a key component of which is the supplementation of the existing White Sturgeon population through broodstock collections, hatchery rearing, and stocking of juvenile White Sturgeon (UCWSRI 2002).

In total, 130,636 hatchery-reared juvenile White Sturgeon have been released into the TRA from 2002 to 2012 (yearly releases ranging from 4,302 in 2012 to 21,603 in 2005). These juveniles are being monitored annually by various agencies (i.e., Golder, BC Hydro, Washington Department of Fish and Wildlife (WDFW)). Results from monitoring indicate that hatchery-reared juveniles are growing and surviving well in the LCR. These juveniles represent a significant learning opportunity as juvenile age classes are lacking in many sturgeon populations throughout the world. Though this program serves as a means of identifying wild juveniles, they remain rarely encountered and represent < 1% of the total catch to date since the monitoring program began. One of the management questions of this work is to evaluate how normal river operations affect juvenile habitat conditions in the LCR. In the first 5 years of this program, we have used a spatially balanced and randomly assigned sampling design and documented habitat use throughout the entire LCR. Results suggest that habitat is characterized primarily by deep slow moving water and smaller substrates (e.g., sand, gravel, cobbles). These habitats are available throughout the upper section of the river and become more isolated further downstream (e.g., Kootenay River confluence to the US Border). These deeper slow moving habitats are not limited by the current operational regime of the LCR. Importantly, juvenile habitat distribution is similar to, and overlaps with, adult habitat use (described in BC Hydro, 2013b and 2015).

While monitoring studies to date have provided data regarding the distribution, growth, and condition of the hatchery-reared juvenile sturgeon, data and analysis regarding their survival have been limited. The next steps of this program will be to develop a dataset that includes juvenile captures throughout the TRA to provide a preliminary analysis of hatchery reared juvenile White Sturgeon population abundance and survival estimates, similar to other populations (Justice et al. 2009). Results from this work can then be used to guide future aquaculture efforts (e.g., size at release and release numbers) and management decisions (long-term population targets).

4.4 Age Structuring

While the management questions for this program are generally operationally focused; this program also serves as the sole method of detecting wild recruitment. As a result, it is critical that the age of wild juveniles is determined with as much confidence as possible to determine the year they were born. This will allow the operational conditions present in those years with detectable recruitment to be evaluated. The presence of known-age juveniles in the LCR helps to address uncertainties regarding ageing accuracy. We found that mean (± 1 SD) aging error across all age classes evaluated overestimated true age by 1.09 ± 0.81 years since hatch (Table 20). This was similar to the results of Rein and Beamesderfer (1994) and Paragamian and Beamesderfer (2003). Further, ageing error decreased with increasing age and was highest at the youngest ages examined (3-6 years), which is about the age wild juveniles are expected to be encountered in sampling gear. Low confidence in ages estimated from pectoral fin rays of white sturgeon continues to complicate recovery as this structure represents the only nonlethal method to age sturgeon. Describing the source of ageing error will be an important goal of this program in the coming implementation years.

4.5 Diet Assessment

Sturgeon are known to be generalists, however it is important to determine how prey are selected and their relative proportion in the diet of juvenile White Sturgeon compared to their availability in the river. Developing sampling methods that provide more information on prey selectivity at the larger juvenile sizes (>1 m) as they start to compete for sub-adult and adult food sources will be useful for this population. Larger fish (>1.5 m) will likely begin taking advantage of seasonally abundant high quality food resources like Kokanee *Oncorhynchus nerka* or Mountain Whitefish *Prosopium williamsoni* spawners or excavating eggs from Rainbow Trout *Oncorhynchus mykiss* redds (Irvine et al. 2013). Being able to track annual trends in the diet will be important to the long-term management of this population (e.g., identifying density dependent effects on growth) as conservation aquaculture remains the primary form of recovery to replace wild juvenile age classes that have been absent for several decades. Additionally, despite success in implementing flow protection measures to promote native species (e.g., Rainbow Trout and Mountain Whitefish), the aquatic community in the LCR has been altered in the past decade with the invasion of new fish species (e.g., Northern Pike *Esox lucius*, Ford and Thorley 2012) and discussions around reintroduction of salmonid species back into the LCR are underway (details available at www.ucut.org). The addition or deletion of species from a community can have significant effects on the growth rates of fish (Werner et al. 1983) and understanding how resource availability, especially the benthic prey base, is partitioned among competing fish species in the LCR will be important for White Sturgeon recovery. Importantly, determining the reliability of gastric lavage for describing the diet needs to be determined to allow this non-lethal method to be incorporated into more focused sampling designs that acknowledge known biological differences in this population (e.g., growth rates by habitat). Studying the diet to understand the mechanisms associated with differential growth in the river is important to recovery of the LCR White Sturgeon population moving forward, as hatchery reared juveniles are released annually.

4.6 Habitat Mapping

The lower Columbia River (LCR) was surveyed with a sidescan sonar, primarily to map riverbed character to assist in delineating habitat. Raw acoustic data were used to generate maps of riverbed character by segmenting the survey area into regions of homogeneous acoustic character that are acoustically distinct from other regions (e.g. sand, rock, and silt). Appendix 1 outlines in detail the methods followed to analyze the data. Important next steps will be to ground truth the maps produced to produce a final habitat map for the LCR that can be used to identify important areas for White Sturgeon early life stages.

5 RECCOMENDATIONS

The following recommendations are based on sampling results from the first five years of project implementation. Specific recommendations are provided for larval, juvenile, and habitat sampling.

5.1 Larval Sampling

- Larval sampling should continue to occur annually at the HLK/ALH spawning area to determine spawning timing and frequency at this area and if habitat allows for larvae to develop to later developmental stages prior to dispersing downstream.
  - Sampling should start in early July and continue through the middle of August, as the timing of spawning in the upper parts of the LCR is still uncertain.
- Drift nets have been shown to maximize catch per unit effort of eggs and larvae

from spawning locations upstream of the sampling equipment and should be used as the primary collection method in areas where the exact geographical boundary of the spawning location remains unknown.

  - Additional drift net stations should be deployed downstream of Kinnaird to determine where larvae may be originating from.

  - If hydrology permits, drift net sampling should be attempted in the lower Kootenay River to determine if larval captures near Kinnaird could be originating from this location.

- Tissue samples should be collected from as many larval captures as possible to determine how many adults are contributing using molecular methods. If possible, genetic analyses should address if larval captures near Kinnaird are genetically similar to upstream spawning locations (e.g., HLK/ALH spawning area).

5.2 Juvenile Sampling

- Continue to approach juvenile sampling programs in a spatially balanced random design, to acknowledge variability in growth between habitat types (e.g., upstream versus downstream) and age classes.

- As numbers of recaptured individuals increases, survival should be modelled by year class, size-at-release, and age-at-release to allow for models to be revised as additional data is collected going forward. Results from survival estimates should be used to develop abundance estimates for White Sturgeon of hatchery origin in the LCR. This information can be used to revise the Conservation Aquaculture Program and help guide long-term population targets.

- Sampling effort should continue to be focused using setlines as they minimize harm to the individual and can be fished for longer time periods throughout all areas that juveniles have been identified to use in the LCR.

- Describe the diet of juvenile White Sturgeon in the LCR and evaluate the efficiency of gastric lavage in describing juvenile White Sturgeon diet.

- Use known age hatchery-reared juveniles to develop ageing methodology to improve confidence in the ages of wild origin juveniles.

- Continue to monitor habitat use and distribution of juveniles under varying operational scenarios over the life of the monitoring program.

5.3 Habitat Mapping

- Continue to develop a habitat map for the entire LCR. Validate side scan sonar data collected in years 2 and 3 of this study using videography or physical substrate collection (e.g., ponar grabs).

- Describe the spawning and early life stage habitat at key spawning locations (e.g., HLK/ALH and Kinnaird locations). Focus should be given to determining the suitability of the immediate larval hiding habitat and downstream rearing habitat.

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7 Appendix 1: Habitat Mapping – Acoustic Riverbed Classification of the lower Columbia River

SIDESCAN SONAR RIVERBED CLASSIFICATION

Acoustic Riverbed Classification of the lower Columbia River

Prepared for

BC HYDRO

CASTLEGAR

BRITISH COLUMBIA

Jon Preston, PhD

Consultant in Acoustic Seabed Classification

May 2014

TABLE OF CONTENTS

INTRODUCTION

This report describes the classification of the seabed sediments imaged during a survey conducted with a sidescan sonar system in the lower Columbia River, in British Columbia, Canada. The processing tools included QTC SWATHVIEW™ and QTC CLAMS™, and the software package Surfer was used to generate some final figures.

BC Hydro surveyed the lower Columbia River (LCR) with a Tritech Starfish sidescan sonar, primarily to map riverbed character to assist in delineating habitat. Acoustic classification using QTC SWATHVIEW makes maps of riverbed character by segmenting the survey area into regions of homogeneous acoustic character, regions that are acoustically distinct from other regions in practical ways. Sand, rock, and silt, as examples, backscatter sound quite differently. BC Hydro used SWATHVIEW to classify the river from the Keenleyside Dam to the border. Good progress was made. But it was decided to contract final classification to Jon Preston, previously Senior Scientist at QTC and developer of SWATHVIEW. This is a report of that effort.

A series of evolving reports have been sent to the contract authority at BC Hydro in Castlegar. These were flawed in that they all used nine classes with one very dominant class, and should therefore be discarded. This version, May 2014, is the final report with only class labelling yet to be done. After non-acoustic data for class labelling has been provided, this report will be replaced by a truly final version.

DELIVERABLES

1. This report.
2. Seabed files for each habitat group of the LCR and for the Kootenay survey. Seabed files are ASCII file with times, positions, depths, class assignments and other information about each classified point. The format is in an appendix of the User Manual.
3. Xyz files for each habitat group of the LCR and for the Kootenay survey. These ASCII files should be called xyc files because the columns are xy positions and class number. The positions are on an evenly spaced grid, but points with no class assignment are omitted. Assignments have been interpolated from field data using categorical interpolation. Loading xyz files into a GIS requires care to avoid interpolating class numbers again.
4. Tiff and kmz files for each habitat group of the LCR and for the Kootenay survey, The tiff will display as images and are ready to be loaded into ArcGIS. The kmz files display in Google Earth but with an offset from the correct positions.
5. Powerpoint deck of the class maps as layers in ArcGIS.

Positions in all these files are in UTM zone 11N

CLASSIFICATION OF RIVERBED

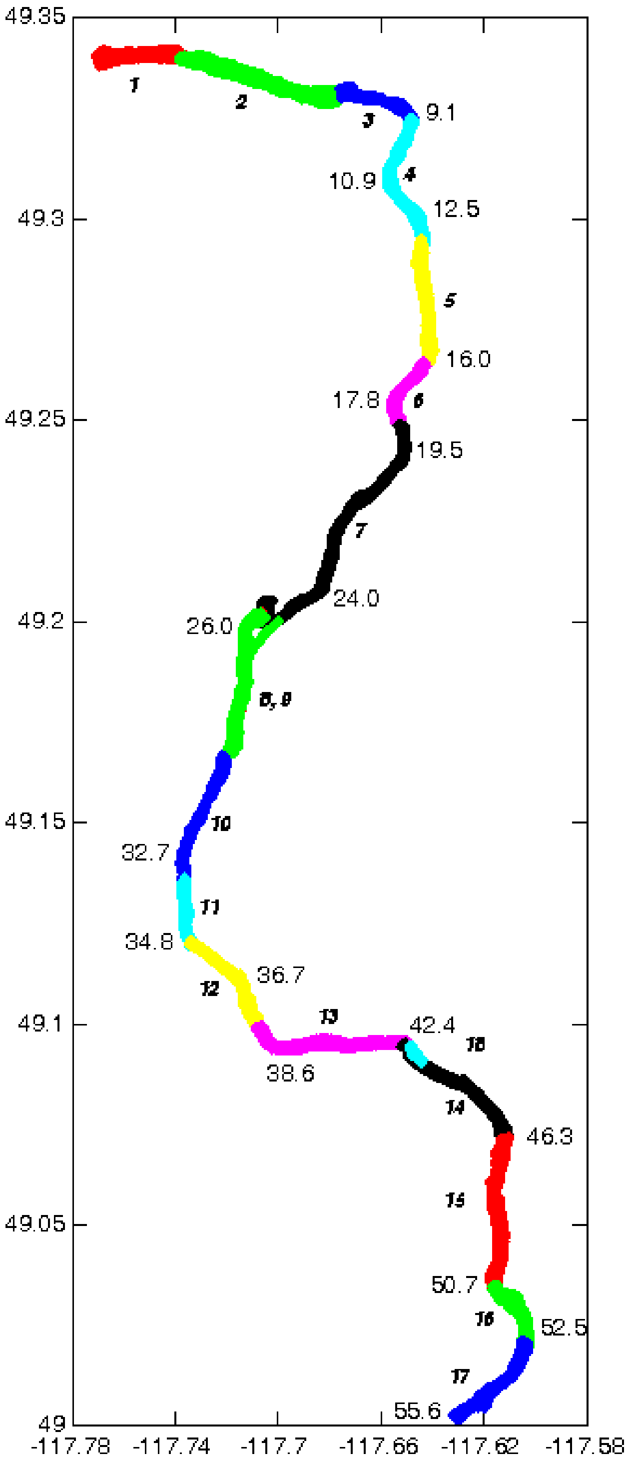


Figure 1. Habitats in LCR. Sections numbered in italics. Decimal numbers are kilometres from Keenleyside Dam.

Survey data

Riverbed images of the entire Columbia River from the Keenleyside dam to the US border were acquired with a Tritech Starfish sidescan sonar. Images and associated data were recorded in XTF format The survey was divided into 18 sections, called habitats, mostly numbered consecutively downstream, as shown in Figure 1 (Habitat 18 is the small cyan-coloured section within habitat 14.).

The survey dates and the number of survey lines (transects) for each of the habitats is listed in Table 1.

Editing bottom picks

Accurate identification of the beginning of the riverbed return is crucial to artifact-free classification. SWATHVIEW has an automated routine for this step, which is called bottom picking. Sometimes, though, manual inspection and editing is needed.

If the sonar passes directly over large rocks or anchors or logging debris, echoes from them can appear in the water column. If they have vertical sides, the image can be black on one side. SWATHVIEW's automated picking can choose the top of these objects. However they are not riverbed and therefore should not be included in classification. Furthermore, the sub-images from which features were calculated include some low-reflectivity regions, making them very different from their neighbours at longer sonar range. In some regions Swathview's pick routine fails to identify the start of the riverbed echo, often because it is continuous with backscatter from the propeller wake. These regions must be picked manually to ensure that no sub-images extend into the propeller wake and to apply the correct altitude to those pings for calculation of grazing angles. As a further aid to ensuring that the sub-images are just riverbed, an offset of 0.5 m from the bottom pick was masked. Rectangles are not placed in masked regions.

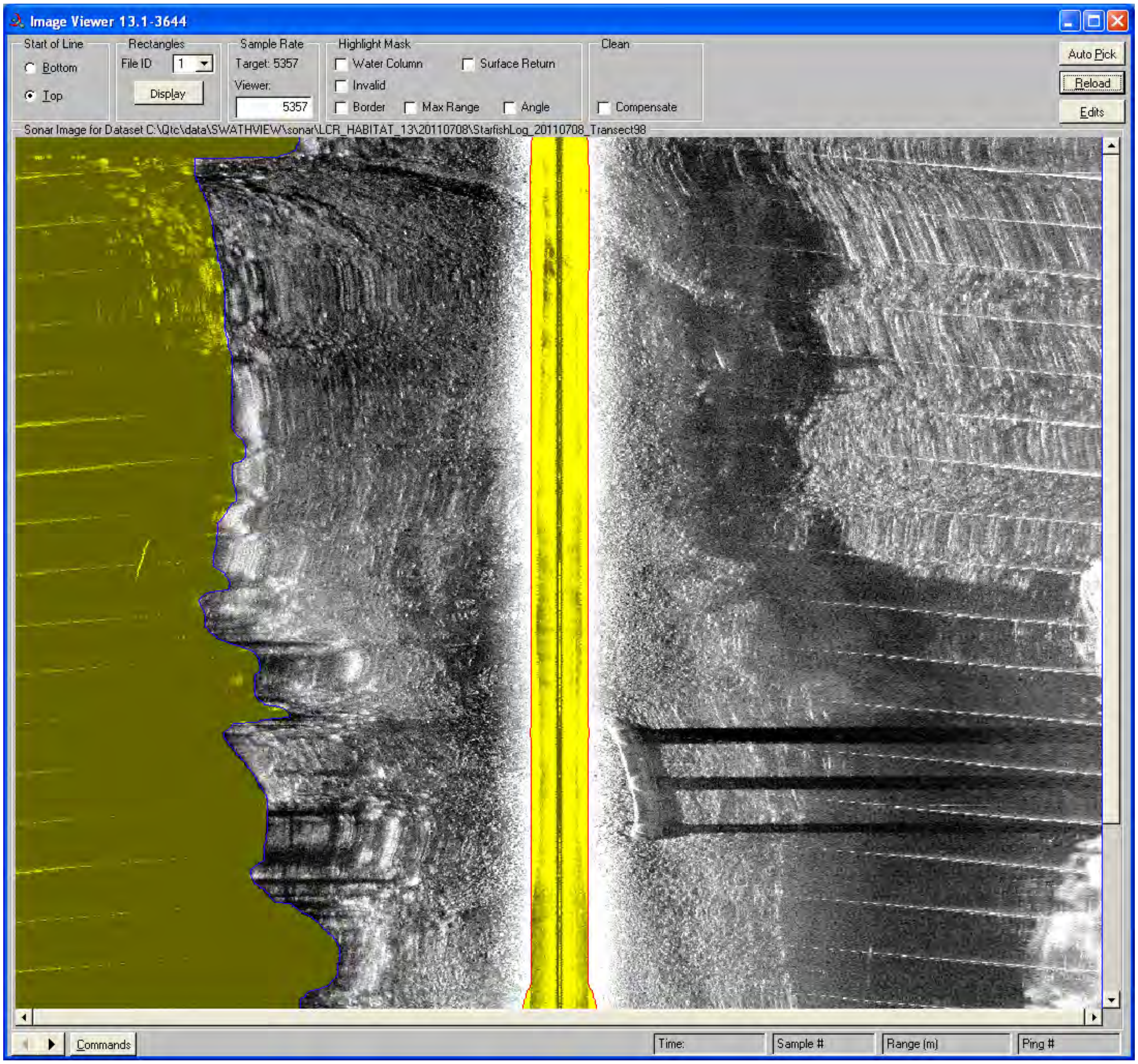
Habitat	Survey Date	Transects
1	16 August 2010	1 - 15
2	16 August 2010	16 - 26
3	17 August 2010	27 - 36
4	17August 2010	37 - 46
5	17 & 18 August 2010	47 - 51
6	18 August 2010	52 - 56
7	18 & 19 August 2010	57 - 70
8	19 August 2010	71 - 76
9	5 July 2011	77 - 81
10	7 July 2011	82 - 85
11	7 July 2011	86 - 88
12	7 July 2011	89 - 94
13	8 July 2011	95 - 98
14	8 July 2011	99 - 102
15	9 July 2011	103 - 106
16	9 July 2011	107 - 114
17	9 July 2011	115 - 119
18	9 July 2011	120 - 122

Table 1. Survey dates.

Setting borders at the edges of uncontaminated riverbed imagery

All through this survey, the sonar range was set to 68 m. Most of this range can be quality riverbed image if the sonar altitude is at least 10 m or so. Usually the sonar is closer than that to the river bed, which allows the direct backscatter path (transducer-riverbed-transducer) to become contaminated with reflections arriving on other paths. Multipath echoes often appear on images as a random brightening that obscures riverbed details. Some survey lines included the river edge because it was less than 68 m away. In some places, sand bars and other high relief created large shadows. A few man-made objects were imaged. In regions with low backscatter strength echoes from the navigation sounder aboard the boat could be seen at ranges exceeding about 40 m since the time-variable gain is much higher there than at short ranges. These appear as dots along diagonal lines. All of these are not riverbed and need to be masked so that they are excluded from the classification process. Not only was this a time-consuming manual task, the borders between good riverbed imagery and these artifacts was not always obvious. It is not clear precisely how the final class maps were affected by the choices that had to be made.

Several of these contaminating artifacts can be seen in Figure 2. This image has not yet been compensated for survey geometry, which is why it is darker at long ranges. Also, the bottom picks are constant at 3.5 m and should be corrected to the start of the riverbed backscatter, which in places merges with backscatter from the propeller wash.



Start of Line
○ Bottom
● Top

Rectangles
File ID 1

Sample Rate
Target: 5357
Viewer: 5357

Highlight Mask
☐ Water Column
☐ Surface Return
☐ Invalid
☐ Border
☐ Max Range
☐ Angle

Clean
☐ Compensate

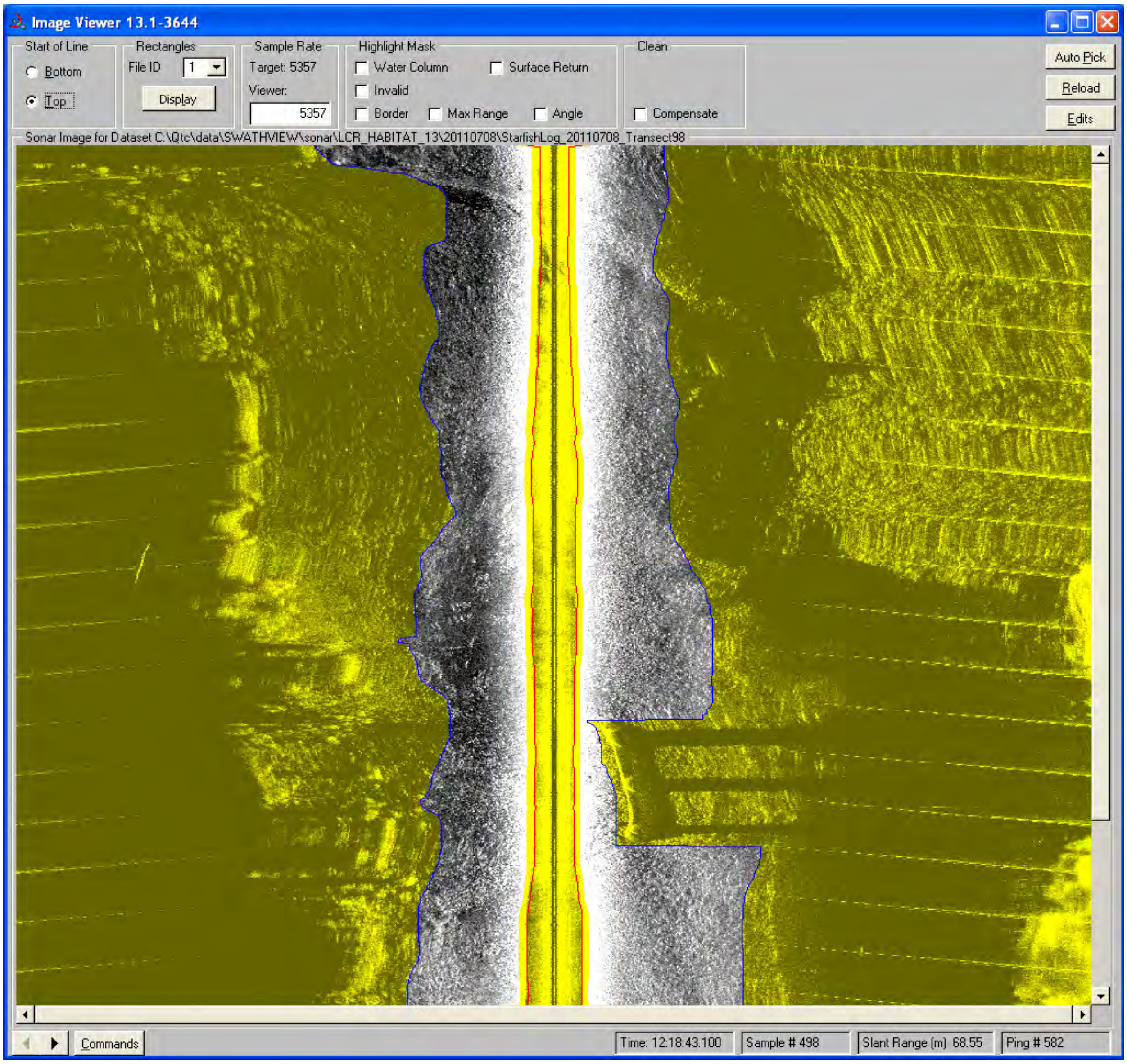
Sonar Image for Dataset C:\Qtc\data\SWATHVIEW\sonar\LCR_HABITAT_13\20110708\StarfishLog_20110708_Transect98

Time:
Sample #
Range (m)
Ping #

Figure 2. Image as displayed by QTC SWATHVIEW from the start of Transect 98 of Habitat 13, showing several types of image contamination. Masked regions have yellow overlays. The large long-range region to port had been masked by BC Hydro presumably because it is beyond the river's edge, There is a pipe or some similar man-made object to starboard with three long deep shadows. All the "pillow" region to starboard at the start of the line (top of the image) is multipath. The dotted diagonal lines seen beyond mid-range are nadir echoes from the boat's navigational echo sounder.

Compensation and dividing survey lines into sub-images

Backscatter amplitude is influenced by the geometry of the system. Changes in grazing angle and range across the swath often lead to regions of high backscatter strength near nadir and low backscatter strength at the edge of the swath. QTC SWATHVIEW performs a patented technique which compensates the image for changes in grazing angle and range. It uses tables of amplitudes and relates values that are calculated during the generation of rectangles. The values are applied to the images during feature generation, and also in Image Viewer if the Compensate box is checked. This is the final step in image preparation before classification.



Start of Line: ○ Bottom ● Top

Rectangles: File ID 1

Sample Rate: Target: 5357 Viewer: 5357

Highlight Mask: ☐ Water Column ☐ Surface Return ☐ Invalid ☐ Border ☐ Max Range ☐ Angle

Clean: ☐ Compensate

Sonar Image for Dataset C:\Qtc\data\SWATHVIEW\sonar\LCR_HABITAT_13\20110708\StarfishLog_20110708_Transect98

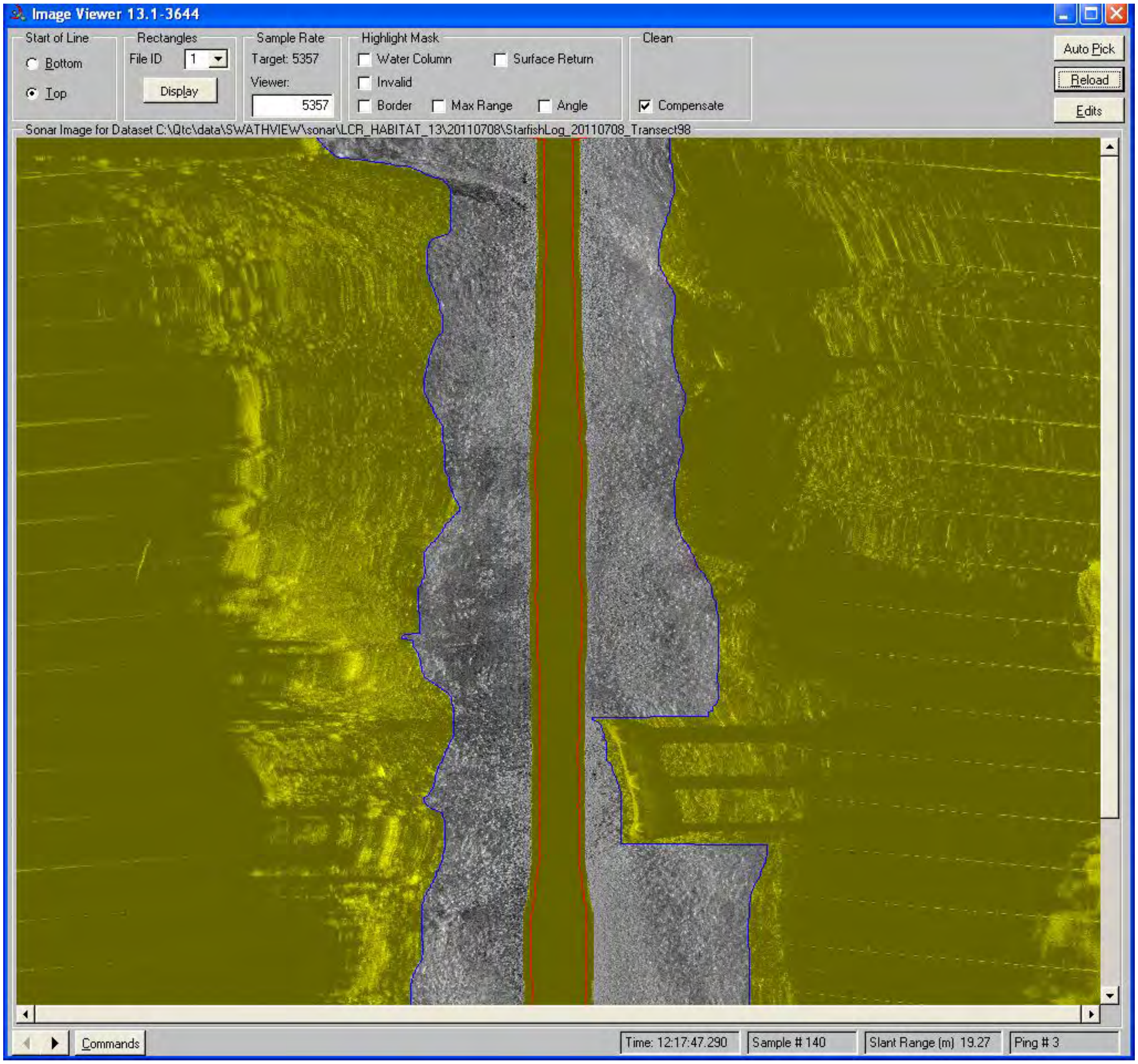
Time: 12:18:43.100 | Sample # 498 | Slant Range (m) 68.55 | Ping # 582

Figure 3. The same image segment shown in Figure 2 masked as described in the text and before compensation for geometrical effects on backscatter amplitude.

Comparing Figure 3 with Figure 2 shows that compensation has made the amplitudes across track much more uniform. Without compensation classes would tend to occur in streaks parallel to the ship track. Figure 12 shows the same image segment with rectangle superimposed. Each rectangle will become a final classification point. Rectangles are not placed where image quality is low, as indicated by the mask. Some rectangles can include a few masked pixels. To be precise, if more than five percent of pixels in a candidate position for a rectangle are masked, a rectangle is not placed there. These isolated masked backscatter amplitudes are replaced by the median of the amplitudes of their immediate neighbours during feature generation.

To start the actual classification process, the image from each survey line is divided into rectangular sub-images. In Swathview, this is called Rectangle Generation. The choice of rectangle size determines the spatial resolution of the final class map. The choice for rectangle size was 33 pixels (across track) by 17 pixels (along track).

These choices in image space correspond to squares approximately 4 m by 3 m on a side on the riverbed. The classified image width varies considerably because of the masking discussed above, so the number of rectangles per swath varied from zero to as many as 15. Figure 5 is an image section with rectangles overlaid.



Start of Line: ○ Bottom ● Top

File ID: 1

Target: 5357

Viewer: 5357

☐ Water Column ☐ Surface Return

☐ Invalid

☐ Border ☐ Max Range ☐ Angle

☑ Compensate

Sonar Image for Dataset C:\Qtc\data\SWATHVIEW\sonar\LCR_HABITAT_13\20110708\StarfishLog_20110708_Transect98

Time: 12:17:47.290

Sample # 140

Slant Range (m) 19.27

Ping # 3

Figure 4. The same image segment shown in Figure 2 compensated for survey geometry using tables of amplitudes as functions of grazing angle and range.

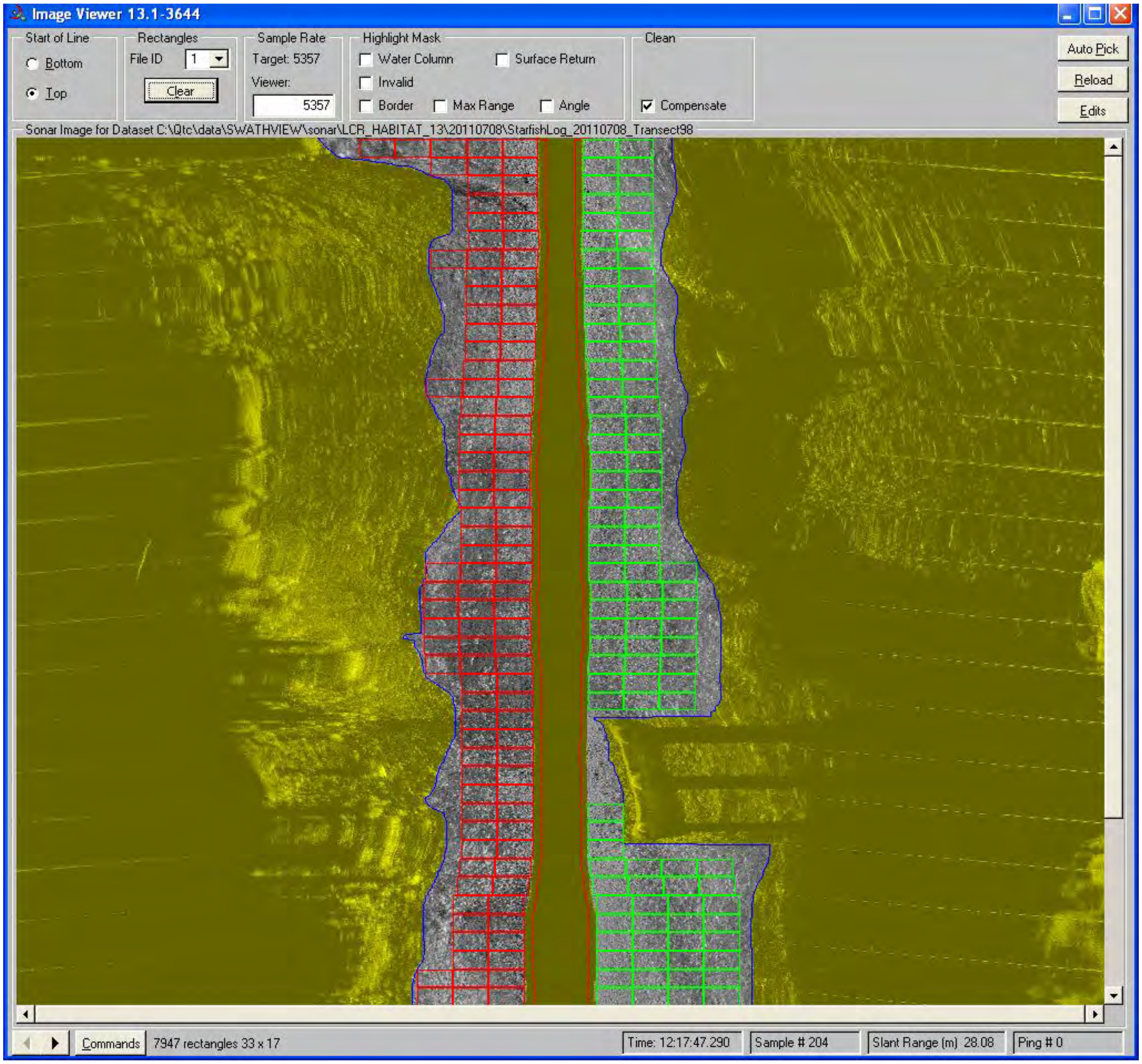


Image Viewer 13.1-3644

Start of Line
○ Bottom
● Top

Rectangles
File ID 1

Sample Rate
Target: 5357
Viewer: 5357

Highlight Mask
☐ Water Column
☐ Surface Return
☐ Invalid
☐ Border
☐ Max Range
☐ Angle

Clean
☑ Compensate

Sonar Image for Dataset C:\Qtc\data\SWATHVIEW\sonar\LCR_HABITAT_13\20110708\StarfishLog_20110708_Transect98

7947 rectangles 33 x 17
Time: 12:17:47.290
Sample # 204
Slant Range (m) 28.08
Ping # 0

Figure 5. The same image segment shown in Figure 2 compensated for survey geometry and divided into rectangular sub-images. Each sub-image will be assigned to a class., based on the amplitude matrix it contains.

Statistical features

After the rectangles were placed on each image to divide it into sub-images, features were calculated from each amplitude matrix. The 29 features for each rectangle were stored in an FFV file for each survey line, that is, each transect. Because the rectangles corresponded to only 3 m x 4 m on the riverbed, this survey included a large number of them. Table 2 lists the number of records (one record per rectangle) in each habitat or group of contiguous habitats.

Positions were not assigned to four rows of rectangles: two in habitat 1, one in habitat 5, and one in habitat 10. This happens if the central ping of that row occurred before the first GPS position of a survey line or after the last position, because Swathview only interpolates positions, never extrapolates. The 88 records put aside for lack of position are not a significant loss from 712684 records. More significant was the erratic GPS positions on

16 Aug 2010 from 11:00:13 to 11:02:40, during the survey of transect 13. During this time 678 records were acquired with no positions and another 443 with positions upstream of the Keenleyside dam. The records with impossible positions were rejected using Swathview's FFV Editor, which allows the user to drag over records based on their position, depth, or slant range. The final number of usable records in habitat 1 was 74813, and 711518 usable records in the entire LCR survey.

Habitat	Total records	Rejected	No positions	Classified
01	75934	443	678	74813
02, 03	132610	0	0	132610
04, 05, 06	119862	0	17	119845
07, 08, 09	169239	0	0	169239
10, 11, 12	57516	0	28	57488
13, 14, 18	73625	0	0	73625
15, 16, 17	83898	0	0	83898
All	712684	443	723	711518

Table 2. Number of records in each habitat or group of habitats. Each rectangular sub-image leads to a record.

Clustering

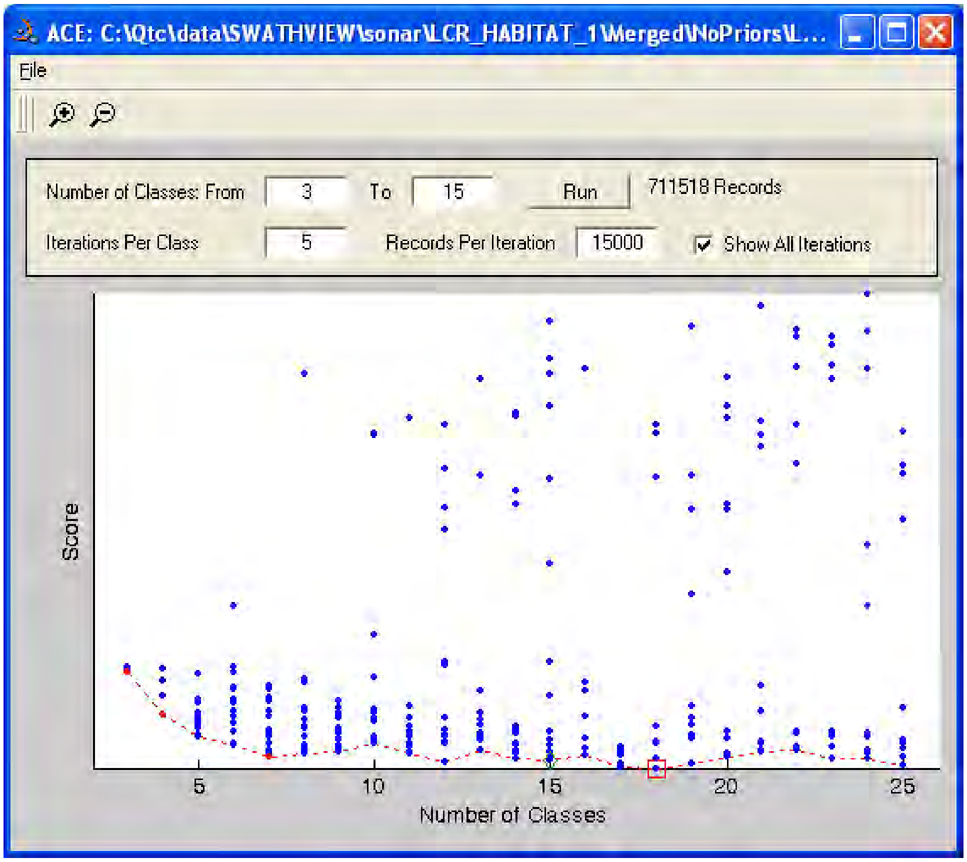
One file with features, an FFV file, was generated for each transect. These contain a feature vector calculated from the amplitude matrix in each rectangular sub-image. The FFV files for all the transects in each habitat were then merged. Finally, all the habitat FFV files were merged to make a a single merged FFV file for the entire lower Columbia River. The motivation for working with such a large set of features is that one unified set of classes was generated for the entire LCR survey.

This master FFV matrix was then analyzed with PCA to find the three principal components that contained the largest possible fraction of the total variance of the features of the complete data set. The components, here called Q-values, form the axes of Q-space in which each record was plotted, as shown in Figure 8. (In this figure they are shown coloured by class, that is, after clustering.)

The next step is segmenting these records into acoustic classes. Quester Tangent developed an objective, automated clustering engine, ACE. It finds the optimum number of clusters and assigns points to these clusters (classes). Figure 6 shows the result of a run of ACE on the records displayed in Figure 8. Each point in Figure 6 is an individual attempt to assign every record to a class, plotted with the number of classes on the x-axis and the score, indicating the quality of the class assignments, on the y axis.

ACE data files contain the full list of class assignments for all the trials, which are shown as blue dots in its main window, of which Figure 6 is a screen capture. Double-clicking on the column of the chosen number of classes brings up details of that set of assignments.

The statistically optimal division into classes, the lowest overall score, is indicated by the red box in Figure 6 at 18 classes. Although 18 classes is the statistically optimal result, the ACE scores for 7, 9, 13, 17, and 25 classes were only slightly inferior. Any of these would be an acceptable choice for making class maps. Since a smaller number of classes eases interpretation and attaching labels to classes, choosing fewer than 18 would be reasonable. But their scores are all similar, so which to choose? Sets of more than 9 classes each had multiple



ACE: C:\Qtc\data\SWATHVIEW\sonar\LCR_HABITAT_1\Merged\NoPriors\L...

Number of Classes: From 3 To 15

711518 Records

Iterations Per Class 5

Records Per Iteration 15000

☑ Show All Iterations

Figure 6. Scores of many attempts by ACE to segment the records of this data set into acoustic classes. Low scores correspond to quality sets of assignments to classes. The statistically optimal number of classes is 18.

classes with small populations, classes that would barely occur in interpolated class maps, so the choice became 7 or 9 classes.

Most riverbeds are more varied and less homogeneous than seabeds. If this were a seabed survey, the natural choice would be seven classes, because any lesser number has a significantly worse ACE score. Here heterogeneity is present and should be accommodated in the class maps, so the number of classes was chosen to be nine.

These nine classes, though, are clearly a poor representation of the riverbed, because one class is so dominant, occupy more than 85% of the survey area. It is not credible that any one sediment type is that ubiquitous. Why does this happen? It seems clear that the root cause is additional layers of reflection atop the sidescan image.

The true riverbed image is formed by sound travelling from the transducer to the riverbed where it is scattered and a fraction returns directly back. Whenever the sonar range exceeds the depth of the transducer, several routes are available to the sound energy, all including at least one reflection off the water-air surface. In this survey the sonar range was always 68.5 m The transducer was about 1 m below the surface. The water depth was rarely more than 20 m and often less than 10 m. These are prime conditions for contributions that followed these multiple paths to overlay the true image, masking its details. Contrast can be much reduced, particularly the acoustic depths of shadows behind ridges, rocks, or sand waves. This multipath scattering tends to flatten the acoustic character of large regions of this survey. Acoustic classes are based on acoustic character. This is thought to be the reason why one acoustic class is so dominant.

Because of multipath, all the images were masked aggressively. In Image Viewer a border can be placed (blue line) marking the maximum range at which rectangles will be placed. Of course this border could not have been set at the transducer depth because that would have masked every image, nor was this necessary because the simplest multipath (transducer-surface-transducer) is heavily suppressed by the 30° downward tilt of the transducers on the Tritech Starfish sonars. The next shortest multipath involves one riverbed bounce and one surface bounce and thus starts at a range that depends on water depth. Sometimes it is evident; sometimes not. Several complicated paths can contribute at longer ranges. Masking regions overlaid with multipath is therefore a long series of judgements, deciding in each case whether an image region is pristine enough to be classified. It was not possible to be correct always. Nor was it practical to follow a rule based on water depth and geometry since that would have dictated masking most of the survey. Figure 7 shows a typical mask in an area with typical water depths (sonar altitude 4.5 to 14.5 m). The image character is bland roughly to the left and above the bottom-left to

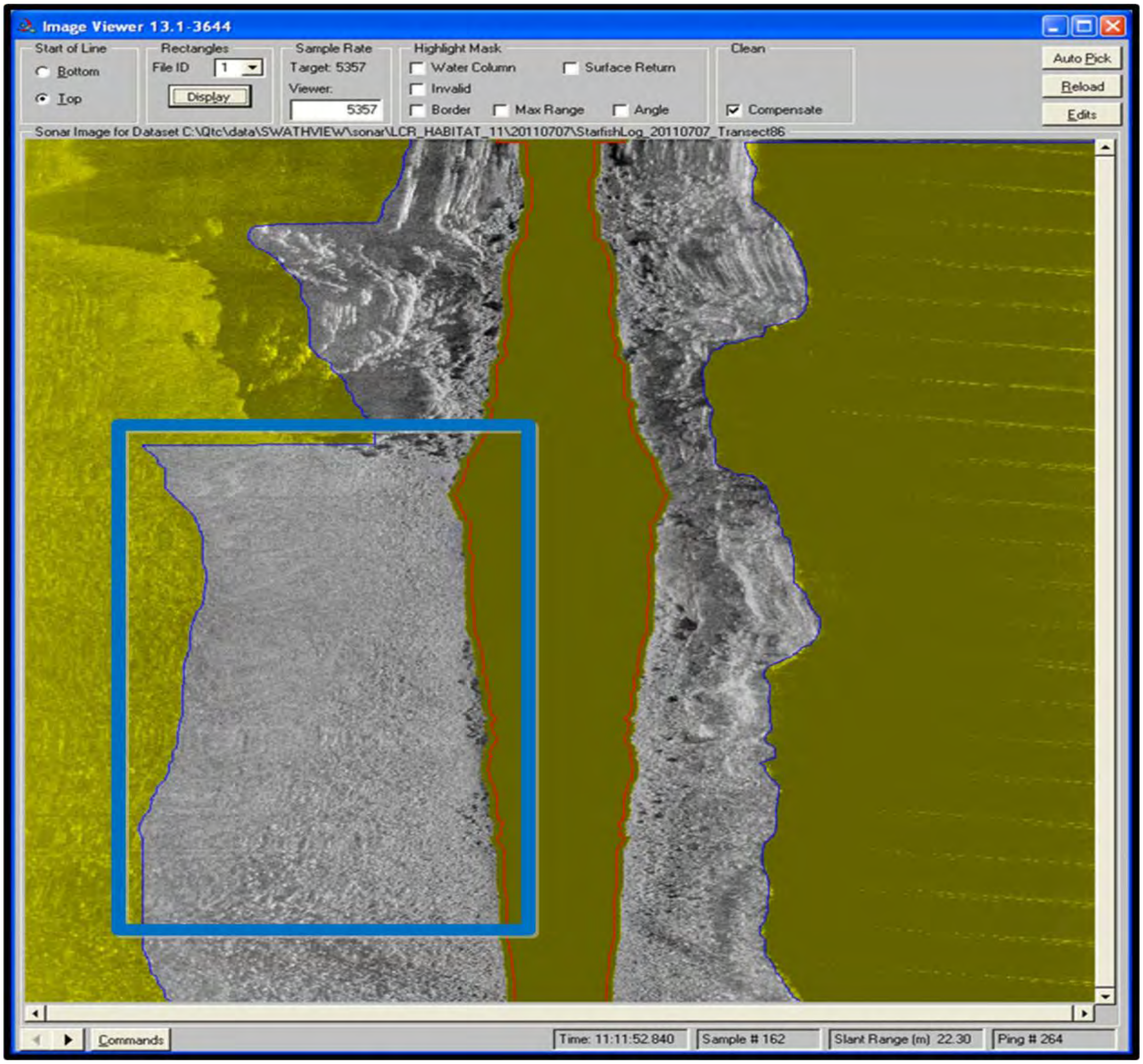


Image Viewer 13.1-3644

Start of Line: ○ Bottom ● Top

Rectangles: File ID 1

Sample Rate: Target: 5357 Viewer: 5357

Highlight Mask: ☐ Water Column ☐ Surface Return ☐ Invalid ☐ Border ☐ Max Range ☐ Angle

Clean: ☑ Compensate

Sonar Image for Dataset C:\Qtc\data\SWATHVIEW\sonar\LCR_HABITAT_11\20110707\StarfishLog_20110707_Transect86

Time: 11:11:52.840 | Sample # 162 | Slant Range (m) 22.30 | Ping # 264

Figure 7. Segment of Transect 86 (start of line). The blue border line has been moved inward to mask image regions overlaid with multipath. Masked areas are coloured yellow. The region within the blue box is discussed in the text.

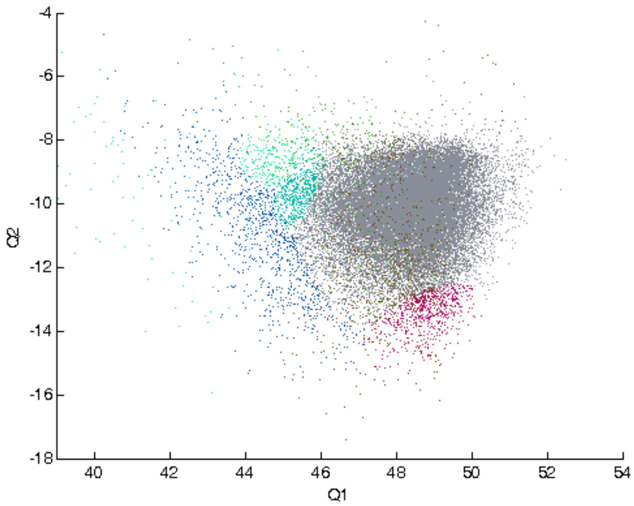


Figure 8. Every twentieth record of this survey plotted in Q-space and segmented into nine clusters. Q space has three dimensions but only two are plotted here. Each cluster is shown in its similarity colour. The dominant class, 3, is the central grey cluster. Plotting only one point in twenty improves the presentation.

upper-right diagonal of the blue box and should have been masked to leave only the pristine image to be classified. Since it was impractical to do so for every transect, the full data set included a wide and gradual range of acoustic character. Swathview's clustering process, in ACE, relies on the data set having distinctive regions: dark, rough, smooth, deep shadows, and so on. Multipath obscures the differences leaving gradual transitions between regions that would be distinctive.

In feature space, the multipath overlays lead to one large broad class surrounded by small classes that each represent small areas that do have distinctive character. Figure 8 is one slice of three-dimensional feature space (Q space). The dominant class, representing this gradual and very common range of characters, is the grey class, class 3.

Since we know that no single sediment type covers this much of the riverbed, it was necessary to split this class. ACE, Swathview's unsupervised automatic clustering module, always left this class intact because it

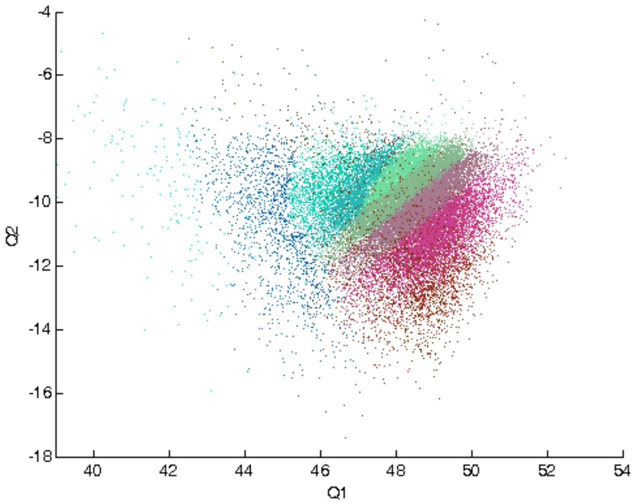


Figure 9. Q space after forced splitting of the dominant class.

minimizes a statistical metric and the gradual changes throughout this class had no clear gaps. The method that did succeed was Swathview's old manual cluster algorithm. In this method the centre of a selected cluster is erased and replaced by two candidate centres at ± 1 standard deviation along one of the principal axes of that cluster's hyperellipse. All the points are then assigned to the cluster whose centre they are closest to, then the cluster centres are moved to the average position of their points, then points are re-assigned, then centres re-positioned, and so on until convergence.

Did this forced splitting give a credible result? Let us examine that in several ways. The revised Q space, Figure 9, suggests that any gaps in the cloud of points that made up the dominant cluster have been used to split it into effectively. That's not enough to build confidence in this division as a basis for environmental understanding of the LCR. We also need to examine these classes in the context of the images that produced them. In Figure 10, left-hand image, almost all the sub-images were classified into the dominant class, class 3, even if there were clear differences in acoustic character. A few rectangular sub-images are in other classes (blue, green, magenta, brown, …), but this is so only when the acoustic character is obviously distinct. The right-hand image, with ten classes after the forced split, is far more realistic. Image regions that are quite irregular with medium average amplitude are in the magenta class, while the light-green class is more bland with about the same mean amplitude. The blue and brown classes represent other distinct character and were largely unchanged by the forced spilt. This is precisely

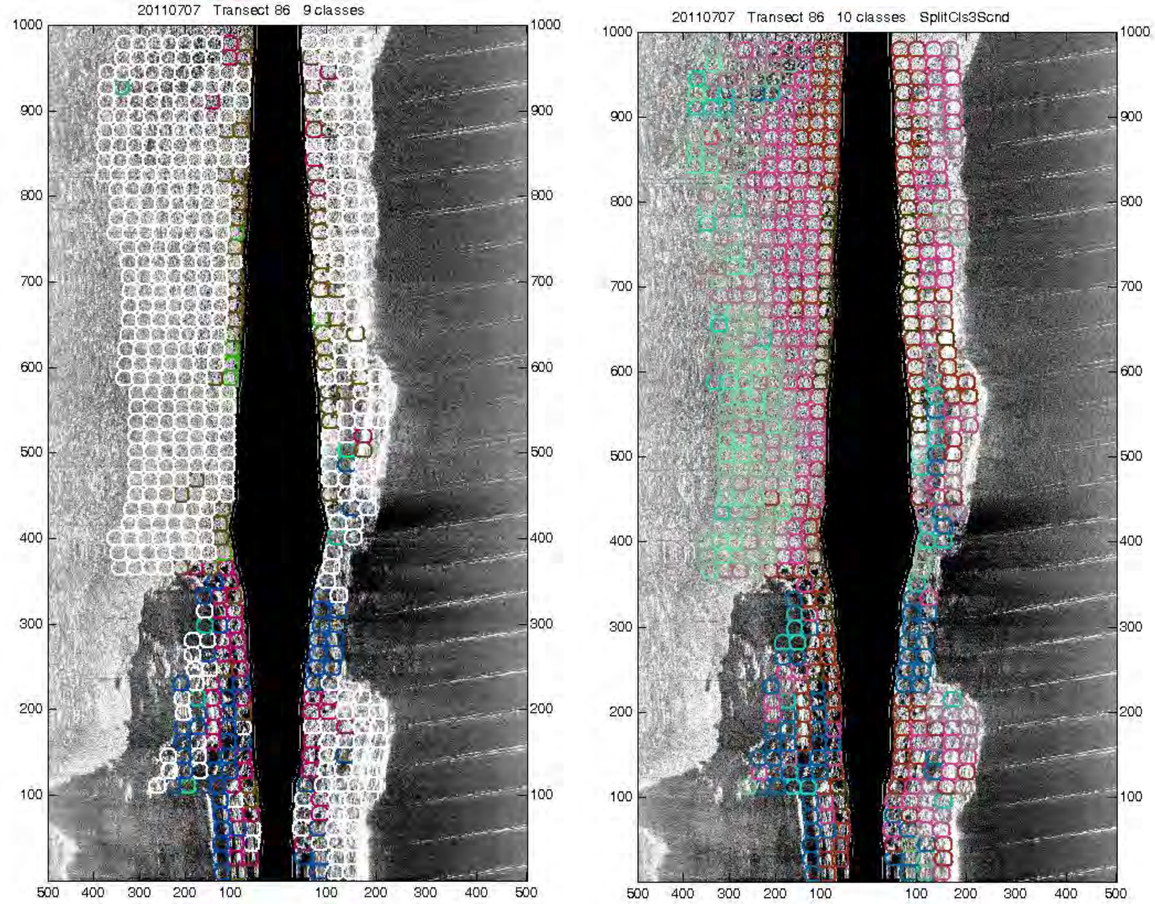


Figure 10. The image segment of Figure 7 (inverted) divided into rectangular sub-images whose borders are the class colours. Left image is for the nine-class ACE classification. In this image the borders of the dominant grey class were changed to white because grey was invisible. Right image is for ten classes after the forced split. X axes are sample number; y axes are ping number.

what we hoped to achieve.

Figure 11 is another convincing example. Almost the entire left-hand image was classified into class 3 in spite of obvious differences in amplitude and texture. The classes in the ten-class overlay shown on the right reflect these differences much more realistically.

As mentioned above, there were three ways to force this split since there are three axes in a hyperellipse. Splitting along the smallest axis was not expected to be effective based on the cluster shape in Q space. This set of classes was set aside because it compared very badly with the others when compared with the ground truth from just below the dam. There was less to choose between the other two. In examples like Figure 10 and Figure 11 they were often similar. Splitting on the second axis (that is, not the longest one) was chosen because its class overlays were somewhat more convincing and because its comparison with ground truth was better.

As a final note, overlays like Figure 10 and Figure 11 cannot be made in Swathview (although that would be a desirable option). They were made using the Matlab version of Swathview's Image Viewer.

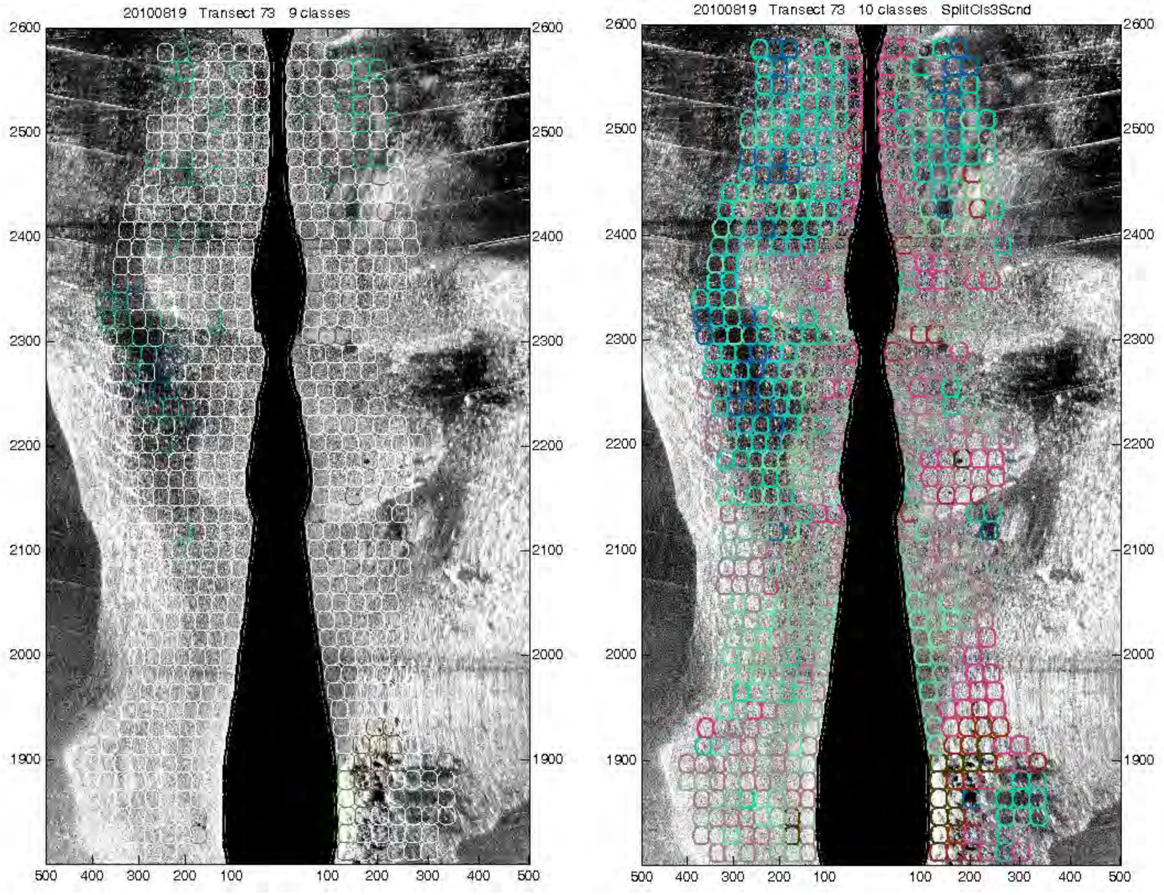


Figure 11. An image segment from transect 73 divided into rectangular sub-images whose borders are the class colours. Left image is for the nine-class ACE classification. In this image the borders of the dominant grey class were changed to white because grey was invisible. Right image is for ten classes after the forced split. X axes are sample number; y axes are ping number.

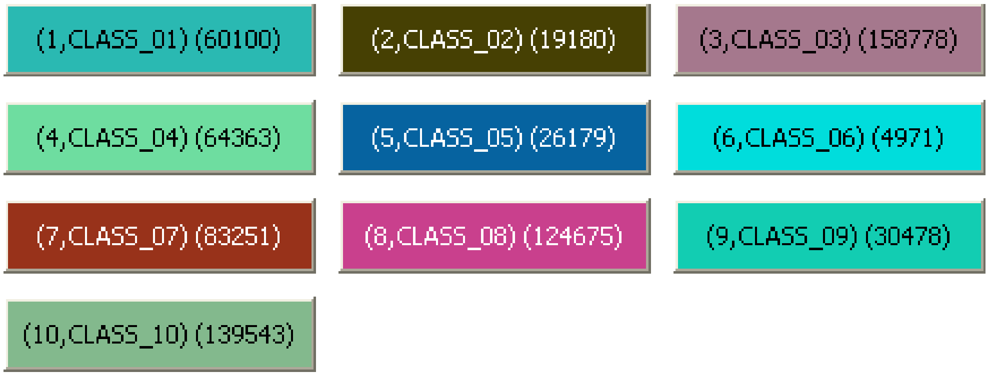


Figure 12. Palette of colours of the ten acoustic classes in this classification of the LCR, with the population of each class.. These are similarity colours. Text, such as CLASS_01, could be replaced with a description such as sand or gravel once known from physical sampling. The total number of classified points is 711518

CLASSES AND FINAL CLASS MAPS

The ten classes

Swathview's automatic clustering engine, ACE, divided the entire LCR data set into nine acoustic classes. One of these was far too common, with more than 85% of the data points. Understanding that this lop-sided division was due to multipath additions to the riverbed image, this large class was split using Swathview's old manual clustering method. The section above describes this process and provides some evidence that we should have confidence in the final set of ten classes.

The colours used to depict the ten classes, shown in Figure 12, are the similarity colours derived from the locations of the ten cluster centres in three-dimensional Q space. With these the colour of each class conveys meaning relative to other classes, in that classes that are similar in colour are neighbours in feature space and therefore similar acoustically. The RGB designations of these class colours are listed in Table 3.

Class	Red	Green	Blue
1	42	185	178
2	70	64	3
3	165	120	141
4	110	221	160
5	6	99	160
6	0	221	220
7	152	50	26
8	201	64	141
9	18	205	178
10	131	185	141

Table 3. RGB characteristics of each of the similarity colours.

The number of records assigned to each class, as shown in Figure 12, does not correspond to the area of each class along the LCR because these points are irregularly spaced and overlap in some places. Areas were calculated after gridding the classes to regularly spaced nodes. Class 6 is the smallest class with only 3.6% of the records of the largest class, but no class dominates.

Because the rectangle size was chosen to correspond to 3 to 4 m on the riverbed, the classified points are no more than 4 m apart. In overlap regions they can be even closer, because each neighbouring survey line has contributed rectangles, and each rectangle leads to a point with a class assignment. Near nadir they can be further apart because the distance between pixels in a raster is higher under the vessel than at far range. Taking all these considerations together, it is reasonable to say that the spatial resolution is 3 m.

Assigning classes to regularly spaced grid points

The class assignments in the seabed files can be plotted on a map as coloured dots, one at the latitude and longitude of the centre of each rectangle. However maps made with hundreds of thousands of individual points are not useful final maps because the points overwrite each other, emphasizing the class that is plotted last. Instead, maps of gridded class assignments were made by interpolation to evenly spaced grid points.

To apply acoustic classifications to further tasks, such as delineating habitat, the class map has to be available as a GIS layer. This requires interpolating class assignment to a regularly spaced grid. Most interpolation routines work with continuous variables, like depth, and not with discrete variables, like class number. QTC CLAMS is one of a very few commercial products that interpolates categorically. Gridding was done with a distance between grid points of 3 m. Only the 12 points closest to each grid point were considered in each interpolation. This choice of search size amounts to moderate smoothing, Another control parameter in CLAMS is the radius that CLAMS searches around each grid point. This search radius controls filling-in of gaps but has no effect on smoothing. Grid points further away than this radius from any classified points are not assigned. A reasonable choice was found to be 25 m. Finally, to prevent unrealistic extrapolation at the edges of the survey area, QTC CLAMS leaves grid points unassigned even if there are classified points within the search radius unless they are largely surrounded by classified points. The chosen sector parameter was to require one or more classified points

Habitat	Easting	Northing
01	443980 to 446562	5465310 to 5465820
02, 03	446371 to 453016	5463590 to 5465630
04, 05, 06	452177 to 453508	5455220 to 5463850
07, 08, 09	447310 to 452710	5445740 to 5455370
10, 11, 12	446145 to 448475	5438620 to 5446250
13, 14, 18	448229 to 455483	5435520 to 5438810
15, 16, 17	453735 to 455981	5427800 to 5435630

Table 4. Boundaries of the survey points in each group of habitats. These are UTM coordinates in zone 11N

Habitat	Easting		Northing	
	Coordinates	Grid points	Coordinates	Grid points
01	443960 to 446600	881	5465300 to 5465840	181
02, 03	446350 to 453040	2231	5463570 to 5465640	691
04, 05, 06	452160 to 453540	461	5455200 to 5463870	2891
07, 08, 09	447300 to 452730	1811	5445720 to 5455380	3221
10, 11, 12	446130 to 448500	791	5438610 to 5446260	2551
13, 14, 18	448210 to 455500	2431	5435500 to 5438830	1111
15, 16, 17	453720 to 456000	761	5427780 to 5435640	2621

Table 5. Details of the grids chosen for each group of habitats

	Acoustic Class										
Habitat	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Total**
01	4.4	3.1	12.0	13.9	1.8	0.3	8.4	1.8	1.4	25.9	73.0
02, 03	26.0	3.4	25.4	32.6	20.3	4.4	17.6	5.0	8.1	49.4	192.2
04, 05, 06	11.9	2.8	73.7	5.1	6.8	0.1	17.6	27.9	7.3	45.2	198.3
07, 08, 09	9.3	2.3	98.1	7.0	2.2	0.2	29.3	58.7	3.3	54.7	265.1
10, 11, 12	2.3	2.4	18.9	0.9	2.3	0.0	46.0	76.8	1.5	7.8	159.0
13, 14, 18	14.4	1.2	42.2	3.3	6.7	0.5	24.5	60.1	8.0	23.8	184.6
15, 16, 17	6.7	2.5	59.8	3.7	2.7	0.3	21.5	96.8	2.7	28.9	225.6
Total	75.0	17.7	330.0	66.5	42.8	5.8	164.9	327.1	32.4	235.5	1297.8

Table 6. Area in hectares of each acoustic class in each group of habitats.

in at least 5 of 8 equal 45° sectors around each grid point.

Gridding the entire survey with a node spacing of 3 m would have involved almost 40 million grid points, which is impractical. Instead, the survey was divided into seven habitat groups, as listed in Table 4 and Table 5. Habitat 1 was kept by itself because of its position close by the dam. Table 4 lists the boundaries of the locations within which any class was assigned in that group. The grid chosen for each region was these boundaries plus a small margin, adjusted so the east and north extents in metres were all divisible by 3 so that all the coordinates are integers. These grid details are listed in Table 5. The total number of grid points is 15580327, still large but manageable after division into seven files. More than 90% of these are on shore and have no class assigned.

An interpolated gridded class map was made in QTC CLAMS for each of the seven groups of habitats. Since each grid point corresponds to 9 m^2, the area of riverbed occupied by each acoustic class could be found by counting the number of points assigned to each class and multiplying. These areas are listed in Table 6 in hectares and in Table 7 as percentages of the total area of the group or of the entire survey. Classes 3 and 8 occupy the largest areas, tied at 23.6% of the total LCR survey area,. Two other significant classes are class 10 at 19.3% and class 7 at 13.2%. No other class occupies more than 10%. Classes 1 and 4 are the largest of these. Among the smallest, classes 2, 5, 6 and 9, there are some interesting distributions, such as class 6 almost entirely in the second habitat group and classes 2 and 5 primarily in the first few groups.

	Acoustic Class										
Habitat	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Total**
01	6.1	4.2	16.4	19.0	2.5	0.4	11.5	2.5	1.9	35.4	100.0
02, 03	13.5	1.8	13.2	16.9	10.6	2.3	9.1	2.6	4.2	25.7	100.0
04, 05, 06	6.0	1.4	37.2	2.6	3.5	0.1	8.9	14.1	3.7	22.8	100.0
07, 08, 09	3.5	0.9	37.0	2.7	0.8	0.1	11.0	22.2	1.2	20.6	100.0
10, 11, 12	1.5	1.5	11.9	0.6	1.4	0.0	28.9	48.3	1.0	4.9	100.0
13, 14, 18	7.8	0.7	22.8	1.8	3.6	0.2	13.3	32.5	4.3	12.9	100.0
15, 16, 17	3.0	1.1	26.5	1.7	1.2	0.1	9.5	42.9	1.2	12.8	100.0
Total	5.9	1.6	23.6	6.5	3.4	0.5	13.2	23.6	2.5	19.3	100.0

Table 7. The areas of Table 6 expressed as percentages of the area in each group and overall

Maps and images

Appendix A contains seven plots of the ten acoustic classes, one for each of the habitat groups. These are interpolated and smoothed class plots with grid points 3 m apart. Figure 13 is a composite class map of the entire survey. Even though this map is much compressed, ir does lead to some observations. Red and pink classes increase downstream. Blue and green dominate within 5 km of the dam and also in sections near Brilliant and Castlegar as well as downstream of Genelle and Trail.

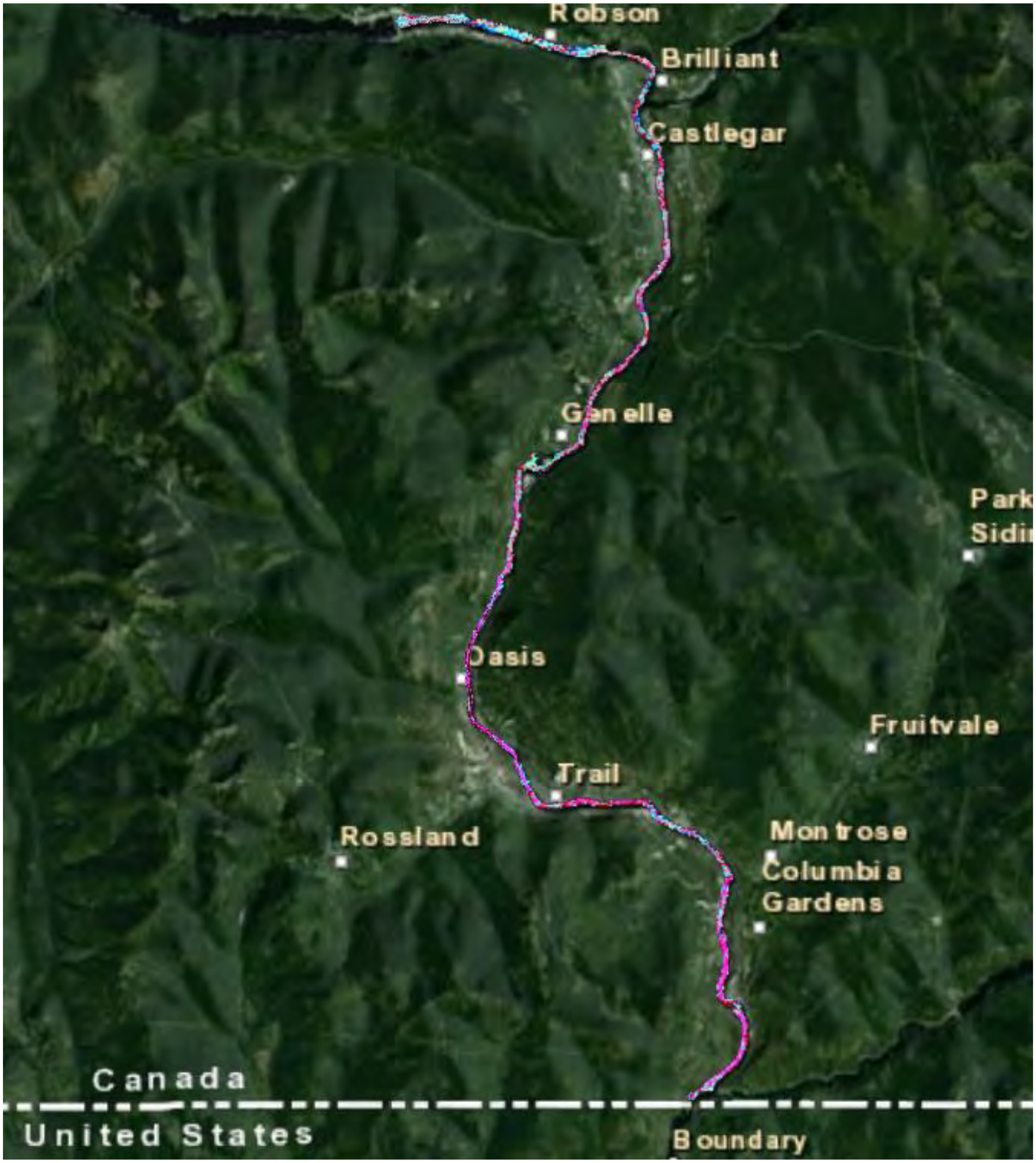


Figure 13. Class map of the entire Lower Columbia River

The use of similarity colours eases interpreting class maps. Each class has a colour whose RGB triad is determined by the position of the cluster centre in Q space. Thus classes with similar colours are near neighbours in feature space and therefore acoustically similar. There are five classes that are green or close to green: 1, 4, 6, 9 and 10, which one would expect to have distinct acoustic character from the red classes: 3 and 8. The khaki (almost black) class, 2, the blue class, 5, and the brown class, 7, are expected to be different again and different from each other.

Green classes are found near the islands south of Genelle, near the junction with the Kootenay River, and in some other places where the river is somewhat wider. The long streaks of green and cyan in the southern part of the LCR are primarily another manifestation of multipath scattering. They cannot be realistic because they are parallel to the boat track, occurring most often at long range. In these transects, number 100 for example, the green classes are not always at long range, in fact sometimes dominating entire sides for hundreds of metres. Thus even though these regions seem artificial, the river bed here is not the same as if it were totally green or red, but rather a mixture.

ATTACHING LABELS TO ACOUSTIC CLASSES

Swathview classes are collections of image regions that are acoustically similar and differ one from the other. In general, it is not possible to attach sediment labels, such as sand or gravel, using acoustics alone. In this survey there are ten classes that, to this point, are labelled by colour or number. To decide which type of riverbed each of these classes is, some additional non-acoustic information is required.

Near the dam

Some insight into the acoustic classes in the first 1.5 km downstream from the dam is available from Figure 14. The tail race, with flow rates up to 1 m/s, starts in the northwest near (444200, 5465770) and flows southeast. That area is mostly cobbles and is a region that has large patches of classes 4 and 10 (green) and 2 (pink), except right at the exits from the turbines and the spillway, which are classes 5 and 6 (blue) and 7 (brown). Further downstream, where the flow rates are less than half that, and also on the sides of the tail race, the riverbed is somewhat smoother gravels or boulders. Here one finds large patches of classes 1 and 4 and 10, except under where log booms are often moored where there are classes 3 and 8 mostly. Behind the earth dam, in the

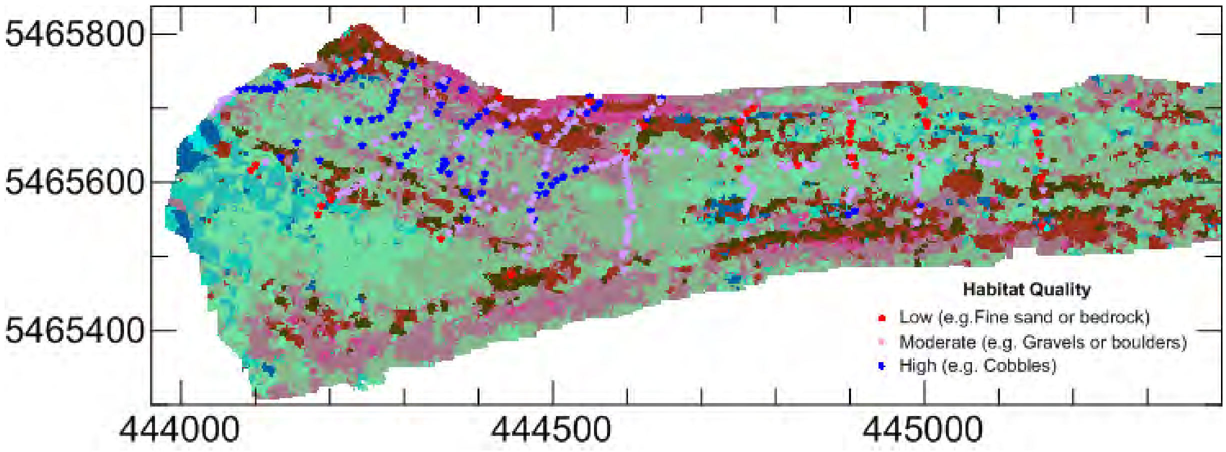


Figure 14. Ten acoustic classes in the upstream half of Habitat 01 overlaid with classes of habitat quality, which were assessed by Golder Associates into three classes, shown by the coloured dots.

HLK eddy, class 9 is dominant where the flow is minimum.

Last fall some transects within 1 km of the dam were visited to assess the river bed for the quality of sturgeon habitat. The locations, classified as low, moderate, or high quality, are shown as red, purple and green dots respectively as a layer in Figure 14. The lower layer is the ten acoustic classes, interpolated to the 3-m grid. These ground-truth data were used in an attempt to label some of the classes. The next few paragraphs explain the process and the results.

The first step was to acquire position coordinates for the ground-truth sites. This was done by digitizing locations on the pdf provided from Golder Associates, using some salient points for registration. (More often, coordinates are provided in a list.) This generated a list of coordinates and the habitat class to which each position had been assigned.

Next, a variant of QTC Clams was run to assign acoustic classes to each ground-truth site. The commercial version of Clams interpolates categorically to find the one class that is best assigned to each of a large set of evenly spaced grid points. This variant operates with a list of positions, not equally spaced. Also, at each position it identifies not just one but up to three classes that occur within the search radius of the point. In making the maps, the search radius was set to 25 m and the search size to 12 points, and the same choices were used here. This gave a histogram of the presence of each class at each site, with the most significant three listed by percentage, for example class 8 at 62%, class 3 at 16% and class7 at 12%. The sites were then broken into three spreadsheets, one each for high, moderate, and low habitat. Within each spreadsheet, the percent presences of each class at each site were collected and added.

The final step was to draw up a matrix of the number of coincidences, that is, percent presences of each acoustic class at the position of each non-acoustic (in this case habitat) site. One then to maximize the number of matches between acoustic and non-acoustic classes. With equal numbers of classes of each type (this might be arranged by grouping acoustic classes) the matrix would be square and the best set of labels can be found by maximizing its trace by interchanging rows or columns. If the correlations are good and the number of classes modest, maximizing the trace can give clear labels, for example that class *n* is high-quality habitat. Particularly with a non-square matrix, firm conclusions can be elusive, which is perhaps why these matrices are usually called confusion matrices. **Error! Reference source not found.** is this matrix with the three classes of habitat quality as rows and the ten acoustic classes as columns. No acoustic class is entirely in a single habitat class. However it is clear that classes 3 and 10 are indicative of high-quality habitat and that classes 4 and 7 are indicative of low-quality, as are probably classes 1 and 2. The appearance of these clear trends lends further confidence to the classification methods used in this report.

	Acoustic class									
Habitat class	1	2	3	4	5	6	7	8	9	10
Low	6%	7%	8%	26%	3%	0%	15%	4%	3%	28%
Moderate	2%	8%	18%	16%	2%	0%	16%	5%	2%	30%
High	1%	3%	24%	7%	0%	0%	8%	7%	0%	49%

Table 8. Confusion matrix. Each entry is the percentage occurrence of that acoustic class at habitat sites that were classified as shown for that row. For example, 4% of the sites of low quality are in acoustic class 2.

Sites for Acquiring Ground Truth

The recommended sequence for making class maps of riverbed sediment types is to first make maps of acoustic classes and then to select locations for non-acoustic sampling that are representative of each acoustic class. In rivers this can be difficult because of the heterogeneity. The current it difficult to return to a small area and hold position in accurately enough to get a grab sample of that class. Also, the classes of prime interest for habitat are rocky or gravelly and thus not suited to grab sampling. Photography might be a better choice.

To identify spot sites representative of each class, maps were made (in Surfer) that showed each rectangle location in its class colour. Table 9 lists some sites at which ground truth could be acquired for labeling these acoustic classes. There are few sites that are homogenous in a single class over more than about 20 m, so some of these locations were difficult to identify with confidence. The green classes often present as streaks parallel to the boat track, which raises fears that they may not be realistic. Streaks parallel to the vessel track are unacceptable in seabed surveys, but may indicate actual riverbed since river sediments are more heterogeneous and tend to align with flow, which was also the direction of travel. In this table, classes 1 and 6 appear together because they are very similar in colour and acoustically, similarly 4 and 10.

Because it would be difficult to get grab samples or photographs from the precise locations in Table 9, a better plan for gathering ground truth seems to be to record video of the river bed over a series of crossings, perpendicular to the flow. The data acquired by Golder Associates near the dam served well to identify trends in

Class	Easting	Northing
Classes 1 and 6, blue-green	448574	5450066
	448197	5464987
	447644	5465140
Class 2, dark khaki	448642	5464838
	444220	5465772
Class 3, purple	452417	5461747
	444389	5465686
	447401	5465445
Classes 4 and10, light green	448687	5450299
	444110	5465520
Class 5, deep blue	452742	5463238
	448121	5465943
	444157	5465635
	444034	5465671
Class 7, brown	448115	5448126
	448969	5449860
	453127	5456935
	444261	5465790
Class 8, pink	447999	5449349
	452226	5462080
	444441	5465694
	453068	5456941
Class 9, deep green	444339	5465549
	444479	5465468

Table 9. Potential sites to collect ground truth for labeling classes.

the acoustic classes, and this suggestion is basically to repeat that exercise in more locations. Experience has shown that grab data from a few dozen sites, such as in Table 9, may not be adequate for confident labelling of ten acoustic classes. Examining video images from a single crossing can generate many data points, and would very likely be more useful. The locations of these crossings could be chosen from the figures in Appendix A, chosen so as to cover all (or almost all) of the acoustic classes. Thus this is the recommended technique for ground truthing.

SUMMARY

It is tempting to think of acoustic classification as a method that maps grain size. Users who make this common error can be disappointed if the correlation between acoustic classes and grain size is somewhat confused. The physics of high-frequency acoustic backscatter depends primarily on surface roughness (in the literature it is called roughness scattering), and also on sediment density and sound speed. These three are strongly correlated with grain size, but in fine sediments there are other influences such as porosity. Thus it is more correct to think of acoustic classification as a method that maps acoustic amplitude and texture, both of which are heavily influenced by grain size.

The class maps in this report are based on sidescan surveys of the lower Columbia River in the summers of 2010 and 2011. Ten acoustic classes were identified. The two that occupy the most riverbed each fill 23.6% and only one is present at less than 1% of the survey area. The most varied region of the LCR is the first 1.5 km downstream from the Keenleyside dam. Correlations between the ten acoustic classes and a previous survey of habitat quality led to some understanding of the nature of most of the acoustic classes.

The survey sonar was a Tritech Starfish 450 series sonar attached to a small boat at a depth of about 1 m. The sonar range setting was always 68 m and the mean water depth under the sonar was 8.2 m, at times even less than a metre. With this geometry, the sound can return to the sonar by several routes involving reflections from the air-water interface, as well as the direct backscatter from the seabed. These multipath additions overlay the actual riverbed image, adding to it by sometimes a negligible amount and sometimes enough to obscure it completely. In QTC Swathview, the software suite that did the classification, it is possible to set, for each ping, a range beyond which the image is ignored. Blatant multipath was masked in this way, but image that was only lightly affected, or not at all, had to be used. With this masking, the statistically optimal set of classes was not useful because most of the regions with small to significant multipath additions were in a single class. This class was forcibly split with a user-controlled algorithm, yielding class distributions that are much closer to expectations. Doing so, however, removed any confidence derived from knowing that the class assignments were statistically optimal. This confidence was restored by examining several overlays of classes atop images and by the correlations with the survey of habitat quality. Thus, even though this classification exercise has been a struggle, there is a basis for confidence that these ten classes are a reasonable picture of the LCR riverbed.

For future work, these acoustic classes do not have labels attached, labels such as cobble, gravel or sand. Additional non-acoustic data are needed for this. Procedures and locations for acquiring suitable data are suggested.

APPENDIX A: CLASS MAPS OF THE HABITAT GROUPS

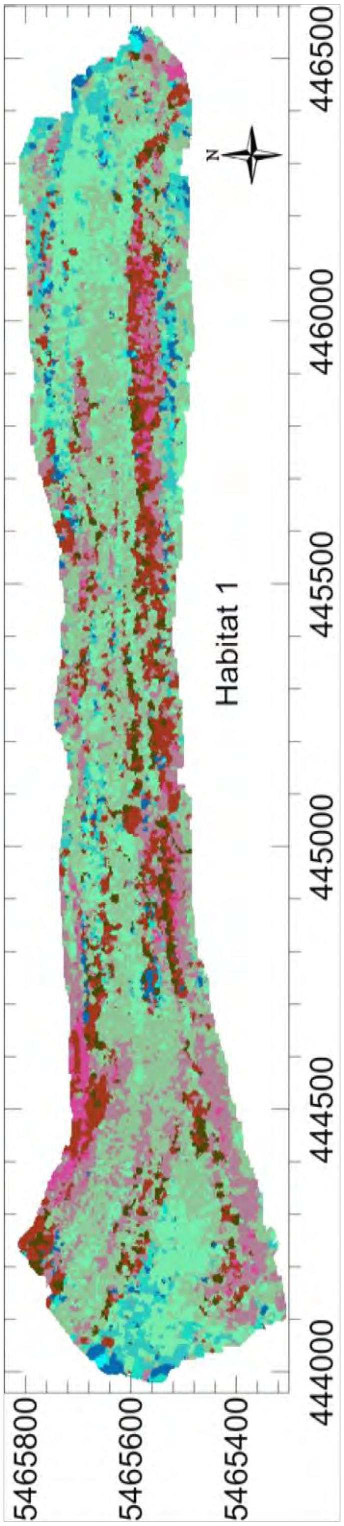


Figure 15. The ten acoustic classes of the first habitat group interpolated to a 3-m grid.

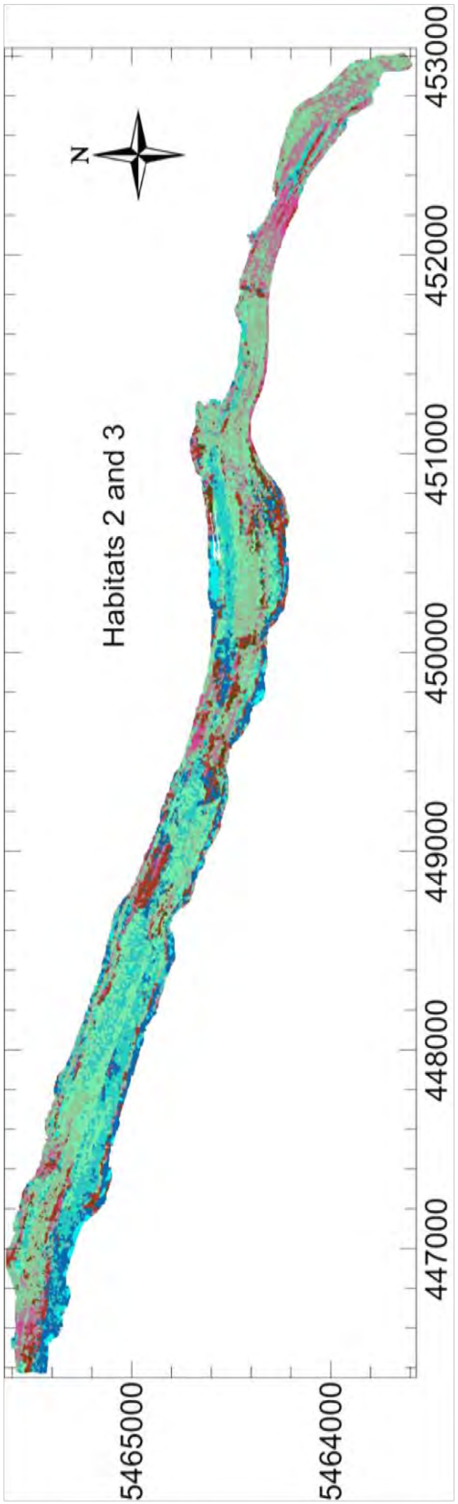


Figure 16. The ten acoustic classes of the second habitat group interpolated to a 3-m grid.

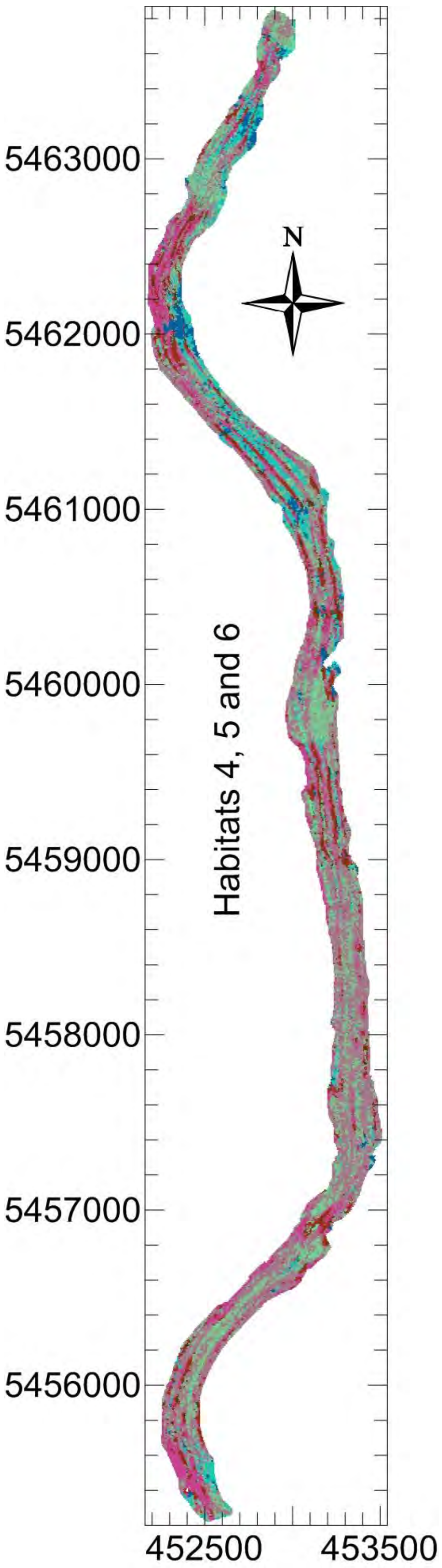


Figure 17. The ten acoustic classes of the third habitat group interpolated to a 3-m grid.

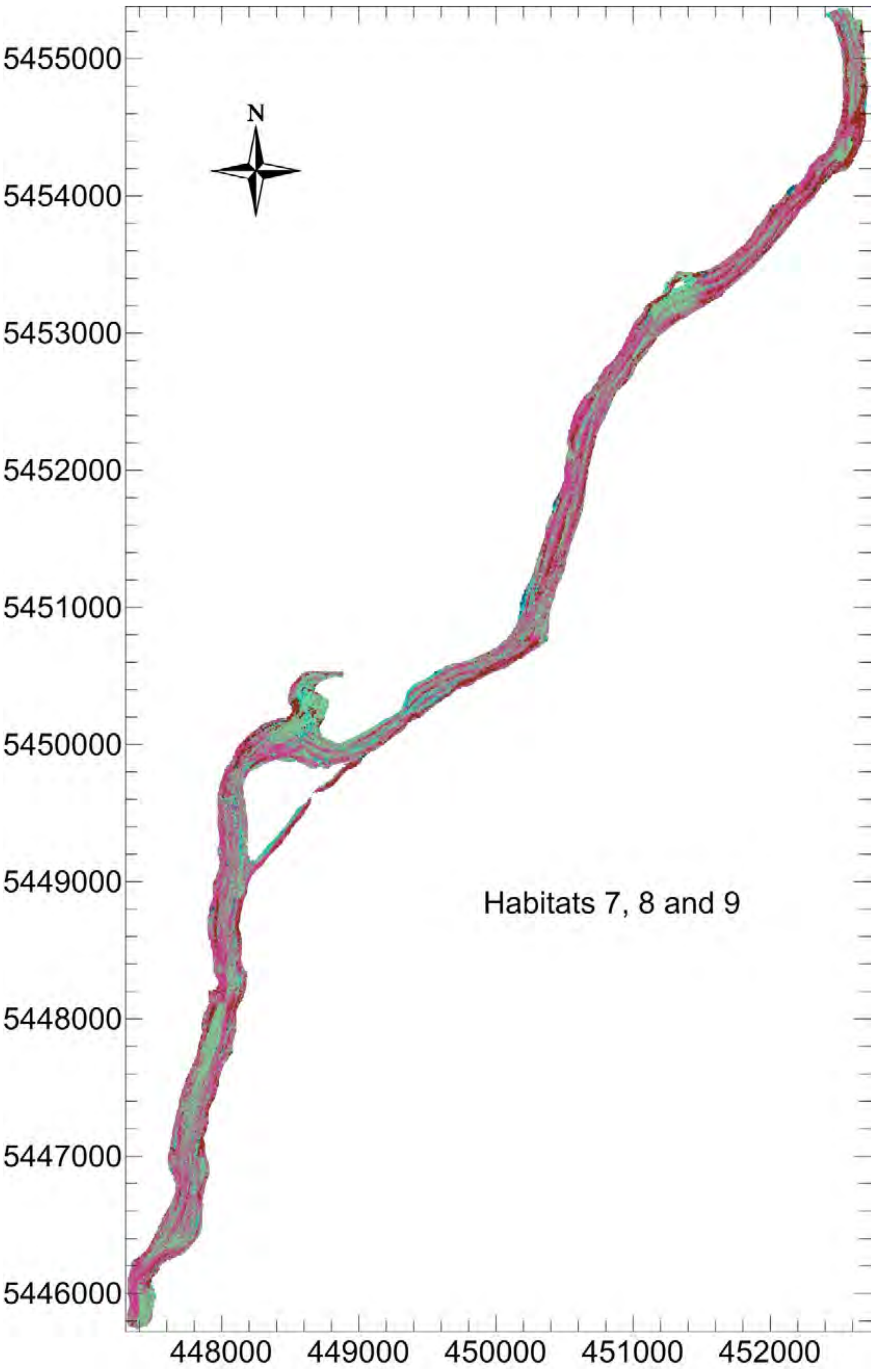


Figure 18. The ten acoustic classes of the fourth habitat group interpolated to a 3-m grid

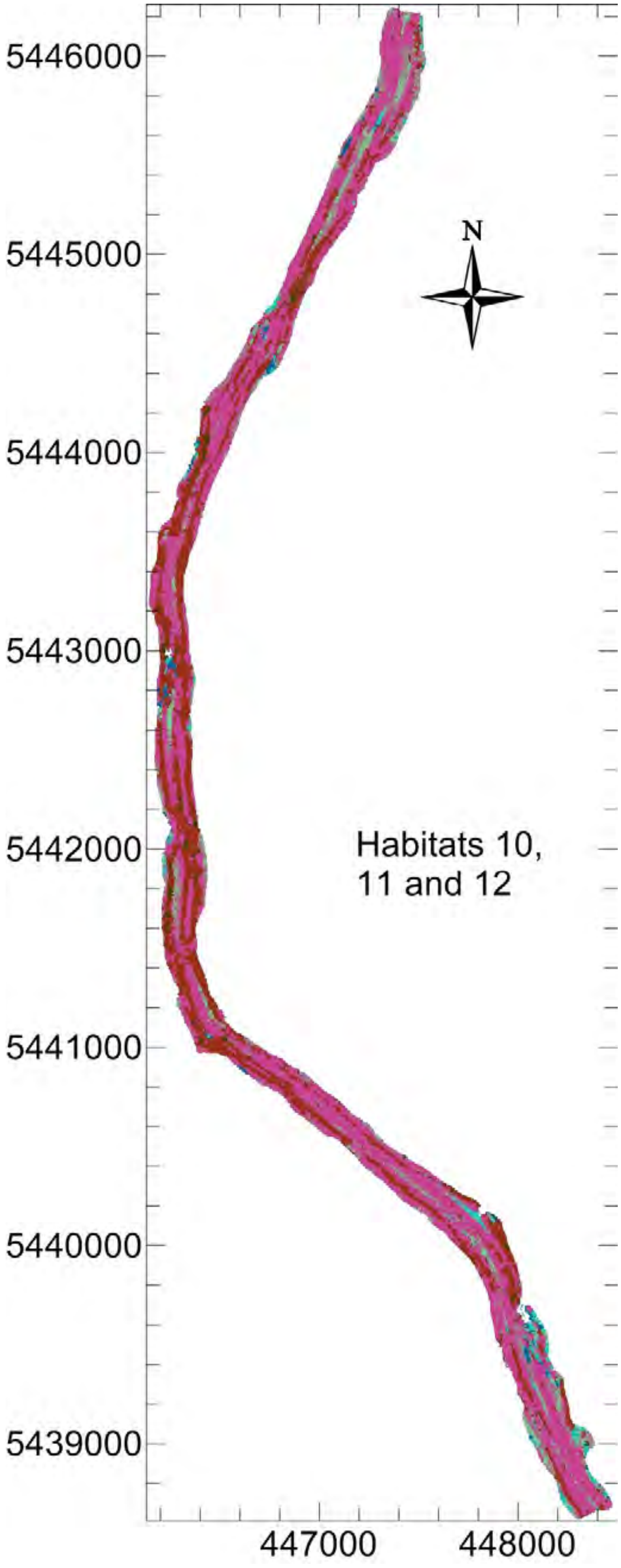


Figure 19. The ten acoustic classes of the fifth habitat group interpolated to a 3-m grid

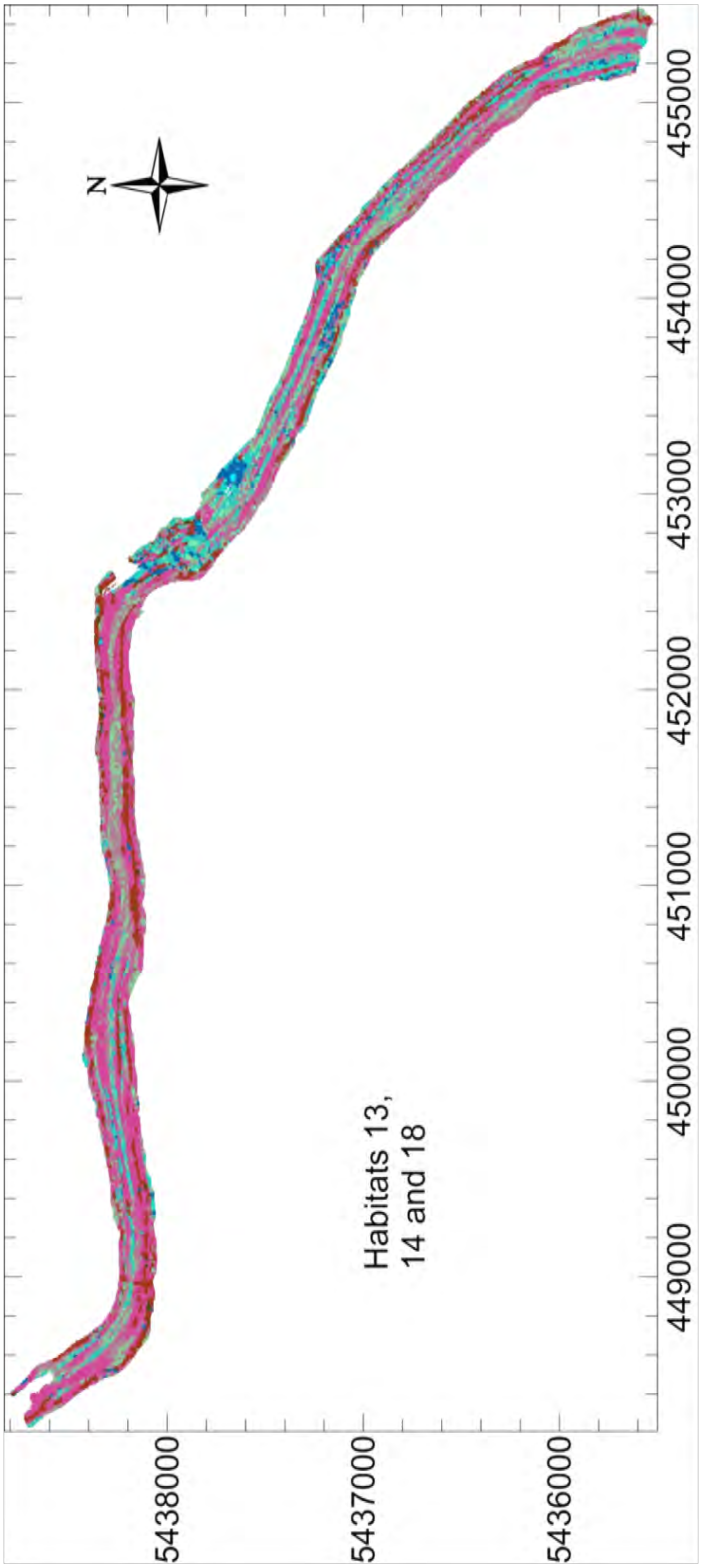


Figure 20. The ten acoustic classes of the sixth habitat group interpolated to a 3-m grid.

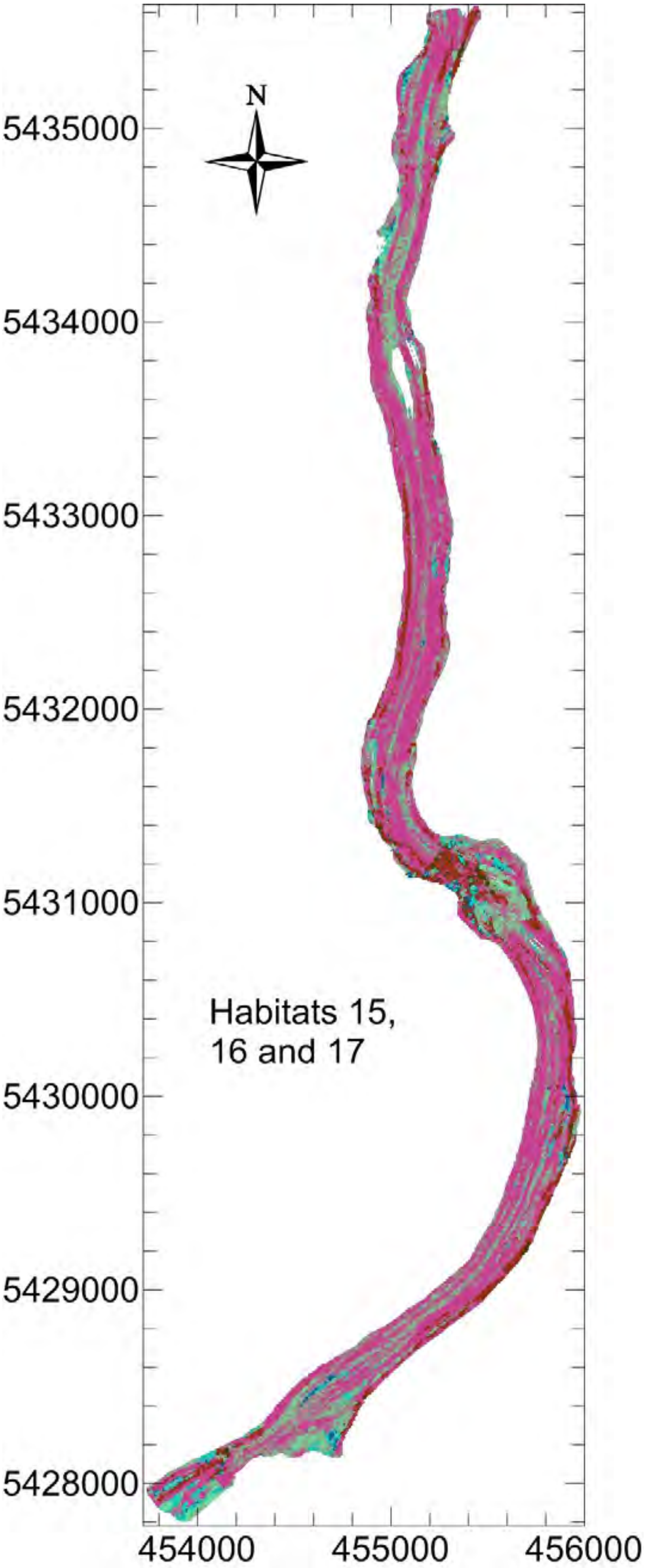


Figure 21. The ten acoustic classes of the seventh habitat group interpolated to a 3-m grid.

APPENDIX B: ACOUSTICS AND THE CLASSIFICATION PROCESS

Introduction

It is well known that the statistical characteristics of a sonar backscatter image depend on the bottom type. Even to a novice user, the texture differences between images of rocks, sand, and mud are readily apparent. Differences between silt and clay are less obvious. Statistical processing can capture many of the pertinent details of the interaction between the sound and the bottom and of its vertical relief. Multivariate statistics can then isolate those details that are rich in information about the bottom, producing features that contain the information necessary for accurate and reliable bottom classifications.

Classification of the river bottom that gave rise to these features is done by an automated clustering method that adapts to the characteristics of the sidescan data set. Each cluster represents a bottom type, which can be identified based on ground truth; for example, photographs, grain-size analysis, or other local data. If the bottom type is known before classification, data from the areas of known sediment type can be used to build a catalogue, which would then be used to classify subsequent or archived data. This is called supervised classification. The alternative, unsupervised classification, forms the data into logical clusters that can then be identified based on ground truth. The effectiveness of unsupervised classification in uncovering practical and valuable information from the acoustic data has been demonstrated in many projects. This clustering technology, with its classification options, forms part of QTC SWATHVIEW and was used in this work.

Riverbed classification can be done visually, mechanically, and acoustically. All visual methods (divers, video, photography) and mechanical methods (divers, grab samples, cores, probes) are slow and manually intensive, thus expensive and not suited to surveys over large areas. Acoustic methods, however, can cover large areas quickly as there is no need to stop the survey vessel. However, sediment identification using acoustics alone is possible only in specific and unusual situations. The information in riverbed backscatter is not specific enough to allow one to state with confidence that the sediment is sand, mud, gravel, or whatever classes are of interest. Instead, acoustic riverbed classification divides survey areas into regions that are acoustically similar and differ from each other acoustically in practical ways. These regions are identified only by numbers. For many purposes they require labels such as sand, mud, and rock. The power of acoustic seabed classification is that far fewer non-acoustic point samples are needed, compared to sampling a grid over a large area. If sampling points representative of each acoustic class are used, sediment properties of those point samples can be applied with confidence over entire regions that have been mapped acoustically. Acoustic classification can therefore be thought of as a technique that extrapolates a few point samples over large survey areas.

QTC SWATHVIEW operates by classifying the riverbed image amplitudes recorded by a sidescan sonar system. Essential preparatory steps are to perform quality control measures on the image and to compensate the image based on the height of the towfish above the riverbed and the survey geometry. The most important part of this compensation is to correct for the large changes in backscatter amplitude with grazing angle, which is calculated assuming a flat riverbed (since there are no other depth data). A compensated image of each survey line is generated as part of the classification process, and a mosaic of those images can be generated.

If there is little or no information about the riverbeds in the survey area, unsupervised classification is used to divide the data set into acoustically distinct classes. This is the technique used in the processing done here, in other words the classes arose from the nature of the acoustic data itself. Alternatively, supervised classification could be used, which involves surveying regions of different riverbed types and building a catalogue of those prior to classifying the complete acoustic survey.

QTC CLAMS™ is a small software package that interpolates class information to grid points using appropriate techniques for categorical, rather than continuous, variables. Using CLAMS is essential for loading class assignments into a GIS because the usual methods of gridding give nonsense results when applied to class numbers.

QTC SWATHVIEW™ and QTC CLAMS™ are commercial software package that were available from Quester Tangent Corp, Victoria, BC, Canada. Quester has recently ceased the marine business. This classification project was done by Dr. Jon Preston, previously senior scientist at Quester now operating as a consultant in acoustic seabed classification (www.acoust-class.ca). Under his direction Quester Tangent Corp. classified at least 50 data sets from multibeam and sidescan sonars. The first of these contracts, in 2002, were done with QTC MULTIVIEW, which made class maps from multibeam images only. QTC SIDEVIEW was brought to market in 2003, for sale and to be used for classification contracts. In 2010, MULTIVIEW and SIDEVIEW were merged to a single product, QTC SWATHVIEW. Throughout these years, class maps were made under contract by Quester Tangent from survey data acquired on or near six continents.

Process Flow

Salient steps in acoustic riverbed classification of sonar images are shown in Figure 22. Not shown is the first step, loading data recorded on the river into QTC SWATHVIEW, during which it is converted and stored in internal formats. Cleaning follows, to set aside regions of the image that do not meet quality standards. Good portions of the image of each survey line are then divided into sub-images. Each rectangular sub-image is the amplitude matrix from which one vector of features is generated, leading to one class assignment for each rectangle.

Typically rectangle sizes are chosen so that there are several to port and to starboard. There are 29 features in each feature vector. These are too many dimensions to plot, so their dimensionality is reduced to three with principal components analysis, or PCA. Classes are generated by an automated clustering method (ACE) that divides the records, one per rectangular sub-image, into acoustic classes based on their similarity.

One important point is that the early stages of classification are done with individual survey lines. Since survey geometry would be lost in the making of mosaics, this is essential for image compensation, which uses beam ranges and angles (for multibeam images) or sonar angles (for sidescan images). The feature vectors from all the survey lines are combined to make a joint full feature vector file, or FFV. PCA and then clustering are done on the combined records.

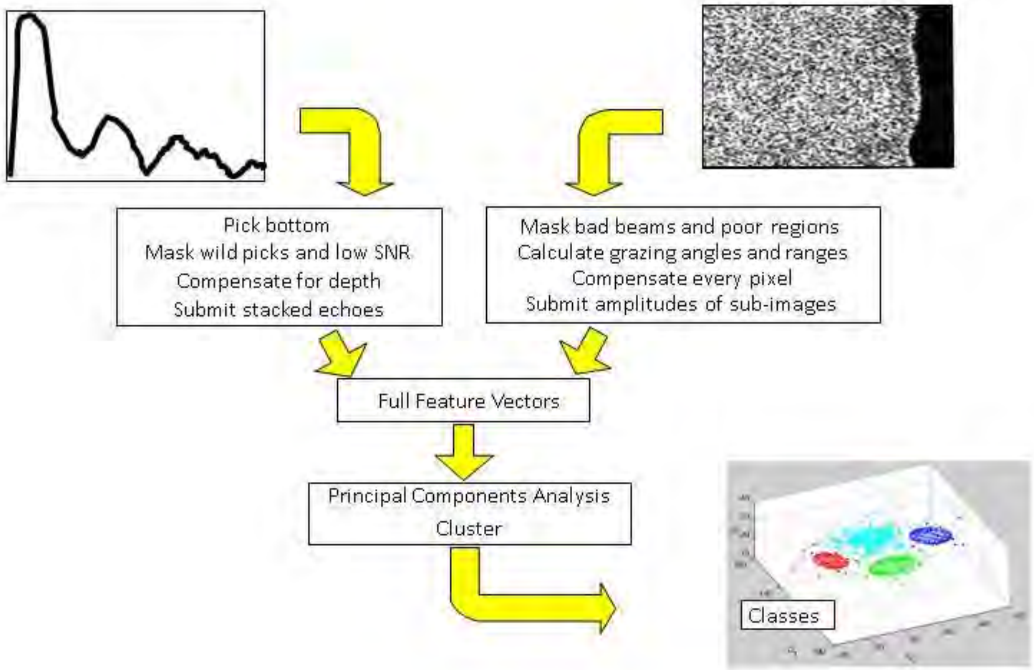


Figure 22. Acoustic riverbed classification processes for single-beam sounders, shown on the left, and for sonar images, on the right. Sounder echoes are classified in QTC IMPACT™ and images in QTC SWATHVIEW™.

Loading original data

The raw sidescan data, as recorded on the boat during the survey, include backscatter amplitudes, positions and other ancillary information. QTC SWATHVIEW classifies images that were generated in any of the three ways used in today's sonar systems:

True sidescan images result from using the transmit transducer for receive. Their only known altitude information is the bottom pick of each ping, that is, the shortest distance between the sonar and the riverbed. Sidescan images can have artefacts such as echo returns from the air-water interface and multipath of the strong nadir echo and other paths.

Picking and Cleaning

Careful quality control is an essential part of reliable and accurate bottom classification. The bottom picks must be accurate because they are used to calculate the grazing angle at each pixel, as shown in Figure 23. Image compensation corrects each pixel based on its range and grazing angle to remove geometrical effects so that the amplitudes are due only to sediment type. Swathview includes an automatic pick routine that picks sidescan images or improves existing picks. Several control parameters are available to guide the pick process including amplitude threshold and number of pixels after a candidate pick that must exceed the threshold for the pick to be valid. Even with expert use, picks often need manual inspection and correction.

Ideally, all the image from the pick to the chosen sonar range is of the riverbed alone. Three types of artifacts can, however, overwrite the riverbed image. An obvious one is man-made objects. These typically appear as bright objects with large deep shadows. If the sonar range is much larger than the towfish altitude there can be

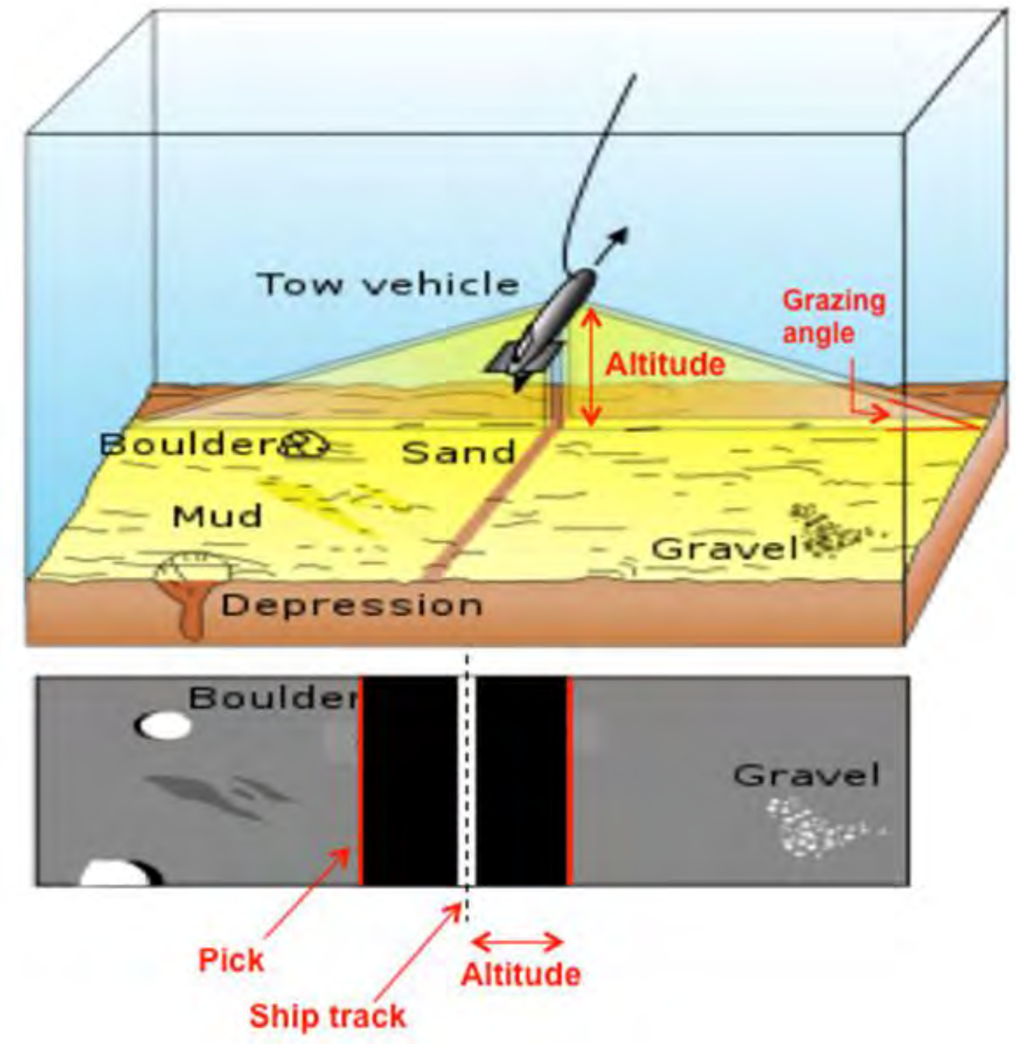


Figure 23. The grazing angle at each pixel of a sidescan image is the angle whose sine is the towfish altitude divided by the slant range. A right-angled triangle has to be assumed because the depth profile acrosstrack is unknown.

multiple routes for the riverbed reflection to return to the towfish. Multipath additions to the riverbed image often appear fluffy, almost pillow-like. With some sidescans there can be strong reflections from the water-air surface, appearing as a strong line at a range that depends on the depth of the towfish beneath the water surface. The third cause is smearing by excessive towfish motion. Yawing is the worst offender, causing a single object such as a rock to appear in the image as a curved line. All of these can be masked from the classification process by manually moving the border (blue line) within them.

Another consideration is that changes in sonar operating conditions can affect image texture. Changes in pulse length or frequency can require breaking the data set into subsets that were collected with consistent sonar operating conditions. Acquisition parameters were consistent in this data set, so all the data could be classified together.

Dividing images into sub-images

The image of each survey line is divided into rectangular patches, port and starboard. The user chooses the patch size, thus selecting the classification spatial resolution. Masks are interrogated to ensure rectangles do not include regions with poor data. The number of samples in each raster, mask constraints, and the user-selected patch dimensions determine the number of patches per side. They abut, but do not overlap. A class assignment will be generated for each patch. These patches are often referred to as rectangles in this context.

Rectangle dimensions are normally chosen in order to generate patches that are approximately square on the riverbed. As the across track resolution of acoustic sonar systems is not constant due to the physics of the operation of the sonar system, and the along track resolution is dependent on the survey speed, ping rate and yaw rate, the sizes on the riverbed are an approximation. Rectangle dimension choice also determines the resolution of the final classification

As QTC SWATHVIEW generates rectangles, a two-dimensional table of amplitude vs. range and grazing or sonar angle is created and filled. Grazing angle is illustrated in . The tables are known as compensation tables. This patented technique allows the image to be compensated for variations in backscatter amplitude with grazing angle and travel time (that is, acting as a residual TVG). The compensation process is performed automatically without any input from the user. Even though compensation is hidden, it is a very important step because backscatter amplitudes vary dramatically with grazing angle, and from beam pattern effects in the case of pure sidescan systems. Without compensation, most boundaries between classes would be parallel to vessel tracks, which is not reasonable. Even with this sophisticated compensation technique, some remnants of classes in streaks parallel to vessel tracks occasionally occur.

QTC SWATHVIEW can store the compensated amplitudes of each survey line, with user-selected resolution. These so-called CompEx files can then be concatenated, either within QTC SWATHVIEW or in some other way. This file, containing only positions and backscatter amplitudes, can then be gridded in any GIS, making a mosaic compensated with this patented technique.

Generate Features

Features are statistics that capture pertinent information about the backscatter amplitudes in each rectangular sub-image. QTC SWATHVIEW uses 29 features, selected so that at least a few give the discrimination we seek with each type of image. Principal components analysis (PCA), in the next processing step, selects those three combinations of features best suited for each classification task. There are four families of features:

Basic Statistics: Mean, standard deviation, and higher-order moments are indicative of overall acoustic impedance changes and average interface roughness.

Grey-Level Co-occurrence Matrices (Haralick): Grey-Level Co-occurrence Matrices (GLCMs) describe the amplitude changes over selected distances and directions in the image patch, and are widely used to assess texture in many types of images. The matrices themselves are not used as features; rather statistics called correlation, contrast, entropy and homogeneity are calculated from them.

Power Spectra: Fast Fourier Transforms (FFTs) are used to find power spectra, which describe statistical characteristics on many resolution scales. The amplitude time series from which these are calculated lie in a spiral pattern around the central pixel of each rectangle, which makes these features sensitive to directional structures in the image.

Fractal Dimension: Fractal dimension is a statistical quantity that gives an indication of how completely a set of data appears to fill space. With images, the space has three axes: sample number (acrosstrack), raster number (alongtrack) and amplitude.

Multivariate Statistical Analysis

A major strength of QTC SWATHVIEW processing is the incorporation of multivariate statistical techniques as they permit the use of many features. Experience has shown that some features are important in what might be called the standard classifications: mud, sand, gravel, and so on. Others are important for more specialised classifications such as discriminating among sand/mud mixtures. For any particular data set, PCA selects the features that are most useful for the discrimination task at hand. Features that are close to constant are largely disregarded. Redundancies, that is, correlated features, are also acceptable, but only one remains significant. What is left is a reduced feature set that compactly describes the diversity of the data set. While some features may have little diversity or be tightly correlated when used to describe one set of riverbed sediments, such as open continental shelf sand and gravel, they may be found to give useful discrimination in other cases, such as on deltaic sediments. Thus, the connection between features and classification adapts to the character of the data set.

For each patch of each image, the features are calculated and then arranged as a row vector containing 29 elements. The name given to these rows of features is Full Feature Vectors (FFVs). Each row contains features from one rectangular patch, with 29 columns. One feature matrix is produced for each survey line and stored in an FFV file.

The goal of riverbed classification is to make class maps for entire survey areas. It is at this point in the process that the feature matrices from each survey line are concatenated to form a single feature matrix, called a merged FFV file, to be supplied to the PCA process. These merged FFV files can be quite large.

The nature of PCA is that the first principal component, that is, the first weighted combination of features, contains as much of the variance of the data set as possible. The second component contains the maximum possible amount of the remaining variance, and so on. In our experience with acoustic classification, the first three components almost always capture a very high percentage of the variance, 90% or more, so the rest of the components can be disregarded. These top three components are what we call Q-values. During this data reduction, a catalogue file is created. This catalogue contains the reduction matrix that is necessary for the creation of the Q-values from features, that is, the PCA weights that multiply each feature to make the top three components.

Divisions into clusters

The acoustic response - represented by Q1, Q2, and Q3 - from like riverbeds will be similar. When plotted in three dimensions, which we call Q-space, points with similar values, from acoustically similar riverbeds, form a cluster. Thus, data from three different riverbeds would form three clusters and new data points would be classified based on their locations relative to those clusters in Q-space.

In QTC SWATHVIEW, clustering is almost always done with its automated objective clustering method, ACE. ACE starts with a random assignment of records to classes, discards those that are obviously poor, and then improves the others through a perturbation method called simulated annealing. This involves perturbing the list of class assignments, assessing the quality of the new arrangement based on changes to a cost function called the Bayesian information content, and accepting any perturbation that improves that score plus some that worsen it. This produces a large number of trial assignments of records to classes, all independent of each other. For each trial number of clusters, the best result is the one with the lowest score, and the statistically best number of clusters is the one with the lowest overall score. For most data sets, ACE is best left to run overnight.

The identification of the appropriate number of classes after an ACE run is influenced by user requirements. Sometimes the statistically optimal number of clusters is too many for convenient labelling or use. In cases like these, it is usually found that some of the classes have few members. The user is free to select a smaller number of classes, guided by the ACE scores.

QTC SWATHVIEW still supports clustering with an older manual method in which the results can be significantly influenced by user choices as clustering proceeds. The only time this continues to be used is if there are fewer than 1000 records, which is the minimum for the statistical background of ACE.

After clustering is complete, the cluster positions and shape information are added to the catalogue. Each catalogue is specific to the sonar system used for data collection and may also be specific to particular operating conditions of that sonar. Catalogues can be based on a set of sample sonar images or on entire data set. It is through the use of catalogues that unsupervised classification can be extended to other areas, without needing to repeat the multivariate statistical processing.

Supervised classification is useful when there is existing knowledge of the riverbed in parts of the survey area. Image patches from those known homogeneous areas are used to make a catalogue. With this process, the clusters have labels, such as sand, mud, or rock, as soon as they are formed, since the points in each cluster have come from that known riverbed sediment. This contrasts with unsupervised classification, which is more common and was used in this work, in which the natural diversity of the data is identified through automatic objective clustering. QTC SWATHVIEW offers both supervised and unsupervised techniques and is the only product on the market that offers unsupervised classification.

Classification of Riverbed

Classify Seabed is the process of assigning records to classes by applying a catalogue to FFV files. Confidence and probability values of these assignments are also calculated. Its output is a seabed file, a comma-delimited text file that includes position, depth, Q-values, class assignment, confidence, probability and supporting data for each record. Each rectangular sub-image leads to one row in this seabed file.

Once a catalogue has been made, each patch from a new survey can be assigned to a cluster, or sediment type, without re-doing PCA and clustering. As well as the class assignment, confidence and probability values for that assignment are produced for each new assignment. Probability and confidence are important in deciding if a sediment type is missing from a catalogue.

Class maps

The most important data in the seabed file are the locations of the centers of each image rectangle and the class to which it was assigned. Class numbers are integers in no particular order. The classified points are distributed irregularly over the survey area, and therefore have to be gridded for use in a GIS. Interpolating categorical data, such as class numbers, is very different from interpolating continuous variables, such as depth. The mean value of class numbers near each grid point is inappropriate for two reasons: it is not usually an integer and a class number between the numbers around the point may be a very different class found only in a remote part of the survey area. Quester Tangent developed and sells QTC CLAMS because very few of the usual GIS suites support categorical interpolation. QTC CLAMS interpolates the point class assignments, or other categorical data, to a regular grid. Each assignment is the mode, not the mean, of the field points near each grid point. In practice, distance weighting is used, meaning that QTC CLAMS creates a mini-histogram of class assignments for each grid point. QTC CLAMS saves its grids of class numbers as geoTiffs and as grid files for use in Surfer™, among other formats. Surfer™ can convert these grid files to the corresponding files for use in many popular GIS suites.

A detail of the class maps produced by QTC CLAMS, and also by ACE's trackplot window is the use of similarity colours. Each cluster is coloured according to the position of its centre in Q-space, with red saturation corresponding to the Q1 coordinate, green to Q2, and blue to Q3. Classes with similar colours are near neighbours in feature space and therefore represent riverbeds that are acoustically similar in the context of the range of acoustic diversity in the full data set.

APPENDIX C: GLOSSARY OF TERMS

ACE, Auto Cluster Engine Automated clustering technique that finds an optimum clustering result in an objective statistically-sound process. It operates by perturbing a set of class assignments, attempting to a lower a cost function, or score. Simulated annealing is used to attempt to find global, rather than local, minima of the score.

Backscatter Reflection or scattering of acoustic energy back to the source. It is dependent upon substrate structure and composition.

Bathymetry Depth values. Tidal corrections are unimportant in acoustic seabed classification.

Bayesian Statistics An important school of statistical theory in which statistics are derived from a model-based probability interpretation. Quester Tangent uses a Bayesian classifier rule that assigns points to clusters based on conditional probabilities, meaning that the covariances and populations of the clusters are considered.

Caris HIPS/SIPS™ A software package for processing survey data, developed by Caris Ltd., Fredericton, NB, Canada.

Catalogue Listing of the information needed to assign a class to an FFV. A catalogue can be used to classify the data set from which it was derived, or other data sets. Catalogues have two parts: a reduction matrix to convert feature values to Q values, and a list of cluster centres and covariances that are used to assign a record in Q-space to the cluster whose centre it is closest to. A Bayesian metric is used to measure these separations.

Class An acoustically distinct riverbed type. Each cluster in feature space is a class.

Clustering A process in which image patches are grouped together as clusters, based on their statistical character as captured in features. Before clustering it is usual to reduce the dimensionality of feature space with PCA or a similar process that concentrates feature variability in a few weighted sums of features.

Compex A tool within QTC SWATHVIEW that writes files of compensated image amplitudes at resolution specified by the user.

Feature A descriptor or statistical attribute of an object for the purpose of classification. The object may be a time series, image segment, or other portion of a set of data.

FFV, Full Feature Vector A series of features from the same object.

FFV file A collection of FFVs from a survey line or survey area.

GIS, Geographic Information System Suite of software tools that manage, analyze, and display data that are linked to positions. Acoustic seabed classes are a type of remotely sensed geographic data that can be presented as a layer in a GIS. This requires that the classes be assigned, by QTC SWATHVIEW, and then gridded, by QTC CLAMS.

GLCM, Gray-level Co-occurrence Matrix GLCMs are second-order statistics of an image, meaning that they depend on the arrangement of pixels. Each entry of a GLCM at position (i,j) is derived from the gray-level image on which it is based and is the number of pixel pairs having amplitudes i and j and separated by a chosen number of pixels in a chosen direction or its reverse.

Grazing Angle The angle between a sonar ray and the seabed, specifically a tangent plane where the ray intersects the seabed.

Image Compensation Sonar images contain systematic variations of backscatter amplitude with range and grazing angle. Compensation removes, or sharply reduces, these geometrical effects, leaving an image that is rich in sediment information.

Mask In image processing, a mask is an array, the same size as the image, of integers that indicate characteristics or dispositions of pixels. As used here, a 0 indicates a pixel that has not been excluded for any reason.

PCA, Principal Components Analysis A process that determines a rotation matrix that maximizes the extents of projection on orthogonal planes. The rotation puts the maximum extent, thus the maximum variance, along the first axis, as much as possible of the remainder on the second axis, and so on. Positions of data points on the rotated axes are called principal components.

FFT, Fast Fourier Transform An algorithm that transforms a time series into its frequency representation, or the reverse. An FFT is often used to find the distribution of power across the frequency band of a signal.

Q-Space A three-dimensional space whose axes are the first three principal components of a set of FFVs. These axes are called Q1, Q2, and Q3. To classify a survey area, FFVs of individual survey lines are merged before the PCA process is run on the merged FFV file. This is the view of the data that the clustering process works with.

QTC Quester Tangent Corporation

QTC CLAMS™ (**CLAssification Mapping Suite)** Software that assigns class numbers to regularly spaced grid points starting with irregularly spaced class numbers. QTC SWATHVIEW assigns classes to locations along survey lines, thus irregularly spaced.

QTC SWATHVIEW™ A suite of software tools that classifies the seabed using sonar images from multibeam or sidescan sonars.

Sonar Angle The angle between a sonar ray and a reference plane of the sonar system. A suitable reference plane is horizontal through the centre of the transducer when it has zero pitch and roll.

Seabed The solid surface between the sea and the underlying ground. Often used as a synonym for lakebed and riverbed.

Seabed File Primary output file of QTC SWATHVIEW and QTC IMPACT. An ASCII file with times, positions, depths, class assignments and other information about each classified point. The format is in an appendix of the User Manual.

Surfer A simple GIS sold by Golden Software Inc., Golden, Colorado, USA.

TVG, Time Variable Gain Almost all sonar systems use amplifiers whose gain increases with time since the ping was transmitted. The motive is to make all backscatter amplitudes similar in spite of the losses due to spherical spreading. TVG could also compensate for absorption in the water, but this is rarely done.

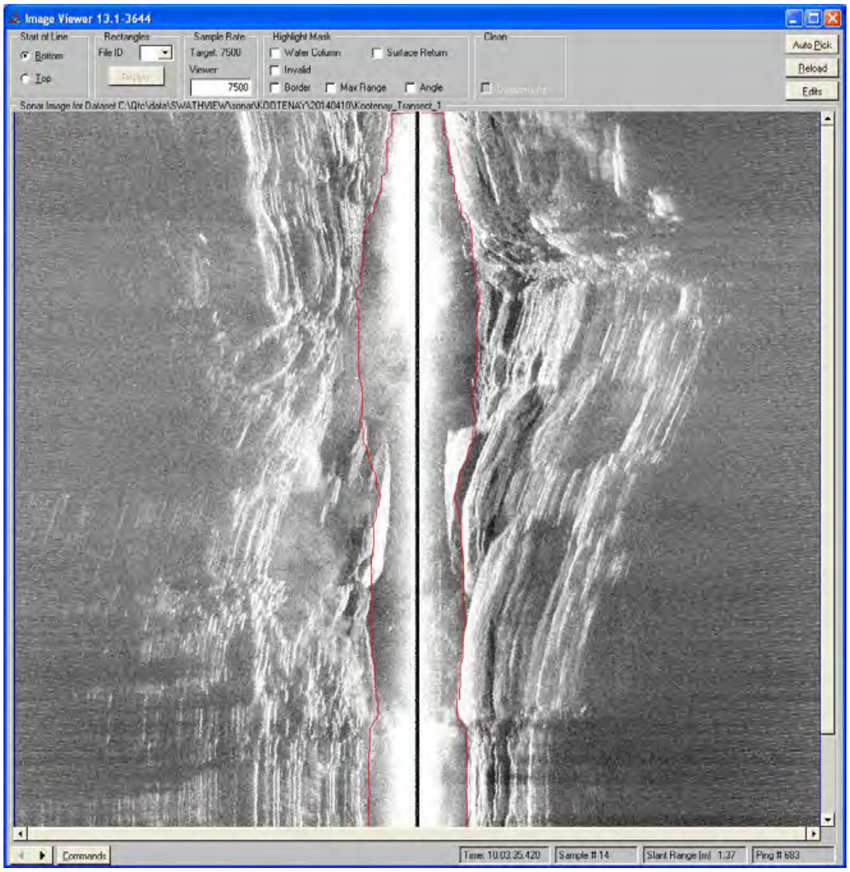
APPENDIX D KOOTENAY RIVER

This appendix describes classification of five transects recorded on the Kootenay river, near the junction with the Columbia, on 15 April2014.

Swathview allows two techniques for classification of a lesser survey completed after a larger data set has been classified. Both start by cleaning the new data, dividing the unmasked parts of the images into rectangles, and generating features. One is to merge all the FFVs, old and new, together and repeat the clustering, mapping, and labelling of classes. The other is to apply the catalogue from the existing survey to divide the new image into the same classes. The latter was done with these five lines., for practical reasons and also because the image quality of the Kootenay survey is poor.

Image Quality

It seems that these images were acquired when the river level was low and the flow was high. When the sonar altitude is less than a few metres, multipath starts early in the image, plus the pick is uncertain. The mask has to start just a few metres into the image with this geometry. Even with the range setting reduced to 50 m (from 68 in the LCR), little image is left to classify. The water flow was turbulent, yawing the boat and generating bubble clouds. Both of these degrade sonar images. In Figure 24 riverbed objects in the starboard image have been stretched into long lines as the boat yaws or turns to starboard, since during the turn the starboard beam insonifies the same piece of riverbed repeatedly. The long black clouds in Figure 25 were caused by almost all the



Target: 7500

Viewer: 7500

Sonar Image for Dataset C:\Qtc\data\SWATHVIEW\sonar\KOOTENAY\20140410\Kootenay_Transect_1

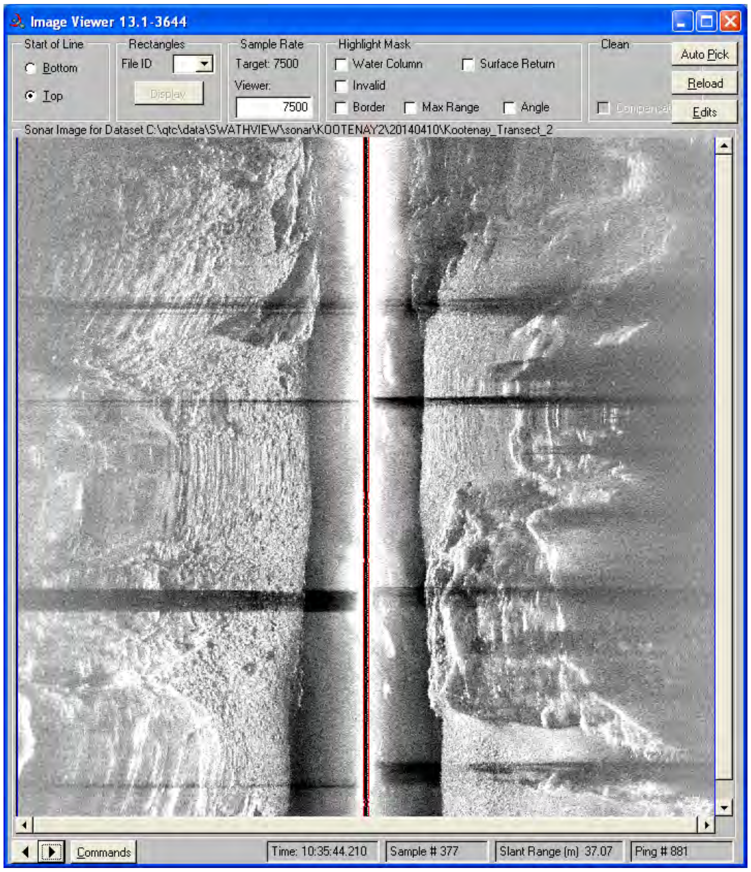
Time: 10:03:35.420

Sample # 14

Slant Range (m) 1.37

Ping # 683

Figure 24. Image distortion caused by yaw.



○ Bottom
● Top

Sample Rate
Target: 7500
Viewer: 7500

Sonar Image for Dataset C:\qtc\data\SWATHVIEW\sonar\KOOTENAY2\20140410\Kootenay_Transect_2

Time: 10:35:44.210 | Sample # 377 | Slant Range (m) 37.07 | Ping # 881

Figure 25. Streaks of the image are in shadows of bubble clouds.

energy of those pings being scattered in the water column. Bubble clouds can certainly do this, as could dense schools of fish, which seems less likely. In these five survey lines, large fractions of each image had to be masked for these three reasons: multipath, yaw motion, and bubble clouds.

Classification Process

The five lines were masked and bottom-picked manually. Further masking was the first one metre of riverbed image and any pixel with a grazing angle more than 80°. These further choices masked only a thin ribbon of each image near the boat. The same masking process had been used with the LCR. Rectangles were generated with the same number of pixels as with LCR, 33 x 17. The sample rate was higher because the range setting was less and there are always 500 samples each side in a Starfish image. This meant that the across-track dimension was less on the ground, but that had virtually no effect on the classes. The same 29 features as in LCR were generated for each rectangular sub-image. The five resulting FFV files were then merged. Swathview's Classify Seabed step was then used, applying the same catalogue used for the LCR classes to the merged FFV file. This assigned each image rectangle to one of the same ten classes used for the LCR.

An inherent risk in this process is that there could be a sediment type present in the Kootenay survey that was absent in the previous LCR survey. From a practical point of view, this is unlikely because the images are similar and not high quality. Nevertheless, this can be investigated by making contour maps of classification confidence and probability, and this was done for this survey. Contours of probabilities of correct classification are shown in Figure 26. The existence of a new riverbed substrate would have been shown by large regions of low probability in this map, but there are none.

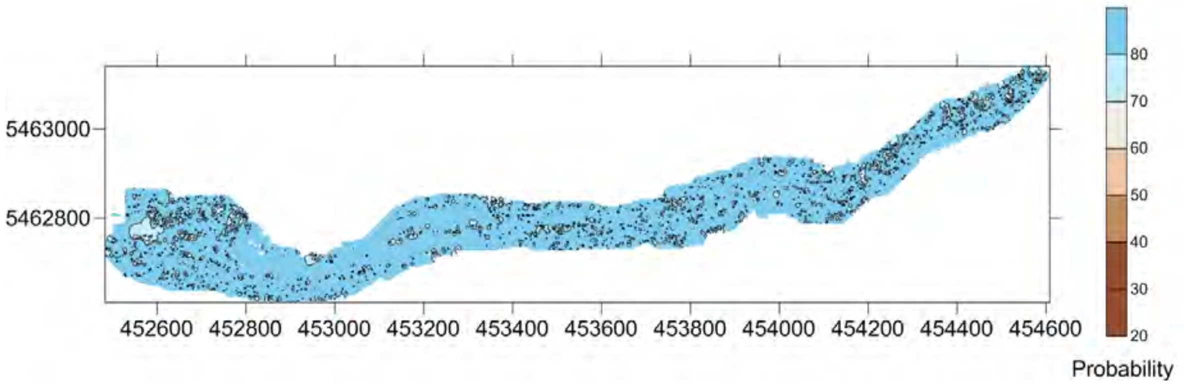


Figure 26. Contours of the probability that a point has been assigned to the class closest to it in feature space. Probabilities less than 50% or so would indicate that the points are far removed from the nearest class centre, and thus that their acoustic character differs significantly from that of the class. Thus any large brown regions in this map would imply the presence of a riverbed substrate that was not in the LCR survey.

The interpolation process in CLAMS was the same as that used for LCR: search radius 25 m, search size 12 points, and a class assigned to a grid point only if field points were present in at least 5 of 8 45° sectors around it.

Map of the lower Kootenay River

Figure 27 is the interpolated class map of this survey of the lower Kootenay River. Quality seems to be good, in that there are no streaks of individual classes parallel to the boat track. However the overlap between this map and the classes of Habitat 4 does not show good agreement. As explained above, though, the image quality from this survey was not good. Further mapping of this area should be based on new sonar images.

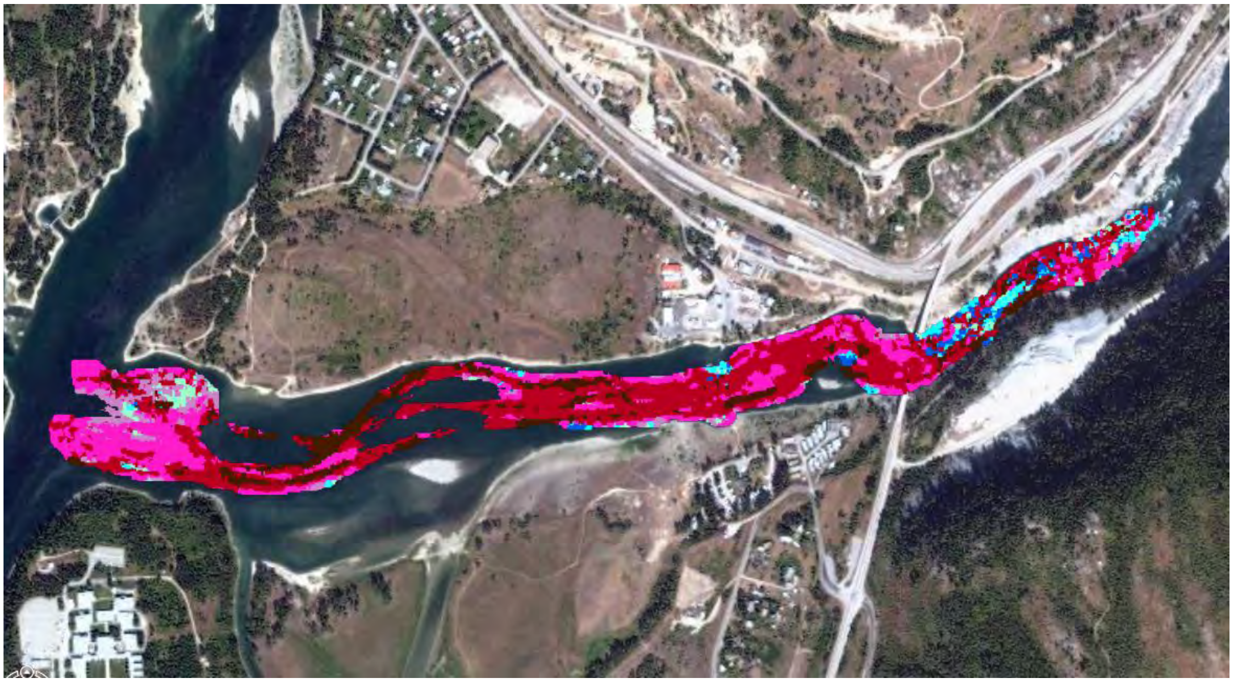


Figure 27. Class map of the Kootenay River through Castlegar. These are the same ten classes present in the LCR classification, with the same colours. Coverage near the junction with the Columbia is sparse because the water is shallow there and for the reasons given in the text.