Factors controlling dissolved oxygen in spawning gravels: evaluation of the Sediment Intrusion and Dissolved Oxygen model (SIDO) for fisheries management

by

Quinn Decent

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Science
in
Geography and Environmental Management

Waterloo, Ontario, Canada, 2020

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

Abstract

Natural and anthropogenic landscape disturbance pressures have accelerated the transfer of fine sediment to streams in forested headwater regions of the eastern slopes of the Rocky Mountains. The accumulation of fine sediment in spawning gravels can reduce survival rates of salmonid eggs by decreasing intragravel flow velocities and dissolved oxygen concentrations. The goal of this study was to examine the effect of fine sediment intrusion on the abiotic characteristics of the salmonid redd and assess the potential consequences for egg development and survival using a physically based numerical model SIDO (Sediment Intrusion and Dissolved Oxygen). Field observations from the Crowsnest River, Alberta, Canada were used to calibrate the model using flow, suspended solids and sediment accumulation data as well as high frequency dissolved oxygen (DO) measurements in spawning gravels. The impact of varying sediment inputs upon sediment intrusion rates, abiotic redd characteristics and fish egg survival rates were assessed using SIDO. Dissolved oxygen concentrations in redds were highly variable both within and between sites and varied with observed changes in river discharge and suspended sediment concentrations. Trends in measured and modelled DO concentrations in redds were generally comparable, reflecting a general decrease in dissolved oxygen levels in spawning gravels over the study period. SIDO was not sensitive to measured short term fluctuations of DO and modelled predictions of DO were higher than measured values. The quantities of sediment ingress predicted by SIDO were lower by an order of magnitude than those measured in ingress baskets. Differences between observed and modelled DO are related to the fact that this physically based model does not include terms that describe the effects of groundwater and biotic (microbial) processes on dissolved oxygen in spawning gravels. The potential of SIDO as a tool for fisheries management will be enhanced by including terms that describe groundwater and microbial processes that influence spawning gravel DO dynamics.

Acknowledgements

I cannot overstate my gratitude to my supervisor Dr. Stone for providing me with this incredible learning opportunity, and for his endless advice, encouragement, and patience along the way. I couldn't have asked for a more supportive supervisor, and my graduate experience has been an extremely positive one because of you. Thank you to everyone at the University of Waterloo; Mia Stratton, Caitlin Watt, Terry Ridgeway, and Vito Lam, for your immense help with the fieldwork. Thanks to the Southern Rockies Watershed Project, specifically Dr. Silins, Chris Williams, Erin Cherlet, and Kalli Herlein for the field support and advice, and it was great experience working with all of you. I would like to extend an immense thank you to Dr. Krishnappan for his invaluable guidance concerning the SIDO model and programming advice. Lastly, thank you to all my family and friends who have been supportive of me along the way. Also, thanks to George Box for perfectly summarizing my thesis by stating "All models are wrong. Some are useful".

Table of Contents

List of Figures

List of Tables

Appendices

Chapter 1

Introduction

1.1 Problem Statement

Landscape disturbances can change the supply and delivery of fine sediment (<2mm) to gravel bed rivers (Owens et al., 2010) which can subsequently alter the form and function of rivers over a range of time scales (Bladon et al., 2008; Hauer et al., 2016). Increased delivery of fine sediment to spawning gravel can dramatically alter the habitat of aquatic biota and lower dissolved oxygen (DO) levels (Newcombe and Macdonald, 1991; Wood and Armitage, 1997; Bilotta and Brazier, 2008). Field and laboratory studies have demonstrated that embryonic survival rates of salmonid species decline in rivers with increasing amounts of fine sediment deposition and ingress into spawning beds (McNeil and Ahnell, 1964; Lapointe et al., 2004; Jensen et al. 2009; Kemp et al., 2011). Fine sediment ingress decreases intragravel velocities and the supply of dissolved oxygen which are critical for healthy embryonic development (Chapman et al., 1988). The degree of landscape disturbance impacts on embryonic survival rates within spawning gravels is governed by the type, duration and severity of disturbance, interactions amongst abiotic and biotic watershed scale controls including the reach morphology, substrate type, geology and hydrology climatology (Chapman et al., 1988). Rigorous quantification of the effects of abiotic and biotic controls to intragravel dissolved oxygen, especially when considering post-landscape disturbance effects, has been identified as a critical priority for managing spawning gravel quality (Grieg et al., 2007a, 2007b; Meyer et al., 2008; Sear et al., 2017).

Previous research on DO dynamics in spawning gravel has included studies of in situ measurements of DO at the field scale (Petticrew and Rex, 2006; Meyer et al., 2008; Malcolm et al., 2010; Sear et al., 2014b), field and laboratory sediment oxygen demand experiments (Sear et al., 2017), and application of models to simulate DO dynamics in spawning gravels (Alonso et al., 1996; Tonina and Buffington, 2009). Collectively, this research has improved knowledge of the effects of fine sediment ingress (Chapman, 1988), particle size (Grieg et al., 2005b) and biogeochemical characteristics (Sear et al., 2017) on DO variability dynamics in spawning gravels.

Other physical parameters influencing DO include bed topography (Carling, 2006), bed mobility (Sear et al., 2014), and groundwater inputs (Malcolm et al., 2004). Notably, this research illustrates that DO dynamics in spawning gravels are complex and highly variable within and between river systems (Peterson and Quinn, 1996; Groves and Chandler, 2005; Malcolm et al., 2010). Accordingly, prediction of the effects of fine sediment intrusion on DO dynamics in post disturbance spawning gravels remains a key challenge for fisheries management. Physically based models such as SIDO (Sediment Intrusion-Dissolved Oxygen) have been used to simulate some of the fundamental processes controlling DO dynamics within spawning habitat (Alonso et al., 1996). However, several questions remain regarding the broader applicability of these models for a range of riverine environments (Sear et al., 2014b).

Gravel bed rivers represent critical habitat for the maintenance of diverse aquatic ecology in the Eastern Slopes of the Rocky Mountains in Alberta (Hauer et al., 2016). Rivers in these forested headwater regions contain high quality spawning habitat for several cold-water fish species, including Westslope Cutthroat Trout (*Oncorhynchus clarkii lewisi*) and Bull Trout (*Salvelinus confluentus*), two species in this region of Alberta that are currently listed as *Threatened* by COSEWIC (Committee on the Status of Endangered Wildlife in Canada). The effects of elevated sediment levels exacerbated by anthropogenic and natural landscape disturbances are recognized as critical threats to native salmonids in the Eastern Slopes of Alberta (Sterling, 1992). Anthropogenic disturbances include logging, natural resource development and exploration, agriculture, motorized recreational activity, and urban/road development (Mayhood et al., 2014). Wildfire is the most severe and dominant natural landscape disturbance in the region, and these climate related disturbances are increasing in severity and frequency throughout northern North America due to factors including higher seasonal temperatures and drought (Westerling et al., 2006). Wildfires can dramatically increase fine sediment runoff and nutrient concentrations into receiving catchments (Moody et al., 2013) and create legacy effects to water quality, nutrient dynamics, and biota within gravel bed rivers (Emelko et al., 2015).

To date, no research has been conducted to rigorously quantify DO dynamics in spawning gravels in the Eastern Slopes of the Rocky Mountains. Specifically, no field-based studies have been conducted in this region of Alberta to provide sufficient data on fine sediment intrusion, intragravel DO, river discharge, and other physical river characteristics to validate and calibrate models that influence DO levels in spawning habitat. The overall goal of this study is to test and validate the SIDO model to predict interstitial DO concentrations and fine sediment intrusion (Alonso et al., 1996). Model validation is based on using long term, high frequency in situ DO data measured directly within interstitial spawning gravel habitat. This "proof of concept" study will assess the utility of SIDO as a tool for regional fisheries and watershed managers to quantify the effects of altered sediment regimes from landscape disturbances on intragravel DO dynamics within spawning habitat in the Eastern Slopes of the Rocky Mountains.

1.2 Research Objectives

The objectives of this study are to:

1. Quantify changes in DO regime and sediment ingress within artificial redds in a gravel bed river during the spawning season;

2. Evaluate the influence of physical processes controlling the DO regime including river discharge, suspended sediment concentration and thermal regimes;

3. Undertake numerical modelling using SIDO to quantify the relative contributions of sediment accumulation, thermal regime and river discharge on the DO regime within the artificial redd;

4. Evaluate the model performance and assess its future applicability as tool for fisheries management in gravel bed rivers draining the Eastern Slopes of the Rocky Mountains

1.3 Literature Review

1.3.1 Landscape disturbances and effects to fine sediment dynamics

The delivery, transport and fate of fine sediment within gravel bed rivers is frequently defined by unique physical, chemical and biological characteristics of a landscape (Collins and Walling, 2007). In high quality gravel bed rivers such as those draining forested regions of the Eastern Slopes of the Rocky Mountains, sediment delivery is elevated during spring freshet, but after landscape disturbance such as wildfire, sediment fluxes can increase dramatically compared to rivers draining unburned landscapes (Stone et al., 2014). For example, largescale wildfires in this region can alter sediment flux at rates and magnitudes that can create significant legacy and short-term effects to river function (Bladon et al., 2008). Some of these effects include impacts to ecosystem structures (Bixby et al., 2015), biota health and diversity (Rieman et al., 1997) and water quality (Silins et al., 2014). The relative impact of large-scale wildfire on river functions is dependent upon the magnitude and severity of the wildfire, resilience of the watershed, and geological and vegetation characteristics (Bladon et al., 2008). Wildfire alters runoff and soil erodibility properties (Moody and Martin, 2001) that ultimately affect the transport properties of sediment such as settling velocity, porosity and density (Stone et al., 2011), and nutrient dynamics (Blake et al., 2009).Accordingly, there is a recognition that improved knowledge of both the quantity and quality (ie. organic content, trace elements, particle size) of sediment delivered to a gravel bed river is required to predict and manage downstream responses (Sear et al., 2016; 2017). In the case of salmonid spawning habitat, changes in the quantity and quality of fine sediment ingress in spawning gravels can have severe impacts to the health of developing embryos (Grieg et al. 2005a; Grieg et al., 2007b; Sear et al., 2014a). These physical and biogeochemical impacts occur in a unique microenvironment selected and built by the female salmonid within the gravel bed river (Chapman, 1988).

1.3.2 The salmonid spawning microhabitat

Female salmonids select spawning sites based on site characteristics (ie. depth, discharge, slope, gravel size, geomorphic features) and availability (Bjornn and Reiser, 1991; Crisp, 1996; Geist and Dauble, 1998; Kondolf, 1993; 2000; Armstrong et al., 2003). Female salmonids excavate a pit in the gravel bed, lay eggs, then cover them with upstream gravel after they have been fertilized (Burner, 1951). The completed dune-like structure is called a “redd” (Figure 1.1). The building process, structure characterization, and egg burial depths have been previously described for many salmonid species (Smith, 1941; Burner, 1951; Chapman, 1988; Crisp and Carling, 1989; DeVries, 1997). Embryos undergo several developmental stages in the redd (up to four months) before swimming through gravel pore spaces and emerging into the channel (Chapman, 1988; Malcolm et al., 2008). Emergence times are dependent on a range of biological, chemical, and environmental conditions in the redd (Malcolm et al., 2008).

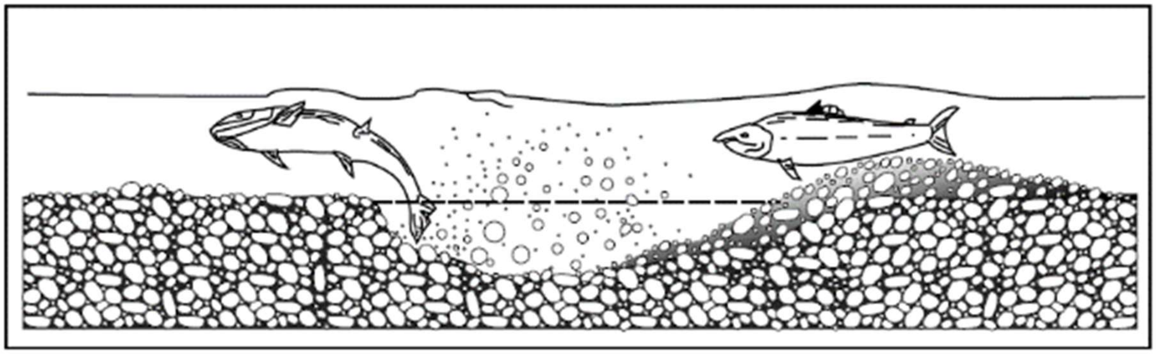


Figure 1.1. Construction of a redd. From Burner (1951).

The redd provides a microenvironment unique from the surrounding gravel due to its morphological feature and substrate composition. During the construction or “cutting” of a redd, a large proportion of fine material is flushed downstream (Chapman, 1988). Kondolf et al. (1993) reported that this construction process can decrease the amounts of fine material by up to 37% compared to surrounding gravel. Other authors have estimated lower percentages of fine sediment removal (Crisp and Carling, 1989). Redd cutting coarsens the gravel bed (Buxton et al., 2015; Dusterhoff et al., 2017) and can lower the threshold for bedload movement by loosening the pavement layer (Hassan et al., 2008). Typically, the dune structure remains intact during the entire spawning period unless sufficient shear stress occurs to mobilize gravel during high flows (Soulsby et al., 2001). The dune structure of the redd causes downwelling of surface water into the egg pocket, which increases dissolved oxygen levels and removes metabolic wastes (Carling et al., 2006; Tonina and Buffington, 2009; Cardenas et al., 2016; Figure 1.2). Downwelling currents also occur at a larger scale within many spawning reaches, due to changes in hydraulic gradients within pool-riffle transitional areas that are frequently chosen by the female during spawning site selection (Chapman, 1988; Figure 1.2). Permeability of the redd matrix frequently decreases over the incubation period due to ingress of fine sediment or sand into pore spaces (Chapman, 1988). The spatial and temporal variation of sediment infiltration is a function of characteristics of the channel and redd including suspended sediment concentrations, particle size, gravel matrix composition, and channel and interstitial hydraulics (Beschta and Jackson, 1979; Chapman, 1988; Cardenas et al., 2016).

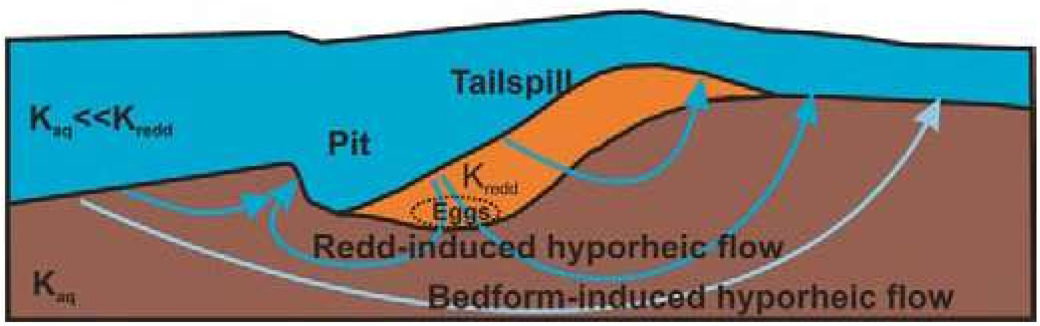


Figure 1.2. Flow dynamics within the redd. Hyporheic flow caused from downwelling and by the redd structure (i.e. hydraulic conductivity (K_{aq}) of the undisturbed gravel bed and hydraulic conductivity (K_{redd}) of the redd. From Tonina and Buffington (2009).

1.3.3 Intragravel dissolved oxygen dynamics and influences

Survival of salmonid eggs are influenced by a multitude of physical, biological, and environmental processes (Malcolm et al., 2008). However, the supply of DO is frequently defined as the most critical factor for the survival and healthy development of salmonid eggs (Wickett, 1954; Daykin, 1965; Garside, 1966; Chevalier et al., 1984; Grieg et al., 2007a, 2007b). Previous studies have defined "critical" (Daykin, 1965) and "sub-lethal" (Davis, 1975) DO thresholds that include DO concentration (mg l^{-1}), percent saturation (%sat.) and partial pressure (PO_2; mm Hg) (Malcolm et al., 2010). Evaluating specific tolerances during incubation is difficult and there are relatively few experimental studies in this area. Tolerance varies with egg growth rate and genetics (Hamor and Garside, 1976; Bloomer et al., 2019; Wood et al., 2019) and duration of exposure (Malcolm et al., 2008). Most measurements of hypoxic tolerance have been conducted within controlled laboratory settings, void of the fluctuating river processes summarized in Figure 1.3 (Hamor and Garside, 1976; Crisp, 1981; Chevalier et al., 1984). It has been previously suggested that DO levels between 5mg l^{-1} (Hickman and Raleigh, 1982) to 8mg l^{-1} (Bjornn and Reiser, 1991) is the minimum concentration range needed for healthy development for some salmonid eggs. Extreme embryonic mortalities are likely to occur at 2mg l^{-1} (Alonso et al., 1996).

DO in a redd is supplied by surface water and thus concentrations are dependent on physical and environmental characteristics within the channel (ie. atmospheric and hydrostatic pressure, temperature, salinity, ice cover, photosynthesis) as well as characteristics of the gravel bed that affect supply, including surface roughness, water velocities, matrix permeability and local bed topography (Grieg et al., 2007b; Figure 1.3). In some locations, groundwater influx can contribute substantially large inputs of water into the redd, however, DO concentrations of groundwater are frequently very low (Sowden and Power, 1985).

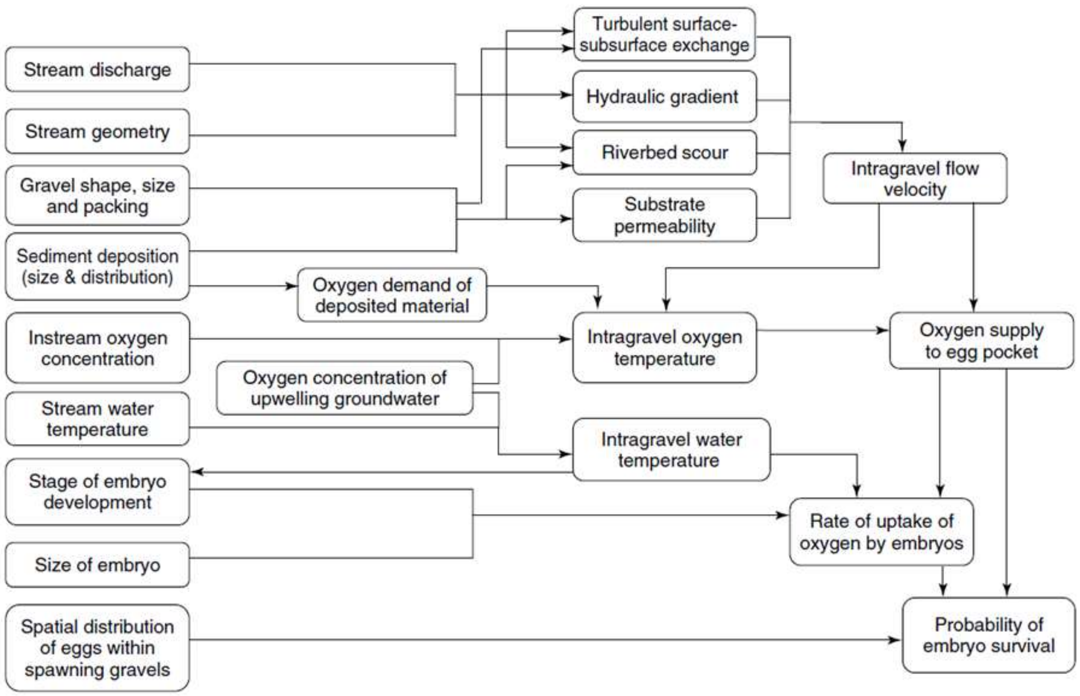


Figure 1.3. Processes affecting interstitial DO and embryonic survival. From Grieg et al. (2007b).

Sediment ingress causes decreased availability of DO to embryos by three primary mechanisms: a) decreased intragravel flow, b) clogging of membrane pores used for respiration, and c) exerting sediment oxygen demand (SOD) that will compete with embryonic metabolic requirements (Grieg et al., 2005a, 2005b). These processes are detailed in previous literature (Chapman, 1988; Grieg et al., 2007b), and briefly reviewed in this section. A reduction of intragravel flow due to sediment ingress is frequently the most important contributor to DO reductions within the redd (Grieg et al., 2005b). The physical blockage of pore spaces can prevent surface water supply and increase levels of metabolic wastes from the embryos, causing additional toxicity within the redd (Chapman, 1988). Fine sediment can also physically obstruct pores on the egg membrane used for respiration, and this can lead to asphyxiation (Grieg et al., 2005b).

Membrane pores typically cover one tenth of the total surface area of the egg, and egg diameters are approximately 0.5-1.5 um (Bell, 1969). Subsequently, any clay particles within this diameter can reduce oxygen diffusion across the cell membrane. Research on this physico-biological process and its effect to DO dynamics is limited (Grieg et al., 2005b), however the observation that finer particles pose the highest risk for embryos due to their high mobility within the redd matrix, even at low flows, is documented (Julien and Bergonen, 2006; Sear et al., 2016). Due to lack of standardization between measurement methods, SOD rates are difficult to compare between literature (Ziadat and Berdanier, 2004). To date, there is a paucity of information on the effect of SOD within redds, despite recognition of the important role this may exert in some environments with high organic content (Sear et al., 2017).

Quantification of the effects of sediment ingress, and other processes on DO within spawning gravels is challenging. One approach has been to measure DO concentrations over the incubation period in the field. These measurements have varied substantially in both the methodology and spatial context (Table 1.1). Due to high temporal variation of DO in the field, high frequency measurements using remote loggers have been suggested as the most representative field method (Sowden and Power, 1985; Peterson and Quinn, 1996; Malcolm, 2010). Despite this recognition of the benefit of high frequency measurements, their use is relatively infrequent in literature, and these data are limited to a small set of locations (Table 1.1).

1.3.4 Assessment of spawning gravel quality and model development

In response to the decline of many salmonid populations worldwide, protection, enhancement, and rehabilitation of spawning habitat are identified as primary goals for many fisheries managers (Chapman, 1988). These goals partly resulted from recognition that fine sediment runoff from landscape disturbances was a leading contributor to the degradation of spawning habitat quality (Chapman, 1988). Accordingly, scientifically based definitions of spawning habitat quality were required to implement sediment mitigation strategies, such as gravel jetting, flow flushing, bank stabilization, and land use restrictions (Walling et al., 2003). Descriptors of spawning gravel quality include substrate size (Kondolf, 1993), percent fines (Kondolf, 2000), and use of the Fredle index (Beschta, 1982). Kondolf (2000) summarized the applicability of these habitat quality metrics as limited, based on the observation that spawning gravel and the redd microhabitat “quality” can rarely be summarized based on a single variable.

Table 1.1. Published in situ hyporheic DO sampling methods in spawning gravel and redds (including flume studies). Adapted from Malcolm (2006).

Reference	Method	Sampling Interval[1]	Country
Briggs et al. (2018)	Colorimetric	Single measurements	U.S.A
Cardenas et al. (2016)	Logger[2]	Hourly	U.S.A
Schindler-Wildhaber et al. (2014)	Logger	10-minutes	Switzerland
Sear et al. (2014b)	Optode	------------	UK
Malcolm et al. (2011)	Meter	Single measurements	UK
Malcolm et al. (2010)	Logger	15-minute	UK
Yamada and Nakamura (2009)	Meter	Twice during study period	Japan
Meyer et al. (2008)	Optode	Monthly intervals / 6 total	Germany
Grieg et al. (2007)a	Meter	10 measurements/2 months	UK
Dumas et al. (2007)	Meter	4 measurements	France
Heywood and Walling (2007)	Meter	5-seconds /10 total samples	UK
Petticrew and Rex (2006)	Logger	15- minute	Canada
Malcolm et al. (2005)	Logger	15-minute	UK
Youngson et al. (2004)	Meter	2-week	UK
Groves and Chandler (2005)	Meter	Monthly	USA
Malcolm et al. (2004)	Meter	Weekly	UK
Bowen and Nelson (2003)	-------	three occasions/ 5 months	USA
Malcolm et al. (2003)	Meter	Weekly intervals	UK
Ingendahl (2001)	Meter	2-week intervals	Germany
Peterson and Quinn (1996)	Titration	Weekly, bi-weekly	USA
Rubin and Glimsater (1996)	--------	Approximately fortnightly	Sweden
Havis et al. (1993)	Probe	8 measurements	USA
Curry and Noakes (1995)	Meter	Single sample	Canada, USA
Sowden and Power (1985)	Meter	~monthly /5 total	Canada

[1]Intervals not explicitly stated left blank, [2]Flume study

Other studies have supported this conclusion, citing the natural complexity of river systems; including the interactions and timescales between the relevant physical channel and redd processes, and the differing biological effects between embryo species and growth stage, as important considerations (Malcolm et al., 2008).

Physically based models can be built to mathematically represent a multitude of processes within the natural world. They provide an alternative to long-term research studies and are therefore convenient when policy makers do not have time or funds to commit. Despite their advantage, the results from model simulations must be applied cautiously, as predictions may become misinterpreted during policy making or management applications. Misinterpretation can often result from ignoring mathematical limitations and sensitivities of the model; therefore, identifying these limitations and/or mathematical misrepresentations within a given system must always be an important consideration for policy makers.

To date, relatively few models accurately simulate and predict abiotic intragravel processes within a redd or gravel spawning gravel, such as dissolved oxygen transport or fine sediment ingress. Wu (2000) developed a complex model quantifying fine sediment accumulation in redds, with the goal of describing appropriate flushing intervals. In this study, deposited material was typically defined by sand sizes, rather than <63µm fractions, and no environmental parameters such as temperature or DO were considered. Meyer et al. (2005) developed a model to explain the role of sand seals, the process of larger grained material clogging pore spaces in the redd. Variables including entrainment flow, discharge, coarse and fine sediment distributions in the riffle and egg pocket of the redd, suspended sediment dynamics, and the distribution of predaceous oligochaetes were used. While their study concluded that more precise field measurements would have been beneficial during the validation process, it highlighted the importance of sand within the redd, and supported claims that fine sediment measurements alone are not predictive of survival to emergence without consideration of other river parameters. Tonina and Buffington (2009) developed a complex 3D fluid dynamics model to represent hyporheic flow patterns within the redd and flow supply to the egg pocket. They suggested that a 3D framework would be useful for future research questions related to survival to emergence and intragravel DO supply. Tonina et al. (2016) presented an analytical model that predicted DO concentrations in the hyporheic zone by using 3D gravel bed bar morphology and terms to express advection and diffusion of SOD. Agreement of 58% between predicted and observed DO was measured. This model did not represent the redd structure or include any biological spawning data. Cardenas et al. (2016) modelled 2D hyporheic flow fields in redds using flume experiments to validate flow path predictions. They discussed the importance of sediment texture and geomorphic structure redds in simulating flow patterns to the egg pocket, however this study did not explicitly provide estimates of survival to emergence.

To date, SIDO (Sediment Intrusion-Dissolved Oxygen) and SIDO-UK are the only models to simulate embryonic survival rates and dissolved oxygen concentrations based on variables within the channel and redd which include interstitial velocities, substrate composition, and temperature. SIDO was developed by Alonso et al. (1988) to predict survival rates of chinook and steelhead trout in Tucannon River in Washington, USA, a river that was threatened by excessive sedimentation caused by agriculture and forestry disturbances. SIDO was peer reviewed in Alonso et al. (1996), and this documentation and non-proprietary software is available at the USDA-ARS National Sedimentation Laboratory (NSL) website (https://www.ars.usda.gov/southeast-area/oxford-ms/national-sedimentation-laboratory/). The SIDO-UK adaptation of the original SIDO code implements some modifications including biological variables of local salmonid embryos, and conversion of measurements from imperial to metric. SIDO is designed to be applicable to any spawning reach within a gravel bed river, for a wide range of gravel types, sediment conditions and salmonid species (Havis et al., 1993).

1.3.5 Description of the SIDO model

SIDO is a deterministic, physically based numerical model originally developed for use in the Tucannon River in Washington, USA. It has since been used in the USA, Canada and the UK (See Table 1.2). SIDO simulates flow, fine sediment and dissolved oxygen transport within two separate domains: the stream and redd. The stream domain includes water routing, sediment routing, and near-bed channel dissolved oxygen concentrations. Water routing in the stream domain includes calculation of flow resistance and hydraulic properties, calibrated using cross sectional measurements and channel characteristics. Sediment routing includes bedload transport calculated through the Einstein-Brown equation, and suspended sediment transport. Dissolved oxygen in the channel is taken from field measurements of temperature and elevation.

Table. 1.2 Previous research and development of the SIDO and SIDO-UK model

Reference	Country	River	
Sear et al. (2017)	UK	River Ithon	AS, BT
Sear et al. (2014b)	UK	River Rede	AS, BT
Pattison et al. (2012)	UK	River Ithon	AS, BT
Clement (2003)	Canada	Credit River, ON	AS
Alonso et al. (1996)	U.S.A	Tuccanon River, Washington	CH, ST
Havis et al. (1993)	U.S.A	Salmon river, Idaho	CH
Alonso et al. (1988)	U.S.A	Tuccanon River, Washington	CH, ST

*AS=Atlantic Salmon, BT=Brown Trout, CH=Chinook, CO=Coho, ST=Steelhead

The output from the stream domain output is then input into the redd domain, which simulates the transport of water, sediment, and dissolved oxygen constituents through the redd matrix represented as a 2D representation divided into four distinct zones: the pit, disturbed, undisturbed, and egg zones (Figure 1.4).

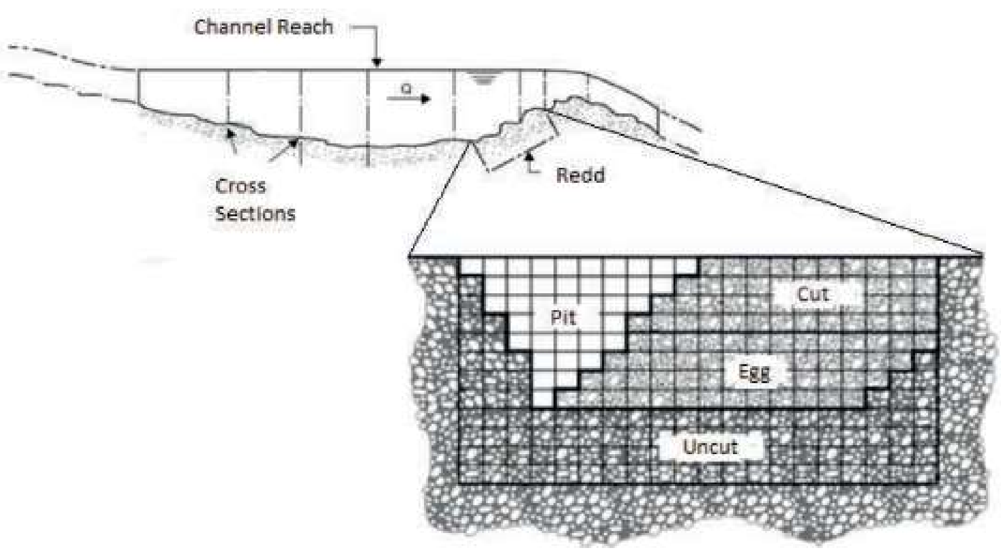


Figure 1.4. 2D representation of the redd zone in the SIDO. From Alonso et al. (1996).

Within each area of the redd, the consumption of dissolved oxygen by embryos and organic matter carried within silt and clay fractions of sediment are calculated. To run SIDO, the user must calibrate the model using daily sediment, hydrological, and temperature inputs, and supply detailed bed morphology and gravel bed particle size inputs. These inputs are best filled using data from detailed field measurements (Alonso et al., 1996). Additionally, the user must select a salmonid species.

To estimate hatching time, SIDO uses daily temperature and dissolved oxygen parameters, and determines fry emergence from the relationship described by Theurer and Miller (1986). Simulated predictions from SIDO of DO, embryo survival, or accumulation of fines may be validated using field measurements. A full description of the model is available within USDA documentation in Alonso et al. (1996). From a management perspective, SIDO has the potential to be a valuable fisheries management tool because it predicts DO dynamics, ingress and embryonic survival by simulating multiple processes in spawning gravels. SIDO can therefore be used as a tool to quantify intragravel DO regimes and assess the effects of landscape disturbances on these intragravel dynamics.

1.4 Thesis format

Chapter 1 includes the Problem Statement, Literature Review and Research Objectives. Chapter 2 describes the study area and methodological approach used in this study. Chapter 3 presents the results of the field monitoring program, and SIDO model predictions. Chapter 4 provides a synthesis and review of conclusions, addresses research gaps, and provides areas for future research and model development.

Chapter 2

Methods

2.1 Experimental Design

The goal of this research is to examine the utility of the SIDO model as a fisheries management tool to simulate the impacts of fine sediment ingress on dissolved oxygen concentrations in spawning gravels of the Crowsnest River. A rigorous field monitoring program was conducted in the Crowsnest River, Alberta between 04/23/18 - 08/03/18 to collect the discharge, suspended solids, particle size distributions, temperature and dissolved oxygen for calibration and validation of SIDO. Three river transects were instrumented in reaches that represent favorable spawning conditions for Westslope Cutthroat trout. Three artificial redds were constructed (Figure 2.1) across each of three transects, and loggers were deployed to record DO and temperature adjacent to ingress baskets used to measure fine sediment ingress.

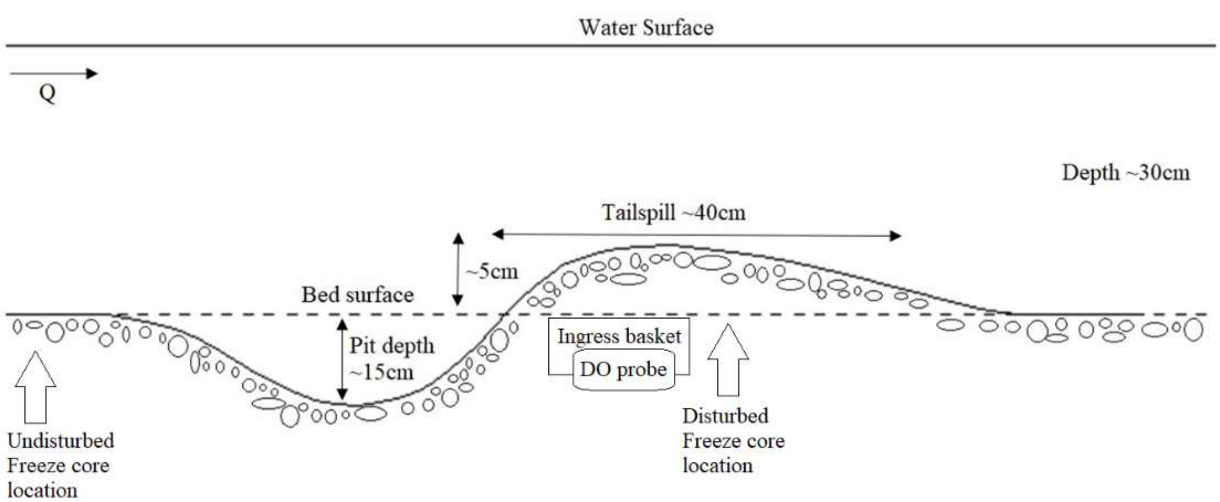


Figure 2.1. Diagram of site instrumentation at an artificial redd

During the study, two sites were vandalized and two of the eleven DO probes, and three of the nine ingress baskets were lost. Suspended sediment concentrations and particle size distributions were measured for a range of discharge conditions (base flow; rising limb, peak and recessional limb) over the study period.

2.2 Study Area

The Crowsnest River is one of three main tributaries of the Oldman Watershed, located in southwestern Alberta (Figure 2.2). The headwaters of the Crowsnest River originate at the outflow of Crowsnest Lake (1357masl) and it flows east through the municipality of the Crowsnest Pass before draining into the Oldman Reservoir (1113masl). Soils are classified as eutric or dystric brunisols that overlay glacio-fluvial deposits of variable thickness (Bladon et al., 2008). Geology of the basin consists of upper cretaceous shales, limestone, dolomite and sandstone overlain by quaternary glacial-fluvial and more recent fluvial deposits (Stone et al., 2014). Surficial deposits in this basin include glacial moraines, till blankets and till veneers (Stone et al., 2014). Annual precipitation is ~577 mm/year, of which approximately 30% falls as snow (Environment Canada, 2010). Discharge in the Crowsnest River is strongly snowmelt dominated, and stream flow typically peaks between April to early June. The highest freshet flows typically occur after rain on snow events (Silins et al., 2014). Mean annual temperature (1971-2000) ranges between 3-5 ºC (Environment Canada, 2010).

Lower elevation landscapes within the Crowsnest River watershed are classified as Montane, and higher elevation zones are classified as Sub-alpine and Alpine. The Montane region is dominated by coniferous species of Lodgepole pine (*Pinus contorta var. latifolia)*, White spruce (*Picea glauca*) and Sub-alpine fir (*Abies lasiocarpa*). Further downstream, lowland species including Wolf Willow (*Elaeagnus commutate*), River Birch (*Betula occidentalis*), and Willow species (*Salix sp.*) dominate the riparian zones. The Crowsnest River supports many cold-water fish species, including at-risk species of Westslope Cutthroat Trout (*Onchorynchus clarkii lewisi*) and Bull Trout (*Savelinus confluentus*) (Blackburn, 2010). Landscape disturbances in the region include historical coal mining, logging, suburban development, agriculture, motorized off-road recreational vehicles, and natural disturbances including seasonal wildfires (Mayhood et al., 2014).

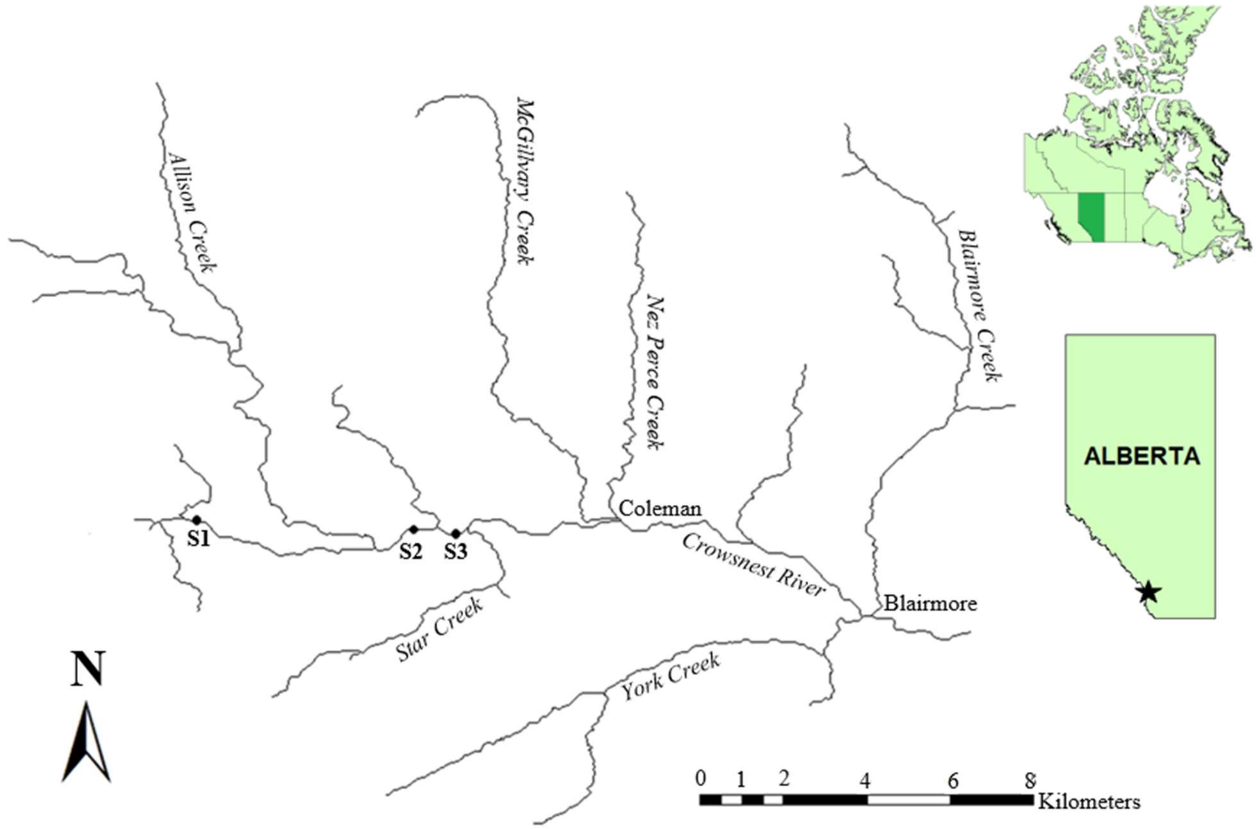


Figure 2.2. Location of the study reaches in the Crowsnest River, Alberta.

2.2.1 Study reach selection

Study reaches in the Crowsnest River (labeled consecutively upstream to downstream; see Figure 2.2 and Figure 2.3) were selected based on the following criteria: i) all reaches had a pool-riffle sequence, ii) all sites were spatially distinct, defined by unique tributary inputs, iii) spawning preferences for Westslope Cutthroat trout were represented (including gravel size and depth) and iv) reaches were located in areas presumed to have minimal anthropogenic disturbances to provide baseline data for the model calibration and validation.

2.3 Reach morphology

Detailed topographical surveys of each study reach were conducted between 04/16/18 – 04/19/18 with a Leica Total Station 405 (See Appendix A) for the purpose of providing the required morphological input data for SIDO. Surveys were conducted pre-freshet melt for a) safety

Figure 2.3. Photos of each study reach. Different stages of the hydrograph are represented: baseflow/slow rising limb (May 4), peak discharge (May 17), recessional limb (May 30), and return to baseflow (Aug 1).

concerns, and b) to avoid disturbance of the study reaches once redds were installed. The survey provided ~ 30-40 transects within the reach, with 10-15 points per transect. Approximately 10 transects (~1-2m apart) were measured within the pool-riffle transitional area, providing extremely detailed topography of the zone where the redds were to be constructed. Approximately 10 more transects were measured upstream and downstream of the pool-riffle transitional area.

2.4 Suspended, surface, and subsurface sediment particle size distributions

In this study, measurements of sediment characteristics for each study reach included 1) daily concentration and particle size distribution of total suspended solids, 2) bed surface roughness, and 3) subsurface particle size distribution and percent fines. The primary purpose of these measurements was to provide input data for SIDO. Details of these methods are described in the following.

2.4.1 Suspended solids

Suspended solids concentrations were collected during the study period using ISCO 6712 portable water samplers. These samplers were installed between 04/20/18-05/03/18 prior to redd installation and programmed to collect a daily composite consisting of 250ml aliquot samples every 6 hours into the same bottle. Each composite was gently inverted (20 seconds), quickly poured into 250ml bottles, and shipped to the University of Waterloo. Total suspended sediment concentrations were calculated using ASTM D 3977 Standard Test Method for Determining Sediment Concentration in Water Samples (ASTM, 2006). Particle size distribution of suspended material was characterized using image analysis described by DeBoer and Stone (1999). In this procedure, water samples were collected using plexiglass settling columns, then filtered onto 0.45µm Millipore HA filters using a low suction handheld vacuum pump. Water samples were collected approximately 3m downstream of the redds within 15-20 cm of the water surface at approximately every 4 days. Filters were dried, prepared with immersion oil, and imaged using a Wild Leitz inverted microscope (resolution 2.5x), equipped with a Sony XC75 CCD camera, and a Pentium computer running Northern Eclipse™ software (Figure 2.4). Between 5000 to 10,000 particles were measured depending on the concentration of particles on the filter. Grain size distributions of clay, silt and sand were converted from vol % to daily concentrations (ppm) using densities of 2.65g/cm^3 2.43g/cm^3, 2.20g/$cm^3$and for sand, silt and clay respectively as reported by Alonso et al. (1996) (See Appendix E).

Figure 2.4. Floc imagery equipment including Wild Leitz inverted microscope equipped with a Sony XC75 CCD camera

2.4.2 Bed roughness

Bed roughness of the gravel bed armour layer was measured using a grid sampling procedure described by Bunte and Abt (2001). A ruler was used to measure the b-axes of all surface gravel at all interstices within the 0.6 x 0.6m grid (Figure 2.5). Sampling transects were located approximately 2 meters downstream of the redds. The sampling frame was placed at equal widths across each transect. This bed roughness sampling procedure was chosen for its greater accuracy over other bed roughness sampling techniques, such as the heel to toe Wolman count (Bunte et al., 2009). Two measurements were conducted per site between late May and early June, when water levels and water temperature were deemed safe for field measurement. Two cumulative particle size distributions were plotted per site from each field measurement, and percentiles were calculated. Grain size of the gravel adjacent to the redds and within the redds was measured at each site using a freeze corer (Crisp and Carling, 1987; Hassan et al., 2008; Franssen et al., 2014) to a depth of 40cm. One core was taken prior to redd construction at each site ~2m meters downstream of the artificial redds (Figure 2.1).

Figure 2.5. Sampling grid for bed roughness measurements

An additional core was collected from the disturbed redd matrix before the installation of loggers and ingress baskets (See 2.5.1). Cores were placed on a plastic workstation to measure and section each core into two fractions (0-15cm and 15-30cm). These sections respectively represented a) typical egg burial depth of genus *Oncorhynchus* (DeVries, 1997) and b) material left undisturbed during the redd building process. Sediment from the cores was air dried, shipped to the University of Waterloo and dry sieved to 63µm using a mechanical sieve shaker. Cumulative size distributions (mass) were plotted for each substrate sample, and percentiles were determined from this curve. Particle size distribution (volume) of material <63µm from 0-15cm sections was also analyzed using a HORIBA™ LA-960 Laser Particle Size Analyzer. Material <63µm was analyzed for organic carbon (±0.5%) and total carbon (±0.01%) (Activation Laboratories, ON).

2.5 Artificial redd construction

Artificial redds were constructed carefully to represent conditions that were similar to that of natural conditions in a salmonid redd. An ingress basket was placed in each redd to measure vertical deposition of fine sediment and a DO logger was installed at a depth of 15cm in the hypothetical egg zone of the artificial redd. The following section provides a detailed description of redd construction and instrumentation.

2.5.1 Construction

Artificial redds were constructed within pool riffle transitional areas at each site according to methods described by Grieg et al. (2007a), Johnson et al. (2012) and Collins et al. (2014).

Construction was designed to mimic the excavation of a female salmonid as described in Burner (1951). Three redds were constructed at each site between 05/02/18 - 05/04/18 to correspond with the beginning of the spawning season for Westslope Cutthroat trout (*O. clarkii lewisi*) (Nelson and Paetz, 1992). Redds were horizontally placed 1.5m apart at a near constant water depth (measured from water surface to bed: 31.33 ± 3.05 cm at Site 1, 25.33 ± 1.57 cm at Site 2 and 31.30 ± 7.51 cm at Site 3) and presumed hydraulic gradients across the pool-riffle transitional area. A pit was dug to a depth of ± 15cm from the bed surface. The gravel bed surface immediately downstream of the pit was then shovelled into the depression creating a new pit. A single freeze core of tailspill material (mound of displaced gravel) was collected (See Figure 2.1). Tailspill material was then carefully displaced by hand, so that one dissolved oxygen logger and one close walled polyethylene sediment ingress basket could be installed and secured to the bed (see Figure 2.6).

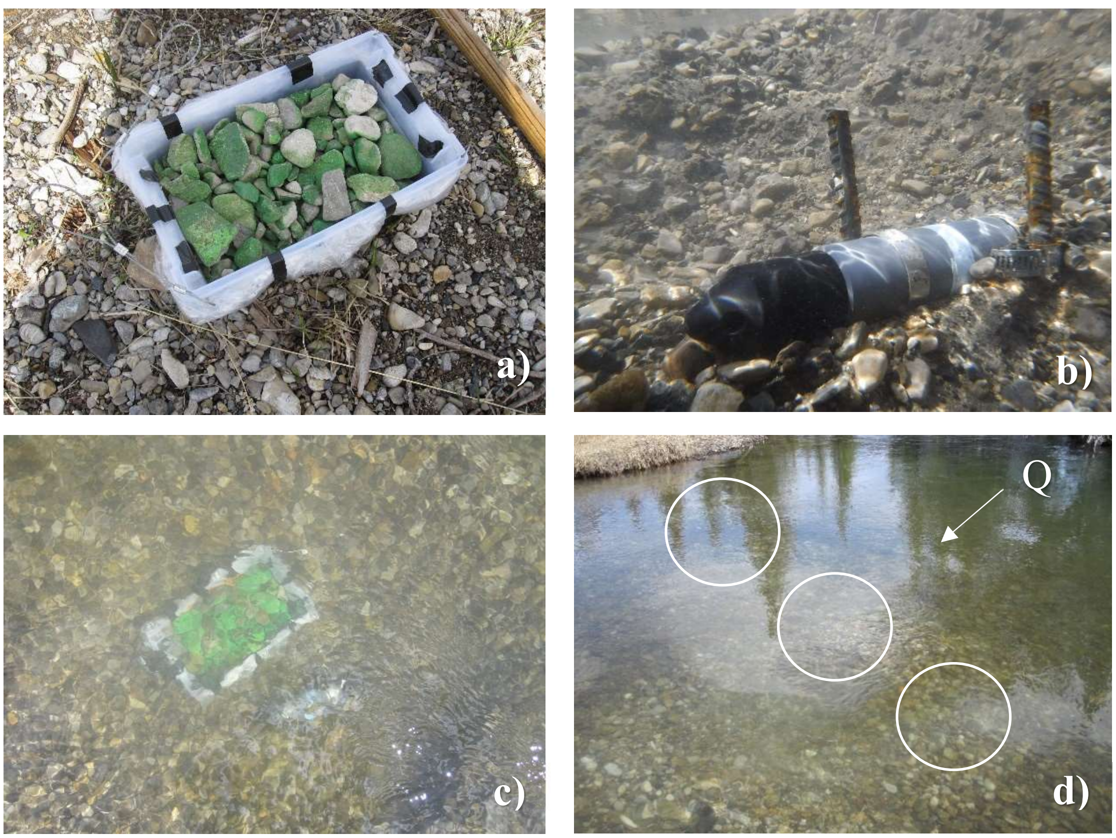


Figure 2.6. The redd construction process. Seen are a) pre-deployment ingress basket, b) deployed DO logger, c) placement in the redd, and d) completed redds

Equipment was installed parallel to flow and covered with the displaced tailspill material by hand. Burial depth of the logger and basket was approximated from egg zone depth literature, which can range between 0.05 and 0.5m depth, depending on the size of the female (Crisp and Carling, 1989; DeVries, 1997; Schmetterling, 2000).Redds had an area of ~ 40cm^2 and were visible in the channel from the dune structure and the cleaned gravel (see Figure 2.6).The size of the completed redd was representative of a large female salmonid (Bjornn and Reiser, 1991). Artificial redds were decommissioned between 08/02/18-08/04/18 after a complete range of discharge conditions before, during and after the spring freshet (base flow; rising limb, peak and recessional limb of the site hydrograph) had occurred.

2.5.2 Fine sediment ingress measurements

Ingress baskets (27.9cm x 16.8cm x 13.7cm) were secured to two lengths of rebar (Figure 2.6). Gravel within each ingress basket was previously collected from surface material within the pool-riffle transitional area at each site; washed, weighed, photographed, and sieved to 2mm to remove fines during redd excavation. Sieved gravel was filled flush to top of the basket, weighed, and sealed before transport to the field site to prevent infiltration of dust or other material. The baskets remained sealed until they were placed in the redd so that minimal material was lost in the flow. Each ingress basket was equipped with a heavy plastic bag for ease of removal during the decommissioning of the sites (Grieg et al., 2007a). Gravel was lightly marked with a waterproof alkyd paint as a visual measure of the retention of original material (Figure 2.6).

During removal, ingress baskets were first sealed tightly with a plastic lid, then transferred to a workstation in the field to guard against spills. Materials in each basket were carefully transferred into freezer bags. Sediment adhering to the walls of the basket was scraped with a plastic knife and washed into bags using squirt bottles filled with river water. Samples were immediately frozen and shipped to the University of Waterloo for processing.

Samples were mechanically dry sieved and particle size of the <63µm fraction were analyzed in the same procedure of the freeze cores (See 2.4.2) to obtain cumulative distributions and percentiles. Ingress rates were obtained by dividing the final mass of fines by 92 days to obtained daily mass, per area of the basket. Mass of fines (<1mm) per volume of pore space in the basket (g/cm^3) was calculated. Pore space in the basket (cm^3) was calculated by subtracting the initial volume of gravel >2mm (mass divided by 2.65g/cm^3) from the volume of the basket (6414.8 cm^3).

2.5.3 Dissolved oxygen measurements

DO loggers (HOBO U26-001 data logger**;** ± 0.2 mg l^{-1} up to 8 mg l^{-1}; ± 0.5 mg l^{-1} from 8 to 20 mg l^{-1}**)** were set to record at 15-minute intervals during the entire study period. This interval was chosen to accurately describe the dynamic DO flux in the redd (Malcolm et al. 2010). In addition to DO loggers placed in each of the artificial redds, DO loggers were installed in the water column (0.6 of total channel depth) at Site 1 and 3 upstream of the redds and adjacent to the ISCO intake (See Appendix A). The purpose of these loggers was to measure temperature and DO in water column controls at the furthest upstream and downstream sites. Daily DO concentrations and associated temperature measurements from each logger were obtained by averaging daily recordings (n=96 per day).

2.6 Streamflow

Instantaneous discharge was measured with a Sontek™ FlowTracker® Handheld ADV® (Acoustic Doppler Velocimeter) with SmartQC™ (2D option) downstream of all redds between 04/23/18 - 08/03/18. Instantaneous discharge was measured once a week. Rating curves for all sites were created from staff gauges installed at each site and instantaneous discharge measurements (See Figure 2.7). The water level at Site 2 was measured with barometric and submerged pressure loggers (HOBO U20; Water Level Accuracy* Typical error: ±0.05% FS, 3.8 cm water; Maximum error: ±0.1% FS, 7.6 cm water). Loggers recorded every 10 minutes, and these values were used to calculate a mean daily discharge from the rating curve at Site 2. At Sites 1 and 3, daily discharges were obtained from instantaneous measurements and manual readings of staff gauges during visits to the site.

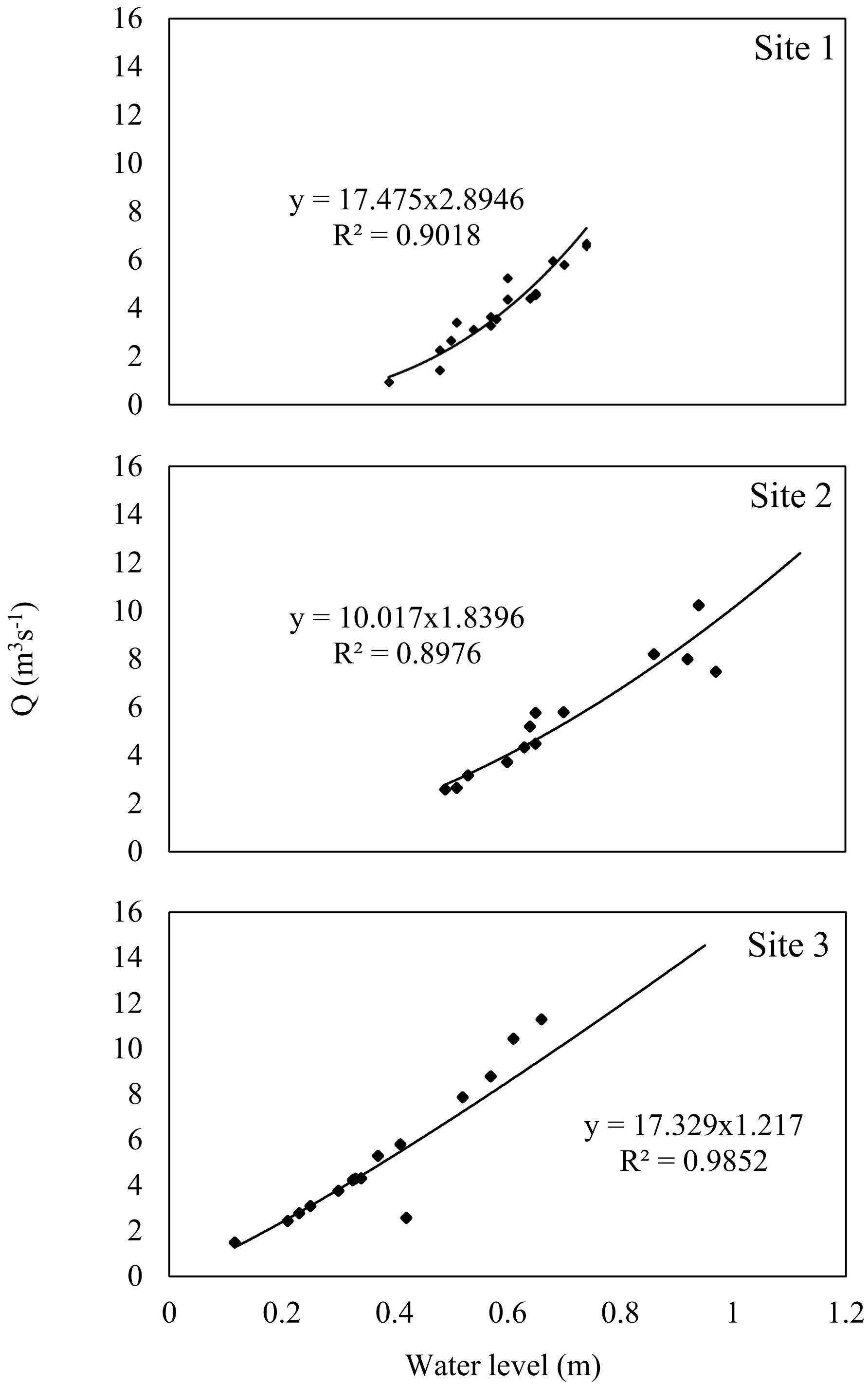


Figure 2.7. Power rating curves developed at three study cross-sections in the Crowsnest River April-August 2018.

2.7 The SIDO Model

The SIDO model is a deterministic, conceptual, continuous simulation model, that can calculate the daily flow of water, DO, and fine sediment ingress within the redd (Alonso et al., 1996). It requires calibration and parametrization using field measurements and adjustment of internal variables. Once the model is calibrated and run for a specific gravel bed system, the model will simulate daily predictions for intragravel dissolved oxygen, sediment ingress quantities, and embryonic survival (survival to emergence). Each of these predictions can be validated using field measurements from the incubation period. In the present study, the model was run for 92 days over a range of hydrological conditions (base flow; rising limb, peak and recessional limb). A rigorous field sampling program was conducted to collect the necessary input parameters for both the calibration and validation process. These methods are described in the following sections.

2.7.1 Calibration

Field data were used to provide the input requirements for the Hydrology and Stream-redd input files of SIDO. Metric field measurements were converted to Imperial equivalents for the required SIDO inputs. Biological parameters, determined through the selection of a salmonid species in the JobControl file, were not altered from the "Steelhead" selection in this study. Biological parameters are an important part of the DO sink term and physical representation of the redd in SIDO, including the code for number of eggs in the egg pocket, egg radius, membrane thickness. Selection of "Steelhead" was justified based on the phylogenetical similarities between Steelhead (*O.mykiss)* and Westslope Cutthroat Trout (*O. clarkii lewisi)* and also evidence that many parameters such as number of eggs and redd size, are size dependant rather than species dependant (Crisp and Carling, 1989). Sensitivity analyses of intragravel calibration variables (ie. CPERM, CBADJ, ALPHA) were conducted for each site, but no single variable had a prevailing effect on ingress quantities or dissolved oxygen levels. Appendix C contains a detailed procedure of the calibration process.

2.7.2 Output and validation

Validation of any physically based model involves comparing simulations and model behaviour to the actual system it is representing. SIDO has previously been validated in three ways: fine sediment infilling, intragravel DO concentrations, and embryonic survival rates. This study validated the model using DO concentrations, and with accumulation of fines at the end of the incubation period. In SIDO, output files can be selected to match user output requirements. To provide best visualization of the output results of the abiotic conditions in the redd, including dissolved oxygen within the egg pocket, sediment ingress, and intragravel velocities, a Microsoft Excel® file was created for the OPTION 4: MODE 7 selection in the Job Control file. Surfer 15® was used to create vector diagrams of the interstitial velocities in the 2D redd framework from the output files. Results of the daily average DO concentrations within the egg pocket of the redd were then compared to the in situ measurements within each of the artificial redds using simple regression.

2.8 Statistical analyses

All statistical analyses were conducted using IBM® SPSS 21 statistical package (IBM Corp, 2018). The differences between dissolved oxygen concentrations were tested using one-way ANOVA. Daily mean temperatures were tested using a one-way ANOVA.

Chapter 3
Results

3.1 Field measurements

3.1.1 Streamflow

Hydrographs for all three study reaches are presented in (Figure 3.1). The data show that discharge peaked during the freshet melt period in May and then steadily declined as the season progressed. Periodic precipitation events increased flow measurements throughout the study period.

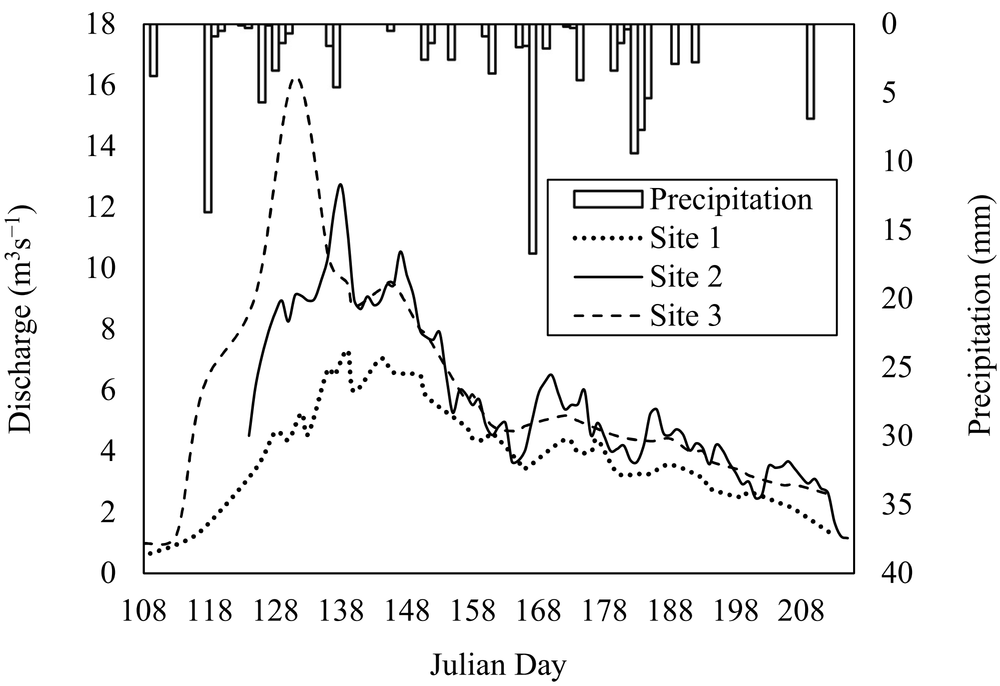


Figure 3.1. Daily precipitation and stream flow at three study sites between 04/19/18-08/03/18. Precipitation was measured by ACIS at Crowsnest Station.

Hydrographs for the three study sites were generally similar (low flow, peak, decline, low flow). However, the furthest downstream site (Site 3) peaked the highest. The high flows recorded during freshet melt corresponded to several rain on snow events, in addition to warming mean daily air temperatures (ACIS, 2019).

3.1.2 Suspended sediment

The downstream gradient in low to high suspended sediment concentrations (Figure 3.2) was observed during freshet melt, with the highest concentrations peaking at Site 3 at 920 mg l^{-1}. Suspended sediment concentrations dropped following the decline of the hydrograph, with peaks throughout the season correlating to some of the precipitation events. The lowest ranges of suspended sediment occurred during low flow conditions. Suspended particle size (%vol) was dominated by sand (63µm to 1mm) during the entire period, followed by silt and clay. Representative photomicrographs of suspended solids over the study period (Figure 3.3) provided evidence that many of the suspended particle size classes measured as sand, silt or clay were flocs or micro-flocs.

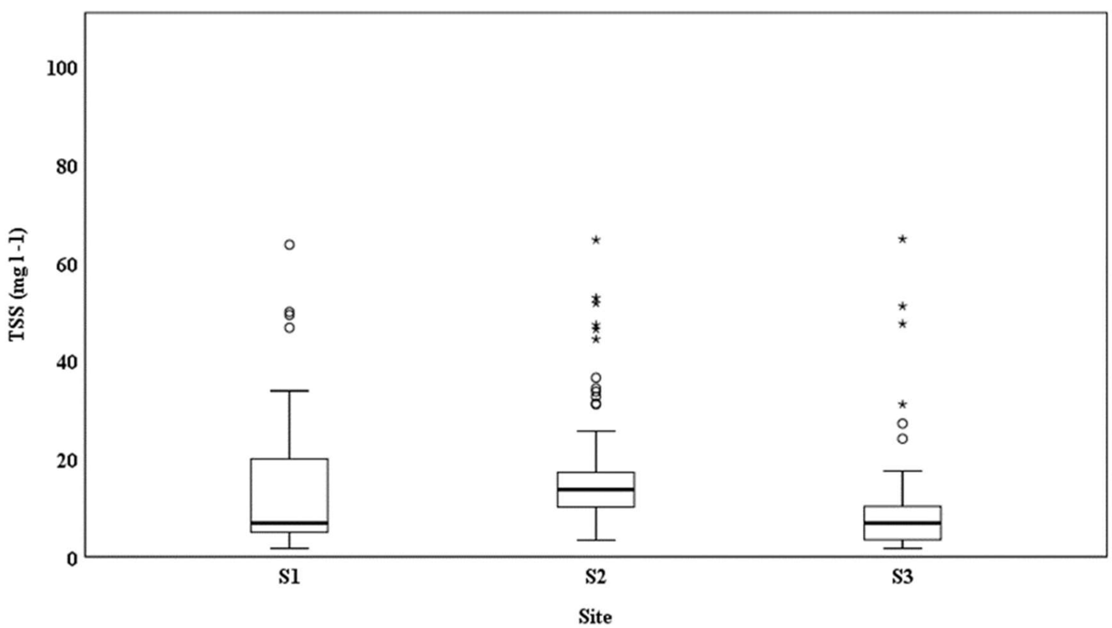


Figure 3.2. Total suspended solid concentrations measured at each study reach. Measurements begin on Day 1 of the SIDO inputs. Three outliers >100mg l^{-1} were omitted from Site 3 in this figure.

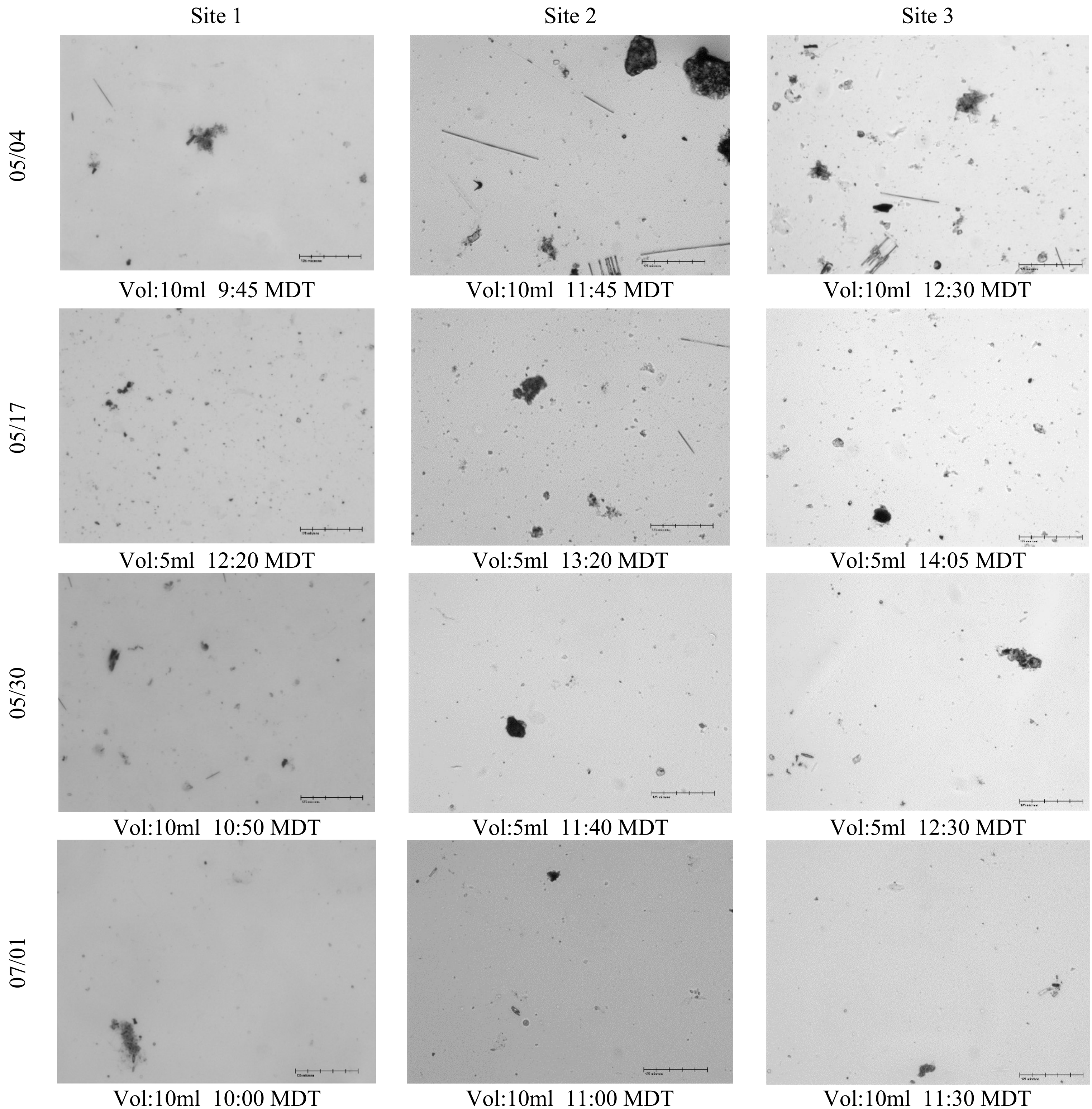


Figure 3.3. Representative photomicrographs of suspended solids at study sites over the study period. Time of sampling and volume of sample are indicated.

3.1.3 Surface and subsurface particle size distributions

Freeze core collection and bed roughness are summarized in Appendix B. Sediment ingress in bed material in all baskets was collected at the end of the study period (Table 3.1). The mean mass of sediment <2mm collected from all baskets was 711.4 ± 224.7g. The average percent fines by mass for the <63µm fraction was 0.37%. Cumulative particle size distribution of material <63µm from each ingress basket was similar (Figure 3.4). Percent by volume of organic carbon of material <63µm averaged at 2.01 ± 0.60. This compared closely to the organic carbon content of the undisturbed freeze cores (0-15cm) taken at the beginning of the study period (1.46 ± 0.15 %). In addition to sediment collected in the baskets, accumulation of some detritus, and biofilms consisting of periphyton were observed within the ingress baskets upon removal, that were not present during the installation of the ingress baskets.

Table. 3.1. Summary of sediment accumulation from baskets deployed between May 2 - 4 and Aug 3 - 4.

	<1mm		<2mm		(<0.63µm)		Cumulative size distribution (Total mass)		
	Mass (g)	Ingress rate ($g/cm^2/day$)[i]	Mass (g)	Ingress rate ($g/cm^2/day$)[i]	Organic carbon %	Total carbon %	D_{15} (mm)	D_{50} (mm)	D_{85} (mm)
S1_R1	----	----	----	----	----	----	----	----	----
S1_R2	224.2	0.005	306.7	0.007	3.00	9.98	7.0	18.0	31.0
S1_R3	----	----	----	----	----	----	----	----	----
S2_R1	731.1	0.017	853.7	0.020	1.60	4.68	3.0	20.0	40.0
S2_R2	789.8	0.018	866.9	0.020	1.40	4.30	4.0	18.0	34.0
S2_R3	532.1	0.012	644.9	0.015	1.60	4.60	4.0	18.0	32.0
S3_R1	523.8	0.012	686.8	0.016	2.30	5.49	3.5	10.0	25.0
S3_R2	834.3	0.019	909.6	0.021	2.20	5.28	5.0	17.0	32.0
S3_R3	----	----	----	----	----	----	----	----	----

[i] calculated from area of ingress basket = $468.7cm^2$

Note: (----) indicates loss of data from vandalization.

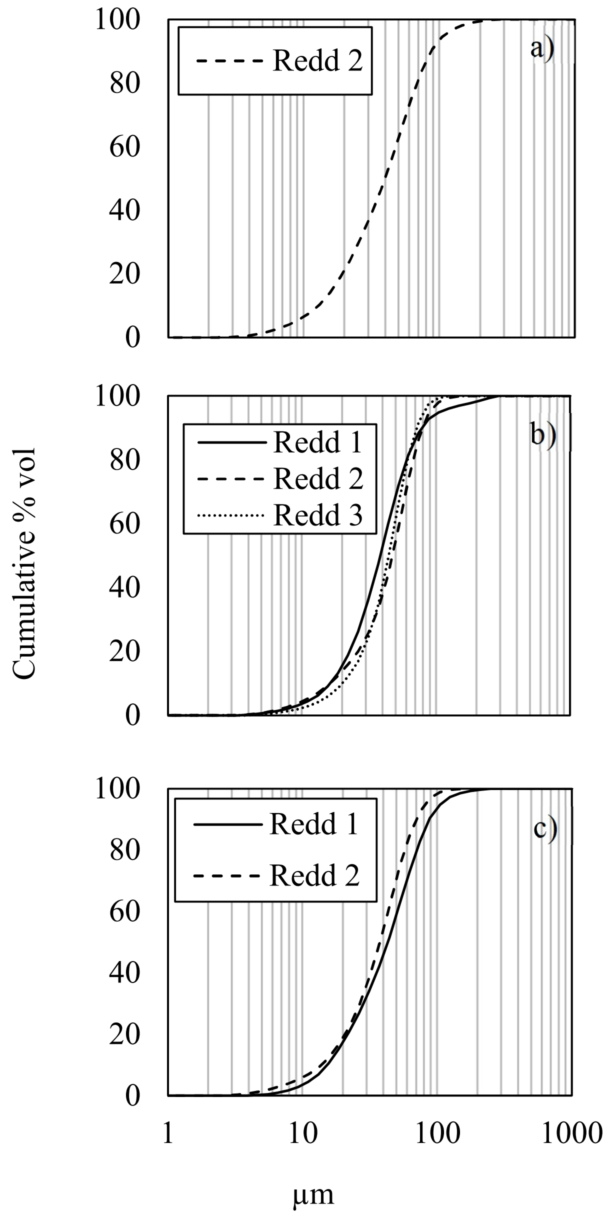


Figure 3.4. Cumulative particle size distribution of material <63µm from each ingress basket at Site 1(a), Site 2 (b) and Site 3(c) in percent by volume

3.1.4 Dissolved oxygen concentrations

Daily DO concentrations varied significantly spatially and temporally between all loggers (ANOVA, p=<0.01; Figure 3.6). In general, daily average DO concentrations in the surface water were higher than concentrations within the redd.

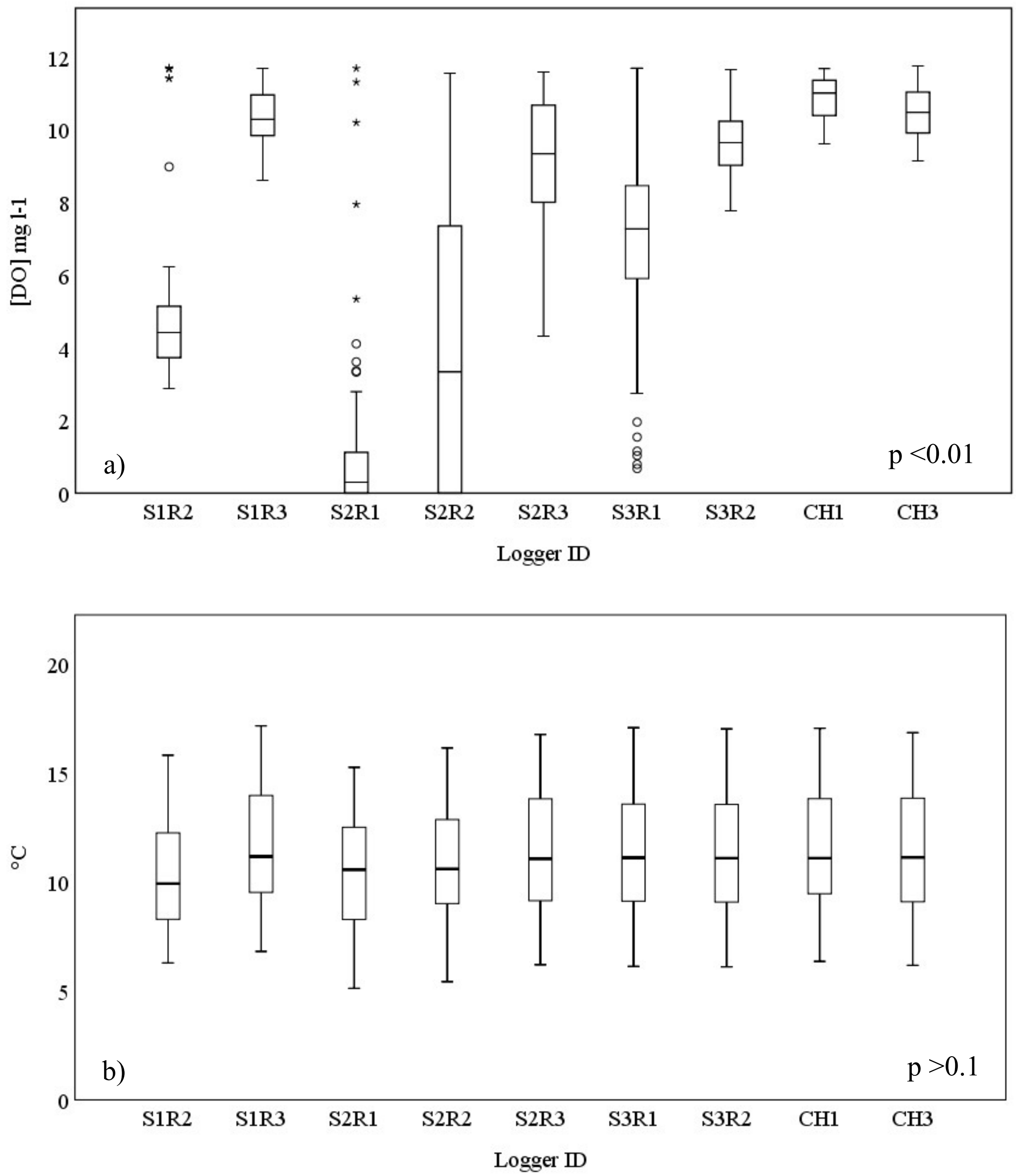


Figure 3.5 Daily mean [DO] (a), and daily mean temperature (b) within artificial redds and channel water column at sites 1 and 3 (CH1 and CH3).

Three trends of DO concentrations appeared during peak flow, a) high amplitude decreases b) relatively steady concentrations during the entire study period, and c) persistent hypoxic conditions appearing in late June. Concentrations lower than 5mg $l^{-1,}$ a proposed threshold for healthy embryonic survival (Hickman and Raleigh, 1982) were recorded at five redds during the incubation period (See Table 3.2). Mean daily temperatures between all loggers were not significantly different ($p > 0.1$), and no incubation effect of the gravel from the channel was observed.

Table 3.2 Minimum interstitial DO concentrations reached during each month

	May		June		July	
	<2mg l^{-1}	<5mg l^{-1}	<2mg l^{-1}	<5mg l^{-1}	<2mg l^{-1}	<5mg l^{-1}
Site 1_R2	✓	✓	×	×	×	×
Site 1_R3	×	×	×	×	×	×
Site 2_R1	✓	✓	✓	✓	✓	✓
Site 2_R2	✓	✓	✓	✓	✓	✓
Site 2_R3	✓	✓	×	✓	×	✓
Site 3_R1	✓	✓	✓	✓	×	✓
Site 3_R2	×	×	×	×	×	×
Channel_S1	×	×	×	×	×	×
Channel_S3	×	×	×	×	×	×

3.2 SIDO output

3.2.1 Accumulation of fines

The SIDO predictions of ingress into the redd and field measurements from the basket over the period of 92 days are presented in mass (<1mm) per unit volume of pore space (Figure 3.6). SIDO underestimated the accumulation in all simulations, except for S1R2, which has a higher initial mass of <1mm in the redd framework (See Appendix A). Most of the ingress predicted using SIDO occurred during the periods of freshet melt, when suspended solid concentrations were highest. Lesser amounts of fines were deposited during lower TSS concentrations. Most redds had either infilled with sediment completely or infilled the egg zone by the end of the simulation period (See Appendix D).

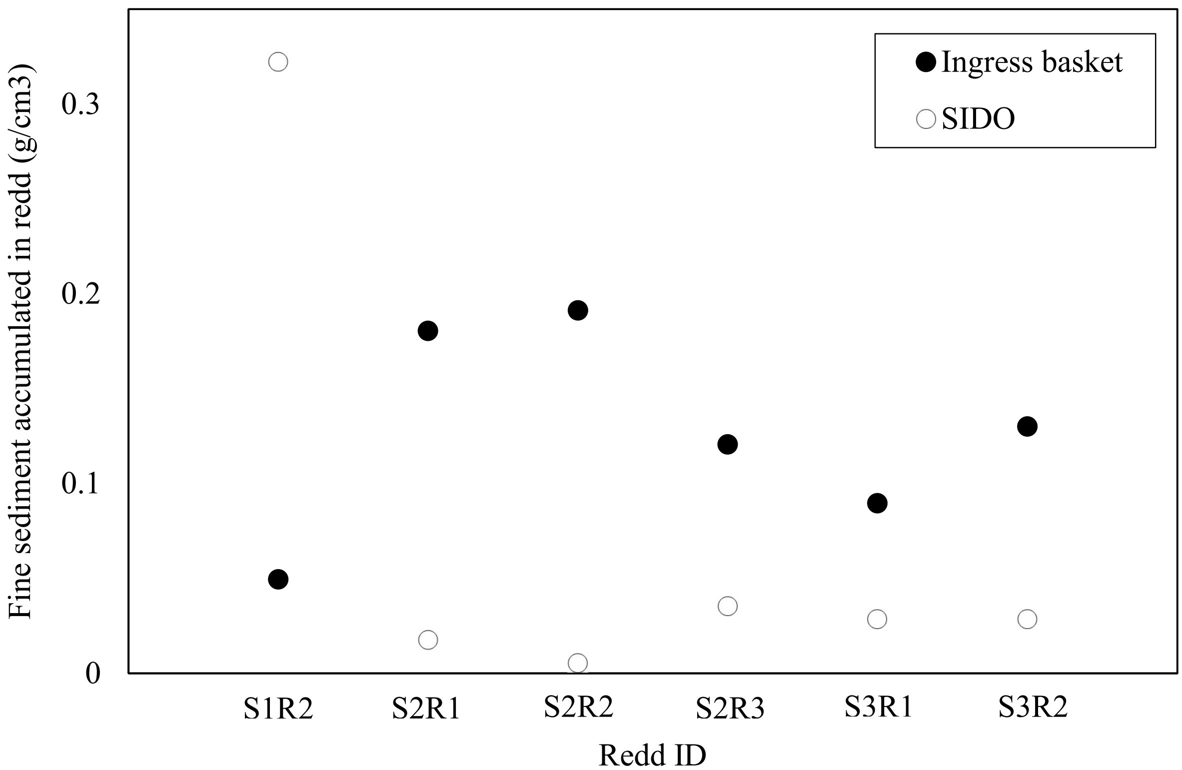


Figure 3.6. Measured and modelled fine sediment ingress after 92-day simulation (g/cm^3).

3.2.2 Dissolved oxygen simulations

There was generally low correlation between the simulated and observed daily average DO concentrations within the egg pocket of the redd. Figure 3.7 presents the temporal trends of both simulated and observed daily average DO concentrations. The modelled results failed to predict the high amount of fluctuation observed over the incubation period, such as during freshet melt, when all redds experienced some drops in DO. As the season progressed, this divergence was especially high at Site 2, which experienced extremely hypoxic conditions in two redds late in the summer. With the exception of S1R2, where the initial particle size of the spawning bed likely prevented emergence (See Appendix A), the relatively high modelled DO suggested that survival to emergence was high (>85%) at the end of the simulation.

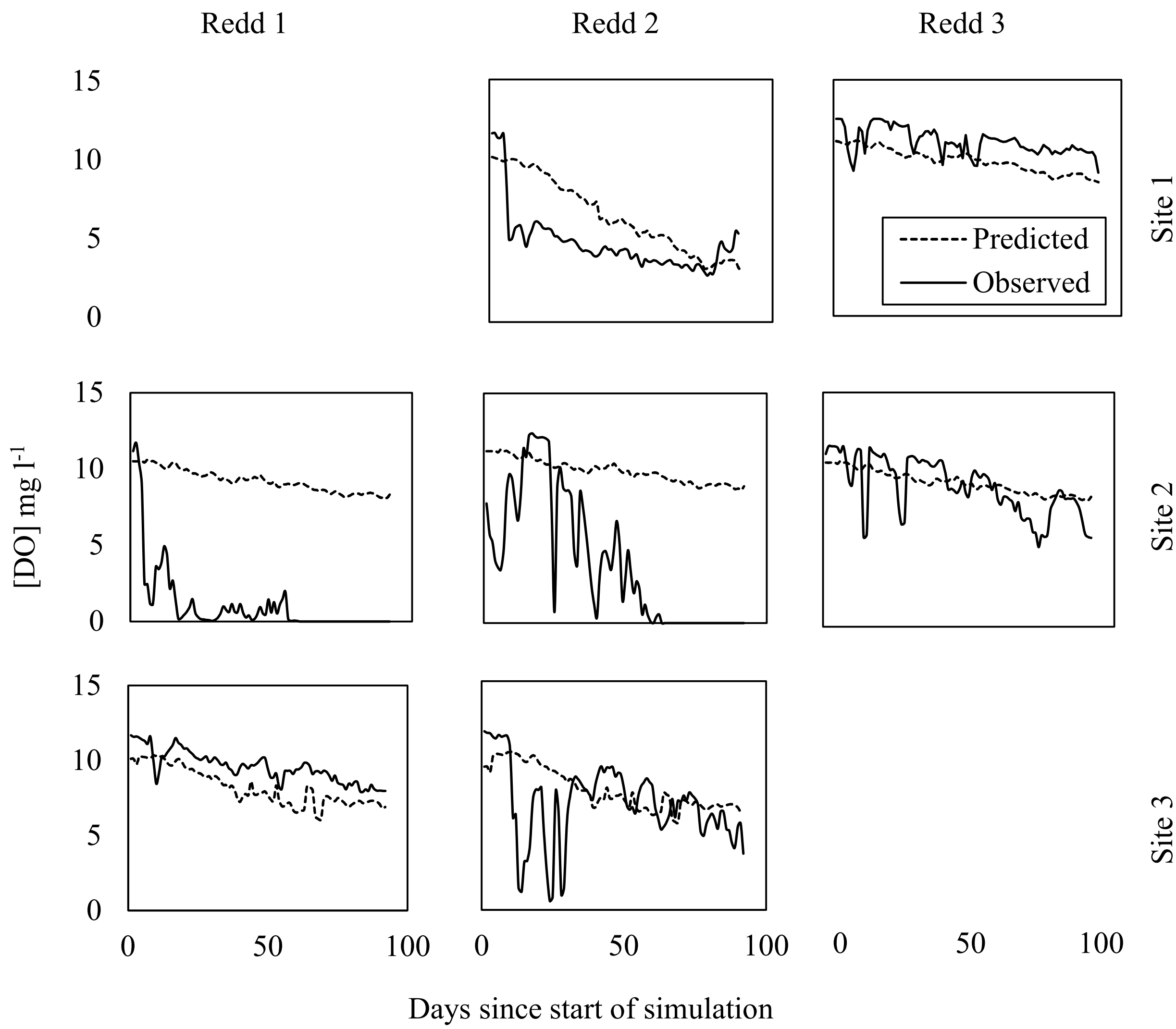


Figure 3.7. Predicted and observed mean daily [DO] within the redd egg zone

Chapter 4

Discussion

4.1 Introduction

Dissolved oxygen is a critical factor in development of the juvenile stages of benthic spawning fish. Factors influencing the DO regime within spawning gravels include fine sediment accumulation, surface and groundwater interactions and consumption of oxygen by microbial and biotic processes. Quantifying these cumulative processes and their impacts to spawning habitat quality remains challenging. Physically based models provide spawning habitat quality assessments and DO characterization through the numerical representation of multiple processes in spawning gravels. The goal of this study was to test the applicability of a physically based model (SIDO) to simulate DO dynamics in spawning gravels within a river draining the Eastern Slopes of the Rocky Mountains. This chapter presents a discussion of 1) factors affecting measured dissolved oxygen concentrations in spawning gravel beds 2) the performance of SIDO to model dissolved oxygen concentrations and 3) the application of SIDO as a tool for fisheries management in gravel bed rivers in forested regions of the Eastern Slopes of the Rockies.

4.2 Factors affecting dissolved oxygen in spawning gravel beds

The SIDO model calculates DO removal from the redd matrix by simulating the physical blockage of pore space from fine sediment accumulation and associated SOD with the daily accumulated sediment. These processes are well described in the literature (Chapman, 1988; Grieg et al. 2007a;2007b), however they are frequently challenging to quantify and model.

4.2.1 Fine sediment ingress and SOD

In the present study, close walled ingress baskets were used to assess fine sediment accumulation rates in spawning gravels. The measured accumulation rates in this study comparable to those observed in forested watershed tributaries (Corrigan, 2016), but lower than the results of studies conducted in heavily impacted streams such as those impacted by urban development (Harper et al., 2017) or salmon spawning and die off (Petticrew and Rex, 2006). Suspended sediment concentrations measured in the Crowsnest River during most of the study period were exceedingly low. The study sites are located downstream of the Crowsnest Lake outflow which moderates sediment supply to downstream reaches of the Crowsnest River. The banks of the Crowsnest River between the lake outflow and the study sites are vegetated and stable and the predominant supply of sediment along this reach is from two small tributary inflows and resuspension of bed materials.

Sediment oxygen demand (SOD) is a critical process controlling oxygen dynamics in spawning gravel and the rate of SOD is strongly controlled by the type and amount of organic matter (Sear et al., 2016; 2017). In spawning gravels, DO consumption rates are influenced by several factors including interstitial flow velocity (Nakamura and Stefan, 1994), flow path length (Malcolm et al., 2008), particle size distribution and surface area available for decomposition (Rex and Petticrew, 2006), distribution of biofilm and diatoms (Sear et al., 2017), microbial concentrations and composition (Rex and Petticrew, 2006) and temperature (Sear et al., 2017). Laboratory and field experiments comprise the bulk of current knowledge of SOD in gravel bed rivers (Grieg et al., 2005a; Sear et al., 2017). A detailed analysis of SOD was beyond the scope of this study. However, cohesive sediment samples from both ingress baskets and undisturbed freeze cores contained low concentrations of organic mater (1.83 ± 0.55%) which is considerably lower than reported in previous studies. For example, organic matter content of cohesive sediment collected from spawning gravels in lowland UK rivers impacted by agriculture was 17.7 ± 0.61% (Sear et al., 2014b). Accordingly, the relatively low organic matter content measured in fine Crowsnest River sediment suggests that organic matter was not a major factor influencing DO concentrations in the instrumented artificial redds. More research is required to quantify the effects of OM on the supply of oxygen in spawning gravel and to examine how the composition and effect of organic matter on dissolved oxygen changes specifically from the supply and delivery from landscape to gravel pore space (Sear et al., 2016).

4.2.2 Groundwater influx within the redd environment

Groundwater typically has low DO concentrations and therefore upwelling of water to the stream via this flow path can influence DO concentrations in spawning gravels (Sowden and Power, 1985; Malcolm et al., 2003; 2011). The rates and magnitude of groundwater inputs to streams are dependent upon several related factors, including variable geomorphology and hydraulics within the channel (Soulsby et al., 2001), porosity of the bed and hydraulic pressure from the aquifer (Sowden and Power, 1985), and landscape and geology (Briggs et al., 2018). Inflows can be identified in the field by their stable thermal regimes, water chemistry (ie. pH, DO), and conductivity through the gravel matrix (Hynes, 1983). Sear et al. (2014b) reported that groundwater upwelling in spawning gravels of a UK river was the primary cause of DO depletion and that sediment ingress was a less significant factor. They found that short periods of upwelling co-varied with rapid, high amplitude fluctuations in DO primarily during the rising and falling limb of the hydrograph (Sear et al., 2014b). Rapid fluctuations of intragravel DO were also observed in the Girnock burn catchment in Scotland, where intragravel DO concentrations fluctuated between 28.3% - 94.1% greater than surface water (Malcolm et al., 2005). Malcolm et al. (2003) suggested that low flow, due to reduction of surface water conductivity within the gravel bed, there was greater influx of groundwater into the hyporheic zone. This effect creates the potential for extended periods of hypoxia during low surface water levels. Malcolm et al. (2003) observed a correlation between lower DO concentrations and groundwater influx in the hyporheic. While groundwater dynamics were not directly measured in the present study, rapid temporal changes of DO in interstitial gravel in the Crowsnest River were similar to those reported in previous studies. This observation suggests that groundwater may have played a role in modifying dissolved oxygen dynamics in the headwater reaches of the Crowsnest River. Deployment of piezometer nests and oxygen sensors across the study reaches are necessary to better understand at the critical role of groundwater on dissolved oxygen in spawning gravel.

4.3 SIDO model performance

SIDO is a physically based model developed to simulate oxygen dynamics in spawning gravels. In this research, SIDO was applied to a headwater reach of the Crowsnest River and calibrated using in situ high frequency measurements of dissolved oxygen. Generally, there was poor agreement between measured and modelled dissolved oxygen concentrations for most of the study sites, despite rigorous parametrization of the SIDO model (Figure 3.7). The data show that while SIDO simulations produced some similar trends between measured and modeled dissolved oxygen concentrations, SIDO was not sensitive enough to simulate short or extended periods of hypoxia. These results are comparable to previous studies using SIDO (Sear et al., 2014; Pattison et al.,

2012) and several reasons have been advanced for the poor performance of the SIDO predictions which include a) violation of assumptions, b) algorithmic misrepresentation of the system, and c) field methodology. The algorithms in SIDO are designed within a set of assumptions, and these are fully described in Alonso et al. (1996). Previous research has identified the limitations these assumptions can impose in some systems (Tonina and Buffington, 2009; Sear et al. 2014; 2017; Pattison et al., 2012). The DO transport sub-model is one of these limitations. For example, SOD consumption in the redd is proportionally defined in SIDO by the daily accumulated silt and clay fractions in the redd. Once infiltrated, consumption rates are static within a given cell during the incubation period. Secondly, when intrusion processes do not represent vertical deposition (ie. from increased lateral transport, advective transport, misrepresentation of the suspended sediment), the accumulation predictions and consequentially SOD rates can become misrepresented. This limitation of the model has been previously addressed by Tonina and Buffington (2009) who demonstrated the applicability of a 3D redd model to compute interstitial hydraulics and sediment transport processes compared to a 2D framework. Lastly, other variables that affect SOD, including localized microbial concentrations and distributions of biofilms, or other benthos, in the redd, are not identified. Landscape disturbances can heavily influence the quantity and quality of fine sediment entering a river and can therefore alter the amount and type of organic matter available for SOD. In these systems, it may be necessary to directly measure SOD in the laboratory to calibrate proportionality constants required for SIDO, or potentially revaluate the SOD algorithms.

The second important DO sink for the redd in SIDO is created from the developing eggs. This thesis research did not account for DO depletion from the eggs in the redd, and therefore the potential effect this could have had on the DO loggers is unknown. However, there are two possible problems with the algorithm in SIDO that may misrepresent the egg sink in the redd. Firstly, some evidence suggests that EOC may not be proportional to egg size. Einum et al. (2002) demonstrated for example that oxygen consumption increased relatively slowly with increasing mass. Larger eggs of Brown trout were also tested against smaller eggs in controlled hypoxic conditions, and this resulted in increased survival from the larger eggs, presumably due to lower consumption requirements. Secondly, the biological characteristics defined by SIDO per species, may likely be misrepresentative in some cases. For example, in the case of egg size and membrane thickness, Bloomer et al. (2019) found that different genetics within the same species (Atlantic Salmon), severely altered their respiration requirements and resistance to hypoxic conditions. In the case of number of eggs, this parameter is more attributable to the size of the female, rather than the species in question (Crisp and Carling, 1989). Therefore, when considering DO sinks in the redd and their assessment both in the field and in models such as SIDO, the parameters may need be directly measured and parameterized in the model.

SIDO focuses on sediment intrusion as the primary factor responsible for decreased DO and consequential embryonic survival. However, groundwater (See Section 4.2) and other biotic and abiotic variables (See Grieg et al., 2007b) can exert strong influences in some river systems. Errors in predictions can also propagate from field methodology for parametrization and validation (Alonso et al. 1996). This study implemented one of the most rigorous multi-site field monitoring programs to date in order to calibrate and validate the SIDO model. However, some uncertainties in methodology are recognized (See Chapter 2). For example, the calculated suspended sediment (ppm) of sand, silt and clay using the photomicrographs likely introduced some bias. Despite rigorous field parametrization however, the gravel bed river type may not be well represented by SIDO. Prior uses of SIDO have all been limited in their geographical representation (UK, Northwestern U.S.A, Central Ontario), and all gravel bed rivers used in these studies have been altered by landscape disturbance, primarily agriculture or loss of vegetation (See Table 4.1). The study reaches used to test SIDO in this study were pristine compared to previous studies and suspended sediment concentrations were exceedingly low during most of the incubation period. Crowsnest Lake was a major influence in the regulation of downstream sediment, potentially making it an atypical example of other gravel bed river systems in the Rocky Mountains.

4.4 Utility of SIDO for fisheries management in Alberta

SIDO was investigated in the present research as a fisheries management tool that could be used to simulate the effect of fine sediment intrusion on dissolved oxygen dynamics in spawning gravels and assess the potential consequences for egg development and survival. The study was conducted in a headwaters reach of the Crowsnest River located immediately downstream of outflow from Crowsnest Lake and characteristics of this gravel bed river were atypical compared to previously studied rivers for applications of SIDO. For example, suspended solids concentrations in the Crowsnest Lake outflow are typically very low (< 0.5 mg/l) but they do increase downstream due to erosion of bank and river bed materials. Accordingly, generally lower sediment concentrations

Table. 4.1 Summary of previous SIDO gravel bed river types and landscape influences		
Author	Gravel Bed River type	Landscape influences
1	Pristine, coldwater, mountainous, forested headwaters region; sediment is supply limited	A large upstream lake limiting sediment outflow; no major landscape disturbance impacts.
2	Lowland river, historically channelized for irrigation, flow regulated by upstream reservoir, paleochannels with high silt and clay and OM.	Upstream reservoir, banks heavily grazed and eroding, other agricultural influences.
3	Upland freshet river, floodplain, flashy discharge response	Livestock farming, surrounding grassland, bank failure, loss of riparian cover
5	High quantities of fine sediment, regulated flow from upstream dams	Agricultural land, deciduous forest, suburban development
6	Some channelization, high suspended sediment concentrations during storms	Loss of forest, riparian areas, and groundcover resulting in increased bank erosion
7	Rich in sand, mountainous, freshet	Upland bank erosion and forestry impacts
1=This study, 2= Sear et al. (2014), 3=Sear et al. (2017); Pattison et al. (2014); Pattison et al. (2012),5= Clement (2003), 6=Alonso et al. (1996), 7=Havis et al. (1993).		

observed in the Crowsnest River may possibly have influenced the results of SIDO in that the model might have minimum thresholds for both sediment size and concentration in order to produce more comparable modelled versus measured dissolved oxygen concentrations in spawning gravels.

Results of the present study illustrate the need to further refine the model to include additional parameters that influence dissolved oxygen concentrations in spawning gravels. For example, SIDO does not include terms that explicitly quantify account for other important processes that control dissolved oxygen dynamics in spawning gravels. These include surface ground water interactions in the hypohreic zone, microbial processes that influence sediment oxygen demand and environmental conditions (pH, redox, biostabilization by benthic communities). SIDO in its present form is a relatively coarse scale tool that has potential for fisheries management. However, additional research at the site and river reach scale in forested regions threatened by landscape scale disturbance such as harvesting, resource extraction and wildfire harvesting is required to evaluate SIDO in different riverine systems with variable hillslope disturbance and river connectivity.

4.5 Conclusion

Landscape disturbance in forested source water regions can accelerate the delivery of fine sediment from hillslopes to spawning gravels, and deposition or ingress of these materials in spawning gravels can produce hypoxic conditions that adversely impact egg survival. Quantifying and predicting intragravel dissolved oxygen dynamics and measuring the effects of river processes and landscape disturbances to dissolved oxygen regimes, remains a critical challenge for fisheries management and spawning habitat quality assessments. Gravel bed rivers draining forested source water regions along the eastern slopes of the Rocky Mountains are vulnerable to landscape disturbances and no previous research has been conducted to quantify and model dissolved oxygen dynamics in this region. To address this knowledge gap, the SIDO model was calibrated during the spring and summer of 2018 and validated using high frequency intragravel DO measurements within artificial redds.

Dissolved oxygen concentrations varied both spatially and temporally within the artificial redds despite their close proximity across each of the three river cross sections evaluated in this study. SIDO represented the general trend of decreasing oxygen as a function of time at three of the artificial redds (one per site) but there was poor agreement for the other redds. In general, the model was not sensitive to measured short term fluctuations of measured DO and modelled predictions of DO were lower than measured values.

The SIDO model was originally developed for an application in gravel bed rivers that were impacted by high sediment inputs from the watershed. In the present study, the physical conditions of the site and generally low sediment concentrations resulting from a lake outflow immediately above the study sites may have also contributed to the poor performance of the model. Suspended solids in the relatively pristine study river reach were primarily from the river channel and bank sources and solids concentrations at the lake outlet were extremely low. The model may work better in rivers impacted by large fluxes of sediment from disturbances such as harvesting and wildfire. Future studies are required to test the spatial and temporal variability in abiotic processes in spawning gravels and the relative effects of the disturbance impacted and non-impacted rivers on these processes in the eastern slopes of the Rocky Mountains.

References

Alberta Agriculture and Forestry's (AF) Alberta Climate Information Service (ACIS). Crowsnest Station. Data provided by Alberta Agriculture and Forestry, Alberta Climate Information Service (ACIS) https://agriculture.alberta.ca/acis (October 2018)

Alonso, C. V., Theurer, F. D., and Zachmann, D. W. (1988). Tucannon River offsite study: Sediment intrusion and dissolved-oxygen transport model. USDA. *Agricul.Res. Serv., Hydro-Ecosystems Res*. Group, Fort Collins, CO.

Alonso, C.V., Theurer, F.D. and Zachman, D.W. (1996). Sediment intrusion and dissolved oxygen transport model – SIDO.Technical Report No. 5, USDA-ARS National Sedimentation Laboratory, Oxford, Mississippi, USA. 232p.

Armstrong, J.D., Kemp, P.S., Kennedy, M.L and Milner NJ. (2003). Habitat requirements of Atlantic salmon and brown trout in rivers and streams. *Fisheries Research*, 62, 143–170.

ASTM. (2006). D 3977-97, Standard Test Method for Determining Sediment Concentration in Water Samples, Annual Book of Standards, Water and Environmental Technology. 11.02, 389-394.

Bell, G.R., Hoskins, G.E. and Bagshaw, J. W. (1969). On the structure and enzymatic degradation of the external membrane of the salmon egg. *Canadian Journal of Zoology*, 47,146-148

Beschta, R.L, and Jackson, W.L. (1979). The intrusion of fine sediments into a stable gravel bed. *J. Fish. Res. Board Can*, 36, 204-210.

Beschta, R.L. (1982). Comment on 'Stream system evaluation with emphasis on spawning habitat for salmonids' by M. A. Shirazia and W. K. Seim. *Water Resources Research*, 18, 1292-1295.

Bilotta, G.S., and Brazier, R.E. (2008). Understanding the influence of suspended solids on water quality and aquatic biota, *Water Research*, 42(12), 2849-2861.

Bixby, R.B., Cooper, S.D., Gresswell., R.D., Brown, L.E., Dahm, C.N., and Dwire., K.A. (2015). Fire effects on aquatic ecosystems: an assessment of the current state of science. *Freshwater Science*, 34(4), 1340-1350.

Bjornn, T. C., and Reiser, D.W. (1991). Habitat requirements of salmonids in streams. *American Fisheries Society Special Publication,* 19, 83-138.

Blackburn, J. Crowsnest River drainage sport fish population assessment. (2010). Technical Report, T-2011-001, produced by the Alberta Conservation Association, Lethbridge, Alberta, Canada.

Blake, W.H, Droppo, I.G., and Wallbrink,P.J. (2009). Sediment aggregation and water quality in wildfire affected basins. *Mar. Fresh. Res*, 60, 653-659.

Bloomer J, Sear D, and Kemp P. (2019) Does variation in egg structure among five populations of Atlantic salmon (Salmo salar) influence their survival in low oxygen conditions? R. *Soc. open sci,* 6, 181020.

Bowen, M.D., and Nelson, S.M. (2003). Environmental variables associated with a chinook salmon redd in Deer Creek, California. *California Fish and Game,* 89(4), 176–186.

Briggs, M.A., Harvey, J. W, Hurley, S.T, Rosenberry, D.O, McCobb, T., Werkema, D., and Lane Jr. J.W. (2018). Hydrogeochemical controls on brook trout spawning habitats in a coastal stream. *Hydrol. Earth Syst. Sci*, 22, 6383–6398.

Bunte, K., and Abt, S.R. (2001). Sampling Frame for Improving Pebble Count Accuracy in Coarse Gravel-Bed Streams. *Journal of the American Water Resources Association*, 37(4), 1001-1014.

Bunte, K., Abt, S.R., Potyondy, J.P., Swingle., K.W. (2009). Comparison of three pebble count protocols (EMAP, PIBO, SFT) in two mountain gravel bed streams. *Journal of the American Water Resources Association,* 45(5), 1209-1227.

Burner, C.J. (1951). Characteristics of spawning nests of Columbia River Salmon. *Fishery Bulletin,* 61 (52), 96-110.

Buxton, T. H., Buffington, J. M., Yager, E. M., Hassan, M. A. and Fremier, A. K. (2015). The relative stability of salmon redds and unspawned streambeds. *Water Resources Research*, 51(8), 6074–6092.

Cardenas, M.B., Ford, A.E., Kaufman, M.H., Kessler, A.J., and Cook, P.L.M. (2016). Hyporheic flow and dissolved oxygen distribution in fish nests: The effects of open channel velocity, permeability patterns, and groundwater upwelling. *Journal of Geophysical Research: Biogeosciences*, 121 (12), 3113-3130.

Carling, P. A., Whitcombe, L., I. A. Benson, B. G. Hankin, and Radecki-Pawlik, A. M. (2006). A new method to determine interstitial flow patterns in flume studies of sub-aqueous gravel bedforms such as fish nests. *River Res. Appl,* 22(6), 691–701.

Chapman, D.W. (1988). Critical review of variables used to define effects of fines in redds of large salmonids. *Trans. Am. Fish. Soc*, 117, 1-21

Chevalier, B. E., Carson,C and Miller, W.J. (1984). Modelling the transfer of oxygen between the stream and the stream substrate with application to the survival rates of salmonid embryos. Colorado State University, Dept. Agr. And Chem. Eng., ARS. Project No. 5602–20813-008A.

Clement, M. (2003). The feasibility of the restoration of Atlantic salmon (Salmo salar) into the Lake Ontario Basin. University of Guelph. Dissertation.

Collins, A. L., Williams, L. J., Zhang, Y. S., Marius, M., Dungait, J. A. J., Smallman, D. J., Dixon, E.R., Stringfellow, A., Sear, D.A., Jones, J.I., and Naden, P.S. (2014). Sources of sediment-bound organic matter infiltrating spawning gravels during the incubation and emergence life stages of salmonids. *Agriculture, Ecosystems and Environment*, 196, 76–93.

Collins, A. L. and Walling, D.E. (2007). Investigating the remobilization of fine sediment stored on the channel bed of lowland permeable catchments in the UK. Sediment Dynamics and the Hydromorphology of Fluvial Systems (Proceedings of a symposium held in Dundee, UK, July 2006). IAHS Publ. 306.

Corrigan, A. 2017. Assessing the Short-term Impacts on Sediment Production following Rapid Harvest and Stream Crossing Decommissioning in Rocky Mountain Headwaters. (Unpublished Masters thesis). University of Waterloo.

Crisp, DT. (1981). A desk study of the relationship between temperature and hatching for the eggs of five species of salmonid fishes. *Freshwater Biology,* 11, 361–368.

Crisp, D. T. and Carling, P. A. (1989). Observations on siting, dimensions and structure of salmonid redds. *Journal of Fish Biology*, 34, 119–134.

Crisp, D. T. (1996). Environmental requirements of common riverine European salmonid fish species in fresh water with particular reference to physical and chemical aspects. *Hydrobiologia,* 323(3), 201-221.

Curry, R. A. and Noakes, D. L. G. (1995). Groundwater and the Incubation and Emergence of Brook Trout (Salvelinus-Fontinalis). *Canadian Journal of Fisheries and Aquatic Sciences*, 52(8), 1741-1749.

Daykin, P. N. (1965). Application of mass transfer theory to the problem of respiration of fish eggs. *Journal of Fisheries Research Board* of *Canada,* 22(1), 159-171.

De Boer, D. and Stone, M. (1999). Fractal dimensions of suspended solids in streams: Comparison of sampling and analysis techniques. *Hydrological Processes*, 13(2), 239-254.

DeVries, P. (1997). Riverine Salmonid Egg Burial Depths: Review of Published Data and Implications for Scour Studies. *Can. J. Fish Aquat. Sci*, 54, 1685-1698.

Droppo, I. G. (2001). Rethinking what constitutes suspended sediment. *Hydrological Processes*. 15(9): 1551-1564.

Dumas, J., Bassenave, J.G., Jarry, M., Barriere, K., and Glise, S. (2007). Effects of fish farm effluents on egg to fry development and survival of brown trout in artificial redds. *Journal of Fish Biology*, 70, 1734–175.

Dusterhoff, S.R., Sloat, M.R, and Ligon, F.K. (2017). The influence of coarse particle mobility on scour depth in salmonid spawning habitat. *River Res.Applic*, 1-9, DOI: 10.1002/rra.3178

Einum, S; Hendry, A.P., Fleming, I.A. (2002). Egg-size evolution in aquatic environments: does oxygen availability constrain size? *Proc. R. Soc. Lond.* B, 269, 2325–2330.

Emelko, M.B, Stone, M, Silins, U., Allin, D., Collins, A.L, Williams, C.H.S, Martens, A.M, Bladon, K.D. (2015). Sediment-phosphorus dynamics can shift aquatic ecology and cause downstream legacy effects after wildfire in large river systems. *Global Change Biology*, 22(3), 1168–1184.

Environment Canada. (2010). Canadian climate normal 1971–2000, Coleman, AB, available at: http://climate.weatheroffice.gc.ca/climatenormals/index e.html

Franssen, J., Lapointe, M., and Magnan, P. (2014). Geomorphic controls on fine sediment reinfiltration into salmonid spawning gravels and the implications for spawning habitat rehabilitation. *Geomorphology*, 211, 11-21.

Garside, E.T. (1966). Effects of oxygen in relation to temperature on the development of embryos of brook trout and rainbow trout. *J. Fish. Res. Bd. Canada*, 23(8), 1121-1134.

Geist, D.R and Dauble, D.D. Redd Site Selection and spawning habitat use by fall Chinook salmon: The importance of geomorphic features in large rivers. *Environ Manage.,*22(5), 655-669.

Greig, S. M., Sear, D. A., and Carling, P. A. (2005a). The impact of fine sediment accumulation on the survival of incubating salmon progeny: Implications for sediment management. *The Science of the Total Environment*, 344, 241–258.

Greig, S.M., Sear, D.A, Smallman, D.J. and Carling, P. (2005b). Impact of clay particles on the cutaneous exchange of oxygen across the chorion of Atlantic salmon eggs. *Journal of Fish Biology*, 66 (6), 1681-1691.

Greig, S. M., Sear, D. A., and Carling, P. A. (2007a). A field-based assessment of oxygen supply to incubating Atlantic salmon embryos. *Hydrological Processes*, 22, 3087–3100.

Greig, S.M., Sear, D.A. and Carling, P.A. (2007b). A review of factors influencing the availability of dissolved oxygen to incubating salmonid embryos. *Hydrol Process*es, 21, 323–34.

Groves, P. A. and Chandler, J. A. (2005). Habitat quality of historic Snake River fall Chinook salmon spawning locations and implications for incubation survival. Part 2: intra-gravel water quality. *River Res. Appl*, 21, 469–483.

Hamor, T. and Garside, E. T. (1976). Developmental rates of embryos of Atlantic salmon, *Salmo salar* L., in response to various levels of temperature, dissolved oxygen, and water exchange*.* *Can. J. Zool*, 54, 1912–1917.

Harper, S.E., Foster, I.D.L., Lawler, D.M., Mathers, K.L., McKenzie, M., Petts, G.E. 2017. The complexities of measuring fine sediment accumulation within gravel bed rivers. *River Research and Applications,* 33(10), 1575-1584.

Hassan, M. A., Gottesfeld, S.A, Montgomery, D.R, Tunnicliffe, J.F., Clarke, G.K.C, Wynn, G., Jones-Cox, H., Poirier, R., MacIsaac, E., Herunter, H., and Macdonald, S.J. (2008). Salmon-driven bed load transport and bed morphology in mountain streams. *Geophys. Res. Lett.,* 35, L04405, doi:10.1029/2007GL032997.

Hauer, F. R., Locke,H., Dreitz, V.J., Hebblewhite,M., Lowe,W.H., Muhlfield, C.C., Nelson, C.R., Proctor,M.F., and Rood, S.B. (2016). Gravel-bed river floodplains are the ecological nexus of glaciated mountain landscapes. *Science Advances* 2:e1600026.

Havis, R. N., C. V. Alonso, King, J.G., and Thurow, R.F. (1993). A mathematical model of salmonid spawning habitat. *Water Resources Bulletin*, 29(3), 435-444.

Heywood, M.J.T and Walling, D.E. (2007). The sedimentation of salmonid spawning gravels in the Hampshire Avon catchment, UK: implications for the dissolved oxygen content of intragravel water and embryo survival. *Hydrol. Process,* 21, 770–788.

Hickman, T., and Raleigh, R.F. (1982). Habitat suitability index models: cutthroat trout. U.S. Fish and Wildlife Service FWS/OBS-82/10.5.

Hynes, H.B.N. (1983). Groundwater and stream ecology. *Hydrobiologia,* 100, 93–99.

Ingendahl, D. (2001). Dissolved oxygen concentration and emergence of sea trout fry from natural redds in tributaries of the River Rhine. *J Fish Biol*, 58, 325–341.

Jensen, D.W., Steel, E.A., Fullerton, A.H., and Pess, G.R. (2009). Impact of fine sediment on egg to fry survival of pacific salmon: A meta-analysis of published studies. *Reviews in Fisheries Science,* 17(3), 348-359. DOI:10.1080/10641260902716954

Johnson, C.L., Roni, P., and Pess, G.R. (2012). Parental effect as a primary factor limiting egg-to-fry survival of spring Chinook salmon in the Upper Yakima River Basin. *Trans. Am. Fish. Soc,* 141, 1295–1309.

Julien, H. P., and Bergeron, N.E. (2006). Effect of fine sediment infiltration during the incubation period on Atlantic salmon (Salmo salar) embryo survival. *Hydrobiologia*, 563, 61-71.

Kemp, P., Sear, D., Collins, A., Naden, P. and Jones, I. (2011). The impacts of fine sediment on riverine fish. *Hydrol. Process,* 25, 1800–1821

Kondolf, G.M. (2000). Assessing salmonid spawning gravel quality. *Trans. Am. Fish. Soc,* 129(1), 262–281.

Kondolf, G.M. and Wolman, M.G. (1993). The sizes of salmonid spawning gravels. *Water Resources Research,* 29, 2275–2285.

Lapointe, M., Bergeron, N. E., Berube, F., Pouliot, M.A., and Johnston, P. (2004). Interactive effects of substrate sand and silt contents, redd-scale hydraulic gradients, and interstitial velocities on egg-to emergence survival of Atlantic salmon (Salmo salar). *Canadian Journal of Fish and Aquatic Science*, 61, 2271-2277.

Malcolm, I.A., Soulsby, C., Youngson, A., and Petry, J. (2003). Heterogeneity in ground water-surface water interactions in the hyporheic zone of a salmonid spawning stream. *Hydrological Processes*, 17(3), 601-617

Malcolm, I. A., Soulsby, C., Youngson, A.F., Hannah, D.M., McLaren, I.S. and Thorne, A. (2004). Hydrological influences on hyporheic water quality: implications for salmon egg survival. *Hydrological Processes*, 18(9), 1543-1560.

Malcolm, I. A., Soulsby,C., Youngson, A. F. and Tetzlaff, D. (2005). Catchment-scale controls on groundwater surface water interactions in the hyporheic zone: Implications for salmon embryo survival. *River Research and Applications*, 21(9), 977-989.

Malcolm, I. A., Youngson, A. F., Greig, S. and Soulsby, C. (2008). Hyporheic influences on salmon embryo survival and performance. Salmonid spawning habitat in rivers. D. A. Sear and P. Devries. Maryland, American Fisheries Society, Symposium 65.

Malcolm, I.A., Youngson, A.F., Soulsby, C., Imholt, C., and Fryer, R.J. (2011). Is interstitial velocity a good predictor of salmonid embryo survival? *Transactions of the American Fisheries Society,*140,898-904.

Malcolm, I.A., Middlemass, C.A., Soulsby, C., Middlemass, S.J., and Youngson, A.F. (2010). Hyporheic zone processes in a canalised agricultural stream: implications for salmonid embryo survival. *Fundam. Appl. Limnol., Arch. Hydrobiol.* 176(4), 319–336.

Matthers, K.L and Wood, P.J. (2016). Fine sediment deposition and interstitial flow effects on macroinvertebrate community composition within riffle heads and tails. *Hydrobiologia*, 776, 147–160.

Mayhood, D.W. (2014). Guerilla Ecology: Toward an effective strategy for monitoring Alberta's trout streams in a hostile climate. Wild Trout Symposium XI -Looking Back and Moving forward.

McNeil, W. J., and Ahnell, W.H. (1964). Success of pink salmon spawning relative to size of spawning bed materials. U. S. Fish and Wildl. Ser., Spec. Sci Rept.-Fish. No 469 15 p.

Meyer, E. I., Niepagenkemper, O., Molls,F., and Spanhoff, B. (2008). An experimental assessment of the effectiveness of gravel cleaning operations in improving hyporheic water quality in potential salmonid spawning areas. *River Research and Applications,* 24(2), 119-131.

Meyer, C, Sparkman, M and Klatte, B.A. (2005). Sand Seals in Coho salmon redds: Do they improve egg survival. *North American Journal of Fisheries Management,* 25, 105–121.

Moody, J.A and Martin, D.A. (2001). Initial hydrologic and geomorphic response following a wildfire in the Colorado front range. *Earth Surface Processes and Landforms*, 26, 1049-1070.

Moody, J.A., Shakesby, R.A., Robichaud, P.R., Cannon, S.H., and Martin, D.A. (2013). Current research issues related to post-wildfire runoff and erosion processes. *Earth-Science Reviews*, 122, 10–37.

Nakamura, Y. and H. G. Stefan. (1994). Effect of Flow Velocity on Sediment Oxygen Demand: Theory. *Journal of Environmental Engineering*, ASCE 120(5), 996-1016.

Nelson, J. S. and Paetz, M.J. (1992). The fishes of Alberta. Second edition. University of Alberta Press, Edmonton, and University of Calgary Press, Calgary, AB, xxvi + 437 p. (English only.

Newcombe, C.P. and MacDonald, D.D. (1991). Effects of suspended sediments on aquatic ecosystems. *North American Journal of Fisheries Management,* 11(1), 72-82.

Owens, P.N., Petticrew, E.L, and Van der Park, M. (2010). Sediment response to catchment disturbances. *J. Soils. Sediment*, 10, 591-596.

Pattison, I., Sear, D.A., Carling, P., Collins, A.L., Jones, J.I., and Naden, P.S. (2012). Assessing the effect of fine sediment upon salmonid egg incubation using a modelling approach: SIDO-UK. *BHS Eleventh National Symposium, Hydrology for a changing world, Dundee 2012. ISBN: 1903741181*

Pattison, I., Dear, D.E., Collins, A.L, Jones, J.I, and Naden, P.S. (2014). Interactions between fine-grained sediment delivery, river bed deposition and salmonid spawning success. IN: Jun Xu, Y. et al. (eds.) Sediment Dynamics From the Summit to the Sea. Wallingford: IAHS, pp. 199 - 206

Peterson, N.P and Quinn, T.P. (1996). Spatial and temporal variation in dissolved oxygen in natural pockets of chum salmon, in Kennedy Creek, Washington. *Journal of Fish biology*, 48, 131-143.

Petticrew, E. L. and J. F. Rex. (2006). The importance of temporal changes in gravel stored fine sediment on habitat conditions in a salmon spawning stream. *Sediment Dynamics and the Hydromorphology of fluvial systems,* Dundee, Scotland, IAHS publication: 306, 2006.

Rubin, J.F and Glimsater, C. (1996). Egg to fry survival of the sea trout in some streams of Gotland. *Journal of Fish Biology*, 48, 585-606.

Schindler-Wildhaber, Y., Michel, C., Epting, J., Wildhaber, R.A., Huber, E., Huggenberger, P., Burkhardt-Holm, P., Alewell, C. (2014). Effects of river morphology, hydraulic gradients, and sediment deposition on water exchange and oxygen dynamics in salmonid redds. *Science of the Total Environment*, 470-471, 488-500.

Schmetterling, D. A. (2000). Redd Characteristics of Fluvial Westslope Cutthroat Trout in Four Tributaries to the Blackfoot River, Montana. *North American Journal of Fisheries Management,* 20, 776–783.

Sear, D.A., Collins, A.L., Jones, J.I., Naden, P.S. Hulin,A., Burke,N., Pattison,I and Bateman,S. (2014a). Does fine sediment source as well as quantity affect salmonid embryo mortality and development? *The Science of the total environment*, 541, 957-968.

Sear, D.A., Pattison, I., Collins, A.L., Newson, M.D., Jones, J.I., Naden, P.S and Carling. P.A. (2014b). Factors controlling the temporal variability in dissolved oxygen regime of salmon spawning gravels. *Hydrological Processes*, 28 (1), 86-103.

Sear, D.A., Pattison, I., Collins, A.L., Smallman., D.J., Jones, J.I., Naden, P.S. (2017). The magnitude and significance of sediment oxygen demand in gravel spawning beds for the incubation of salmonid embryos. *River Res Applic*, 1–13.

Silins, U., Bladon, K.D., Kelly, E.N., Esch, E., Spence, J.R., Stone, M., Emelko, M.B., Boon, S., Wagner, M.J., Williams, C.H.S., and Tichkowsky, I. (2014). Five-year legacy of wildfire and salvage logging impacts on nutrient runoff and aquatic plant, invertebrate and fish productivity. *Ecohydrology,* 7(6), 1508-1523.

Smith, O.R. (1941). The spawning habits of cutthroat and eastern brook trouts. J. *Wildl. Manage*., 5, 461–471.

Soulsby, C.A., Youngson, A.F., Moir,H., Malcolm, I. (2001). Fine sediment influence on salmonid spawning habitat in a lowland agricultural stream: A preliminary assessment. *Science of the Total Environment*, 265(1-3), 295-307.

Sowden, T. K. and Power, G. (1985). Prediction of rainbow trout embryo survival in relation to groundwater seepage and particle size of spawning substrates. *Transactions of the American Fisheries Society,* 114, 804–812.

Sterling, G.L. (1992). Fry emergence survival of rainbow trout, Onchorynchus mykiss (Walbaum), following timber harvest in the two foothill streams of West-central Alberta. University of Alberta. Thesis.

Stone, M., Collins, A.L., Silins, U., Emelko, M.B., and Zhang, Y.S. (2014). The use of composite fingerprints to quantify sediment sources in a wildfire impacted landscape, Alberta, Canada. *Science of the Total Environment, 473, 642-650.*

Stone, M., Emelko, M. B., Droppo, I. G., and Silins, U. (2011). Biostabilization and erodibility of cohesive sediment deposits in wildfire-affected streams. *Water Research*, *45*(2), 521-534.

Theurer,F.D and Miller, W.J. (1986) Draft Tucannon River offsite study: fry emergence model report. 53 pp.

Tonina, D., and Buffington,M. (2009). A three-dimensional model for analyzing the effects of salmon redds on hyporheic exchange and egg pocket habitat. *Canadian Journal of Fisheries and Aquatic Sciences*, 66(12), 2157-2173.

Tonina, D., de Barros, F. P., Marzadri, A., and Bellin, A. (2016). Does streambed heterogeneity matter for hyporheic residence time distribution in sand-bedded streams? *Advances in Water Resources,* 96, 120-126.

Walling, D.E., Owens, P.N, Carter, J., Leeks, G.J.L, Lewis, S., Meharg, A.A, Wright, J. (2003). Storage of sediment associated nutrients and contaminants in river channel and floodplain systems. *Applied Geochemistry*, 18, 195–220.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R and Swetnam, T.W. (2006) Warming and earlier spring increase western U.S Forest Wildfire Activity. *Science*, 313, 940-943.

Wickett, W.P. (1954). The Oxygen Supply to Salmon Eggs in Spawning Beds. *J.Fish.Res.Bd. Canada,* 11(6), 933-952.

Wood, A.T., Clark, T.D., Elliot, N.G., Frappel, P.B., and Andrewartha, S.J. (2019). Physiological effects of dissolved oxygen are stage specific in incubating Atlantic salmon (Salmo salar). *Journal of Comparative physiology B: Biochemical, systemic, and environmental physiology*, 189 (1), 109-120.

Wood, P.J., and Armitage P.D. (1997). Biological Effects of Fine Sediment in the Lotic Environment. *Environmental Management*, 21(2), 203-217.

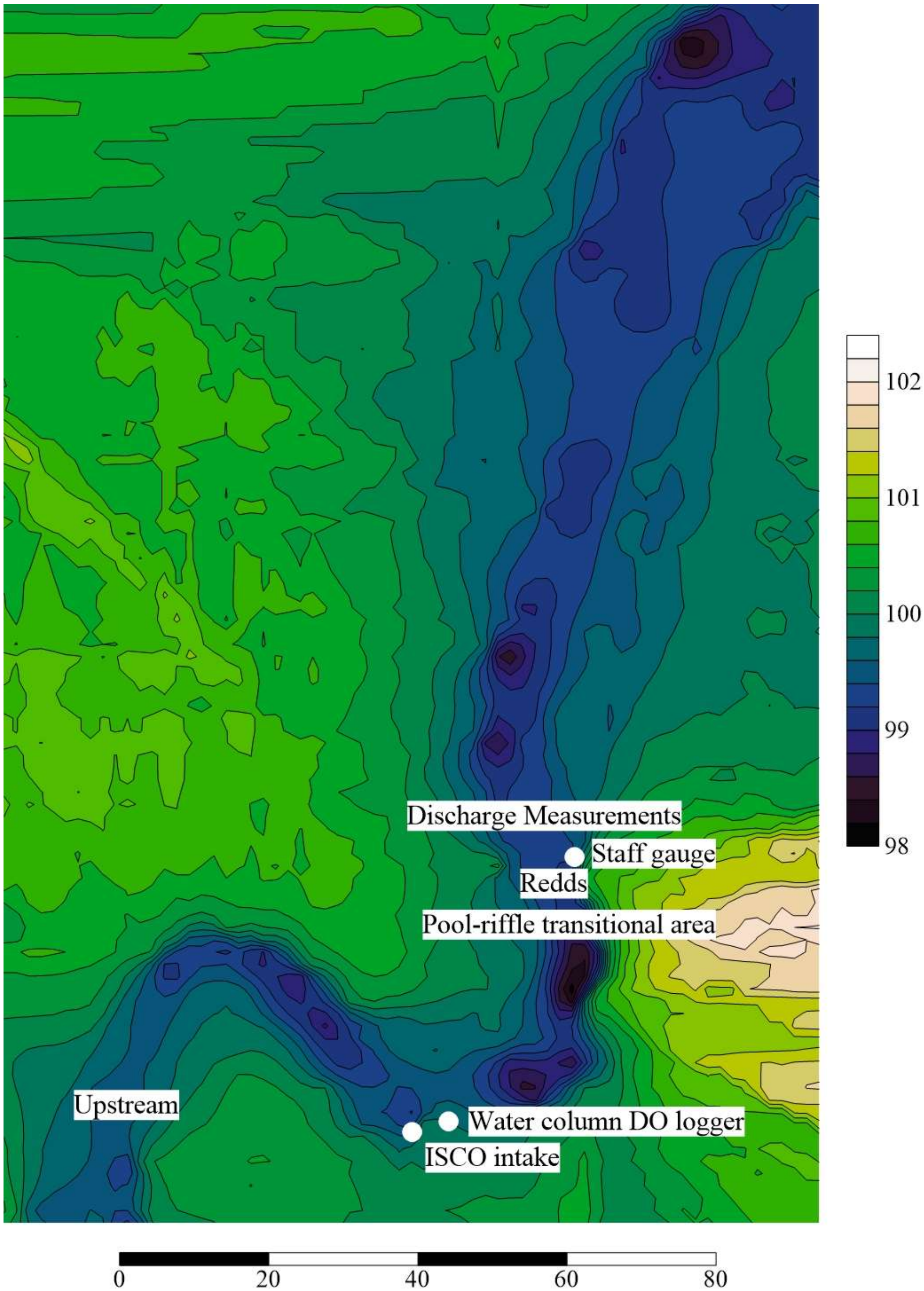
Wu, F. (2000). Modeling embryo survival affected by sediment deposition into salmonid spawning gravels: Application to flushing flow prescriptions. *Water Resources Research*, 36 (6), 1595-1603.

Yamada, H and Nakura, F. (2009). Effects of fine sediment accumulation on the redd environment and the survival rate of masu salmon (Onchorhynchus masiu) embryos. *Landscape and Ecological Engineering*, 5 (2), 169-181.

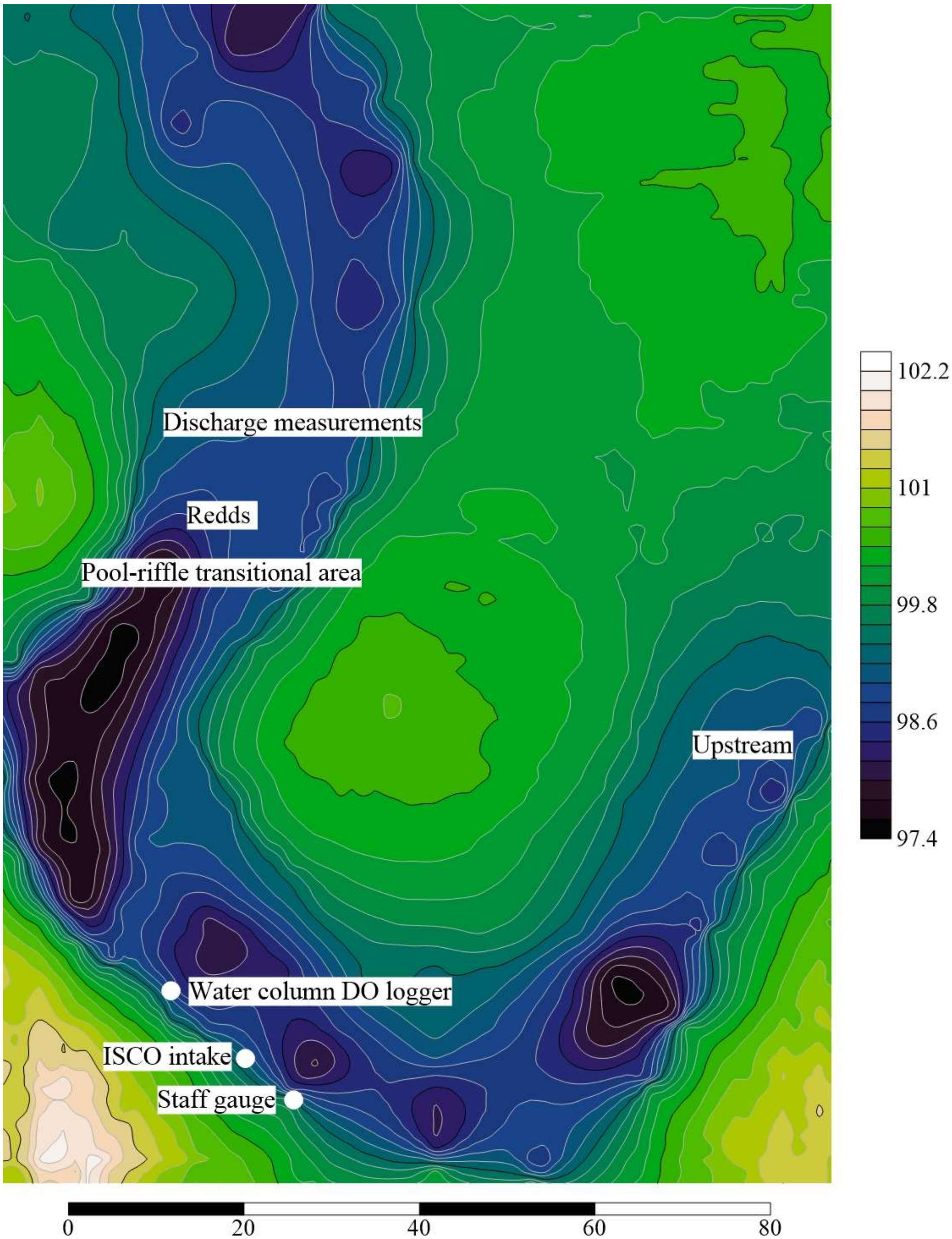
Youngson, A.F., Malcolm, I.A., Thorley, J.L., Bacon, P.J, and Soulsby, C. (2004). Long residence groundwater effects on incubating salmonid eggs: low hyporheic oxygen impairs embryo development. *Can. J. Fish. Aquat. Sci*, 61, 2278–2287.

Ziadat, A.H and Berdanier, B.W. (2004). Stream depth significance during in-situ sediment oxygen demand measurements in shallow streams. *Journal of the American water resources association,* 40(3), 631-638.

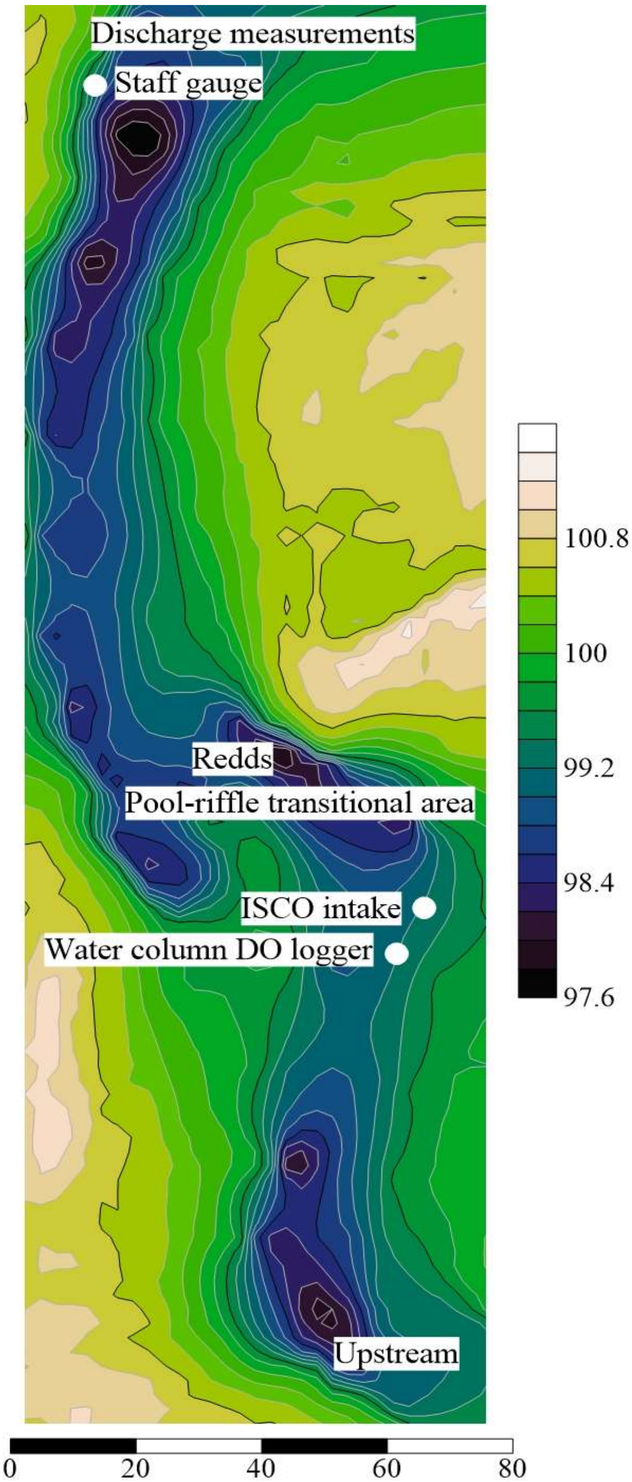
Appendix A. Topographical surveys (in meters) of three study reaches



Site 1


Discharge measurements
Redds
Pool-riffle transitional area
Upstream
Water column DO logger
ISCO intake
Staff gauge
102.2
101
99.8
98.6
97.4
0
20
40
60
80

Site 2


Discharge measurements
Staff gauge
Redds
Pool-riffle transitional area
ISCO intake
Water column DO logger
Upstream
100.8
100
99.2
98.4
97.6
0
20
40
60
80

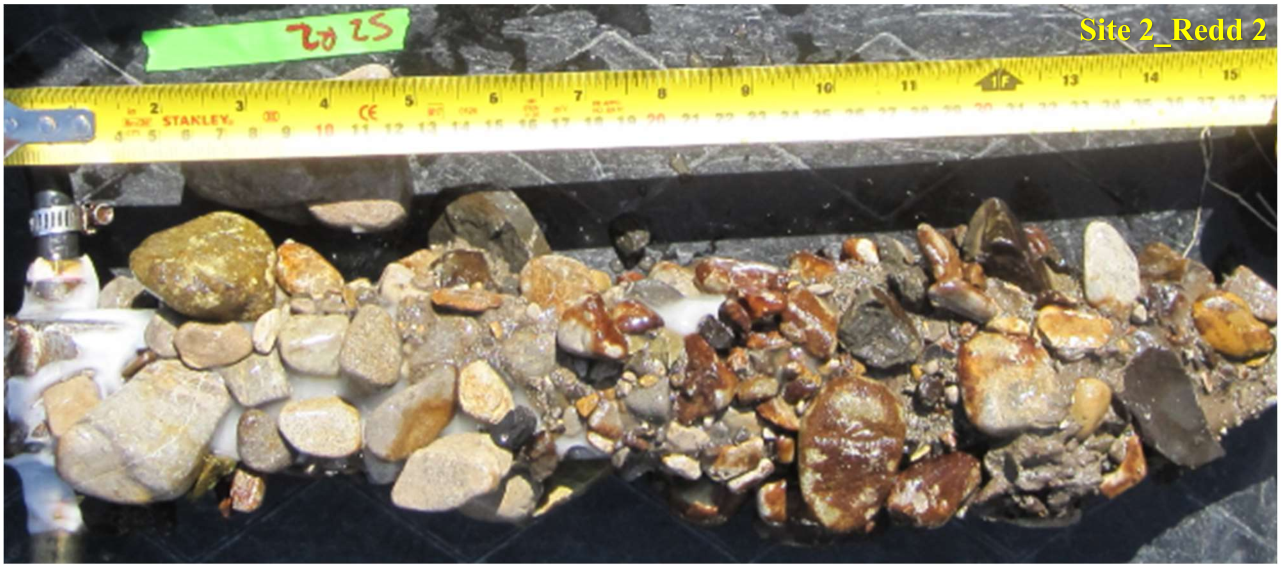
Site 3

Appendix B. Freeze cores and bed roughness


Site 1_Redd 3


Site 2_Undisturbed


Site 2_Redd 1


Site 2_Redd 2


Site 2_Redd 3


Site 3_Undisturbed


Site 3_Redd 1
STANLEY


Site 3_Redd 2
STANLEY


Site 3_Redd 3
STANLEY

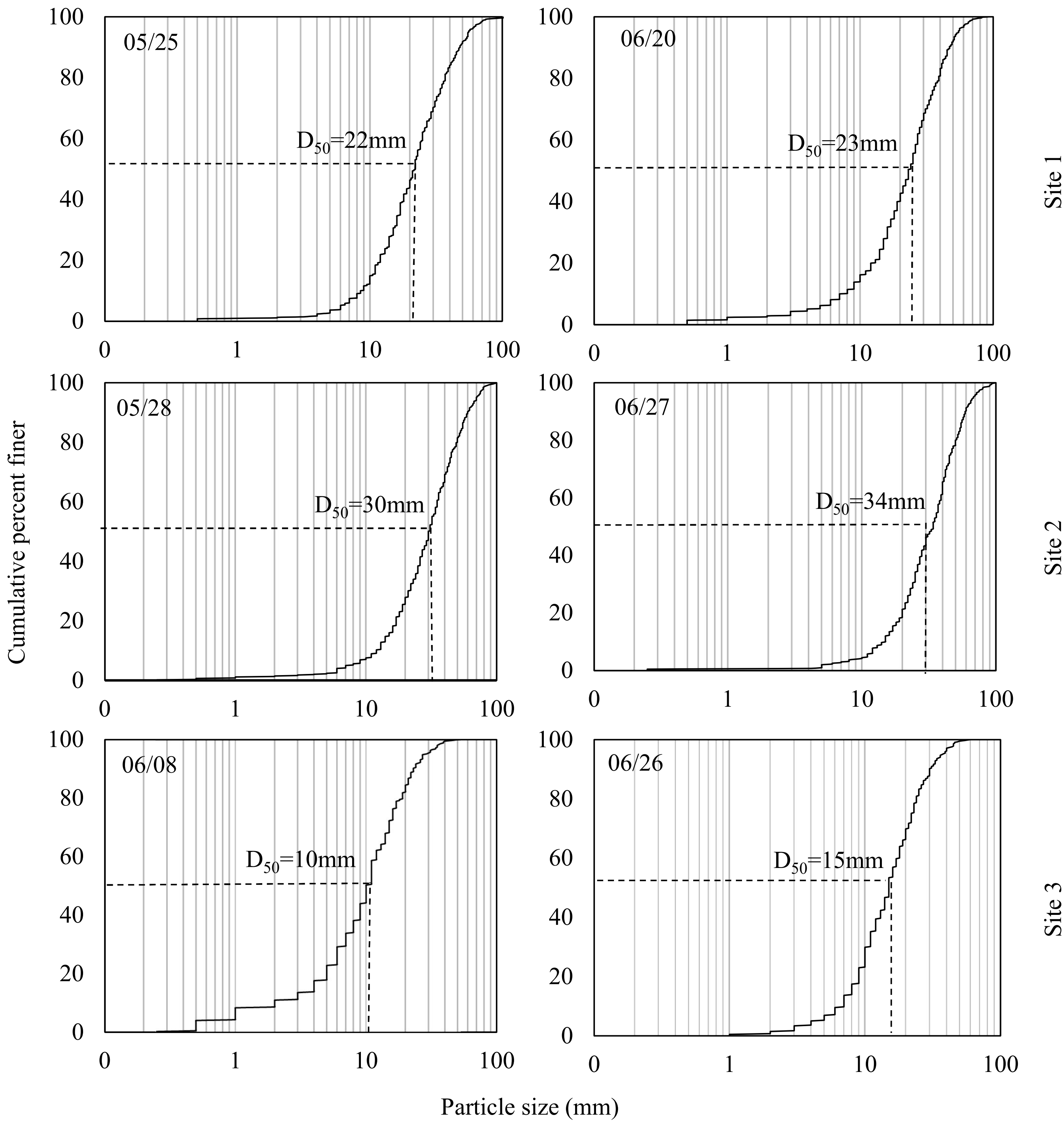


Figure B.1. Particle size distribution of armour layer

Appendix C. SIDO calibration

Job control file

The Job Control file (See below) was the same at all redds. OPTION 4: MODE 7 was used for input into the Microsoft Excel ® file, and OPTION 4: MODE 8 was used to display summaries. Steelhead was selected as the salmonid species.

Job Control File:

RUN	CONTROL	PARAMETERS:			
JSTART	NDAYS	NDOUT	OPTION	MODE	CHINOOK
1	092	01	4	7	FALSE

Verify	Bedload
FALSE	FALSE

Hydrology Input File

An example of the input file structure, for Site 1.

HYDROLOGY INPUT DATA: Crowsnest River: Site 1

Days since fertiliz.	Water Discharge [cfs]	Water Temp. [C]	<--- clay [ppm]	Suspended silt [ppm]	Sediment sand [ppm]
JDAY	QD	TEMP	FSLD1	FSLD2	FSLD3
1	120.47	6.86	0.00	0.15	3.62
2	120.47	7.00	0.02	0.51	12.1
3	120.47	7.30	0.04	0.97	23.1
4	120.47	7.50	0.02	0.51	12.2
5	163.13	7.74	0.03	0.75	17.9
6	163.13	6.85	0.03	0.71	16.9
7	154.61	6.91	0.09	4.33	5.91
8	154.61	6.64	0.08	3.82	5.21
9	185.38	6.86	0.11	5.24	7.15
10	161.01	6.90	0.01	0.82	1.13
11	161.01	7.59	0.07	3.28	4.47
12	161.01	8.29	0.05	2.46	12.2
13	236.11	8.49	0.17	6.72	3.35
14	228.90	7.83	0.09	2.40	9.03
15	228.90	7.18	0.16	4.00	5.32
16	258.03	7.09	0.17	4.26	3.53
17	210.29	7.73	0.08	2.14	1.78
18	210.29	8.33	0.02	0.71	0.59

19	210.29	8.48	0.03	0.71	0.59
20	210.29	8.31	0.08	2.15	1.78
21	297.42	9.07	0.05	1.44	1.19
22	248.06	9.64	0.05	2.15	1.07
23	232.26	9.81	0.05	1.55	1.07
24	232.26	10.33	0.08	2.33	1.60
25	232.26	10.8	0.05	1.56	1.07
26	232.26	10.45	0.05	1.56	1.07
27	228.90	10.36	0.01	0.68	1.89
28	204.84	9.55	0.01	0.69	1.90
29	204.84	9.39	0.01	0.69	1.90
30	204.84	9.67	0.04	2.71	3.88
31	204.84	10.17	0.02	1.03	2.84
32	204.84	10.57	0.02	1.03	2.85
33	204.84	10.34	0.02	1.03	2.85
34	169.50	10.64	0.00	0.30	1.00
35	155.87	11.98	0.00	0.30	1.00
36	155.87	11.65	0.00	0.31	1.00
37	154.61	11.57	0.01	0.61	1.99
38	161.94	10.92	0.01	0.41	2.17
39	161.94	10.3	0.01	0.43	2.26
40	161.94	10.05	0.01	0.43	2.26
41	161.94	10.29	0.02	0.63	3.23
42	128.96	10.18	0.02	0.75	3.93
43	121.21	10.29	0.02	0.29	1.04
44	121.21	9.78	0.02	0.29	1.04
45	121.21	9.75	0.02	0.29	1.04
46	121.21	9.21	0.06	0.86	3.03
47	121.21	9.60	0.03	0.43	1.53
48	121.21	10.25	0.04	0.57	2.02
49	154.40	10.81	0.04	0.57	2.02
50	154.40	11.1	0.04	0.57	2.02
51	140.61	11.02	0.04	0.57	2.02
52	140.61	12.0	0.01	0.25	1.04
53	140.61	12.39	0.02	0.51	2.10
54	154.50	11.92	0.01	0.25	1.04
55	154.50	11.95	0.01	0.51	2.08
56	154.50	11.71	0.02	0.51	2.08
57	116.17	12.00	0.00	0.47	2.13
58	116.17	12.02	0.00	0.56	2.05
59	116.17	11.82	0.00	0.56	2.05
60	115.16	11.65	0.00	0.56	2.05
61	115.16	11.65	0.00	0.56	2.05
62	115.16	11.89	0.00	0.33	0.97

63	115.16	12.01	0.00	0.33	0.97
64	115.16	12.91	0.00	0.28	1.02
65	125.54	13.57	0.00	0.28	1.02
66	125.54	13.67	0.00	0.28	1.02
67	125.54	14.07	0.00	0.28	1.02
68	125.54	13.64	0.00	0.28	1.02
69	125.54	13.72	0.00	0.28	1.02
70	110.03	14.43	0.00	0.16	1.13
71	98.19	15.09	0.00	0.16	1.13
72	98.19	14.53	0.00	0.16	1.13
73	98.19	14.08	0.00	0.32	2.26
74	98.19	14.90	0.00	0.32	2.29
75	98.19	15.47	0.00	0.32	2.29
76	87.85	16.19	0.00	0.40	2.21
77	94.02	15.94	0.00	0.20	1.10
78	94.02	15.53	0.00	0.61	3.33
79	94.02	14.98	0.00	0.30	1.60
80	94.02	14.85	0.00	0.30	1.67
81	94.02	14.90	0.00	0.20	1.09
82	80.28	15.33	0.00	0.40	2.20
83	80.28	14.82	0.00	0.40	2.20
84	73.71	14.87	0.00	0.30	1.00
85	73.71	14.61	0.00	0.65	3.23
86	73.71	14.79	0.00	0.30	1.00
87	73.71	15.23	0.00	0.30	1.01
88	73.71	15.93	0.00	0.60	2.01
89	73.71	16.40	0.00	0.30	1.01
90	43.48	16.03	0.00	0.29	1.01
91	43.48	16.41	0.03	2.33	8.10
92	43.48	15.23	0.03	2.06	7.17

Stream redd input file

The Stream Redd input file contains channel parameters and intragravel transport parameters. This section will briefly summarize these parameters, their function in the model, and how values were chosen for this study. An example of the Stream-redd input file structure, for Site 1_Redd 2 is below.

Channel Transport Parameters

a) The user must define bed slope (S0_below). This was approximated using water level upstream and downstream with the Leica Total Station 405. Due to possible error during this calculation, a slope of 0.004 was used at all sites as default.

b) Channel discharge at which the bed is set into motion (Q_bedload) must be defined by the user. If this discharge is reached, then the simulation stops as the redd is considered obliterated. This value was set to a value high enough that this would not be reached during the simulation period.

c) (Q_calb) defines discharge at the time of the morphological survey. The closest measured discharge to the survey date was selected.

d) SIDO assumes a straight reach. Location of redds are defined as the distance from the end of the reach (X0RDD). These distances were calculated from the morphological survey.

e) Elevation above sea level for the redd zone (RELEV) was determined with a handheld GPS unit (Garmin Etrex 20x).

f) The user can define up to a maximum of 30 cross sections (Num_X_sec) numbered consecutively beginning with the furthest downstream. Each of these cross sections are defined by a set number of points (num_pnts). Transverse and vertical coordinates must be input for each point. At each site, between 6-8 cross sections were chosen from the survey to be included in the model. These cross sections captured the pool riffle morphological profile at all sites.

g) For each cross section the user must define bankfull elevation (bankfull). This was recorded during each cross section from a field estimate at each cross section.

h) SIDO requires D_{50} of the armour layer material (Dn_rough) and D_{50} of the material carried as bedload, (D50_bed) for each cross section. Dn_rough and D50_bed were operationally defined as the average diameter on bed surface (Bunte and Abt, 2001).

i) SIDO calculates the Manning Roughness coefficient to characterize the flow resistance. The user must provide the Manning Roughness Coefficient for the channel flow calibration (N_calb) at each transect, from the known discharge and geometry. N_calb can be adjusted until the water stage profile generated matched the measured profile in the field. The original value used by Alonso et al. (1996) was used of 0.033.

j) N_calb_exponent must be selected for all cross sections, calculated from the linear regression between discharge and conveyance. The original value defined in Alonso et al. (1996) of 0.3 was used.
k) SIDO also requires the Manning roughness coefficient for the overbank areas (N_ovrbank). A value of 0.05 was input for all sites based on readily available literature on this value.

Intragravel transport parameters

a) ALPHA controls the seepage rate at the bottom of the redd and can range from 0-10. A negative value will cause water to flow into the redd, and positive will flow out. Only the lower boundary layer of the redd is affected by this value. Seepage rates were not available for the Crowsnest River. A value for ALPHA was therefore determined by selecting 10 to maximize downward seepage patterns. Values between 0-10 were tested for all runs, but they did not have any significant impact on flow to the egg zone. A value of 10 was selected. As in the Alonso et al. (1996), the value of ALPHA was not important to DO predictions and embryonic survival rates, and any value could have been used.
b) Hydraulic conductivity is controlled by the CPERM parameter. It can be a value between 0 and 100% (100% being the greatest hydraulic conductivity). This parameter left unchanged from Alonso et al. (1996).
c) The CBADJ parameter regulates the suspended sediment concentration at the near bed. At a value of 1, the sediment concentrations at the bed interface is assumed to be the same concentration as the near bed water column suspended concentration, and therefore a small amount of deposition is predicted. This is rarely the case however, as the near bed concentration is typically higher within centimeters from the gravel bed than higher int he column. The parameter and phenomenon is defined by results from the Beschta and Jackson (1979). To maximize sedimentation due to low ingress quantities, this value was set to 100.
d) VASDJ is a constant which controls the rate of infiltration of fine sediments into the redd. Maximum infiltration occurs when VSADJ=1, while sediment is neutrally buoyant when VSADJ =0. To maximize the settling rates of fines in the redd, this value was set to 1. Tests with lower values showed no effect on predictions in this study.
e) The user must specify bulk specific weight of the fine matrix (BSWFNS) and gravel framework (BSWGRV). These values were taken from Alonso et al. (1996).

f) The last parameters the user must input describe the grain size distribution of the redd material, which in this study, were taken from freeze core particle size data. For the particle size of the "disturbed" and "egg" zones of the redd, the 0-15cm portion of the freeze cores taken from the redd during construction were used at all sites. Particle size required by the model of the "undisturbed" zone, underneath the egg zone, was described using 0-15cm from the freeze cores taken at locations prior to redd installation.

STREAM-REDD INPUT FILE: Crowsnest River Site 2: Redd 1

*******CHANNEL PARAMETERS READ IN MODULE STRMRD********

PARAMETERS FOR STREAMFLOW COMPUTATIONS:

S0_below (ft/ft)	Num_X_sec (cfs)	Q-bedload (cfs)	Q-calbN-calb_exp	
0.004	6	2478	21.18	0.3

CONTROL PARAMETERS FOR SETTING UP BOUNDARY CONDITIONS STREAM-REDD

X0RDD (ft)	RELEV (ft)
53.1	4340

CHARACTERISTICS OF INDIVIDUAL CROSS SECTIONS:

CROSS SECTION 1 (XS16)

X_long (ft)	num_pnts (ft)	bankfull (ft)	D50_bed (mm)	Dn_rough (mm)	N_ovrbnk	N-calb
0	12	326.07	22.5	22.5	0.05	0.03

z-tran (ft)	y-elev (ft)	z-tran (ft)	y-elev (ft)	z-tran (ft)	y-elev (ft)	z-tran (ft)	y-elev (ft)
0	327.13	0.74	326.66	5.41	327.16	9.96	326.92
15.74	325.83	19.12	326.07	27.01	325.79	34.61	325.48
36.6	324.73	38.05	324.58	39.05	324.88	39.95	326.59

CROSS SECTION 2 (GSR 11)

X_long (ft)	num_pnts (ft)	bankfull (ft)	D50_bed (mm)	Dn_rough (mm)	N_ovrbnk	N-calb
39.62	11	326.55	22.5	22.5	0.05	0.03

z-tran (ft)	y-elev (ft)	z-tran (ft)	y-elev (ft)	z-tran (ft)	y-elev (ft)	z-tran (ft)	y-elev (ft)
0	328.03	1.22	326.4	4.16	326.55	7.26	326.22
10.76	325.93	14.44	325.71	18.31	325.79	22.44	325.98

29.18	326.02	33.67	326.7	36.5	326.82

CROSS SECTION 3 (GSR 8)

X_long (ft)	num_pnts (ft)	bankfull (ft)	D50_bed (mm)	Dn_rough (mm)	N_ovrbnk	N-calb
53.19	11	325.8	22.5	22.5	0.05	0.03

z-tran (ft)	y-elev (ft)	z-tran (ft)	y-elev (ft)	z-tran (ft)	y-elev (ft)	z-tran (ft)	y-elev (ft)
0	328.18	0.84	324.7	3.74	324.62	5.18	324.72
6.44	325.01	8.29	325.41	10.42	325.77	13.83	325.91
17.21	326.07	20.53	326.81	27.82	327.32		

CROSS SECTION 4 (GSR 5)

X_long (ft)	num_pnts (ft)	bankfull (ft)	D50_bed (mm)	Dn_rough (mm)	N_ovrbnk	N-calb
73.1	13	326.7	22.5	22.5	0.05	0.03

z-tran (ft)	y-elev (ft)	z-tran (ft)	y-elev (ft)	z-tran (ft)	y-elev (ft)	z-tran (ft)	y-elev (ft)
0	327.93	1.02	323.96	3.13	323.84	5.28	323.81
7.72	323.85	10.12	323.91	12.61	324.36	15.26	325.16
17.55	325.86	20.2	326.72	23.55	327.16	27.89	327.45
32.32	327.43						

CROSS SECTION 5 (GSR 2)

X_long (ft)	num_pnts (ft)	bankfull (ft)	D50_bed (mm)	Dn_rough (mm)	N_ovrbnk	N-calb
96.62	13	325.1	22.5	22.5	0.05	0.03

z-tran (ft)	y-elev (ft)	z-tran (ft)	y-elev (ft)	z-tran (ft)	y-elev (ft)	z-tran (ft)	y-elev (ft)
0	328.33	1.54	323.58	1.87	322.89	2.54	322.21
3.01	322.08	9.86	323.41	11.26	324.18	12.88	325.11
15.81	325.66	18.67	326.39	22.31	327.25	26.01	327.7
29.83	327.81						

CROSS SECTION 6 (XS 14)

X_long (ft)	num_pnts (ft)	bankfull (ft)	D50_bed (mm)	Dn_rough (mm)	N_ovrbnk	N-calb
185.44	13	326.9	22.5	22.5	0.05	0.03

z-tran (ft)	y-elev (ft)	z-tran (ft)	y-elev (ft)	z-tran (ft)	y-elev (ft)	z-tran (ft)	y-elev (ft)
0	327.99	0.52	325.38	3.18	325.46	6.47	326.03

14.28	326.29	18.24	326.66	23.83	327.32	27.17	327.52
30.86	327.09	33.19	327.2	36.82	327.45	40.85	327.35
42.56	327.88						

***************INTRAGRAVELTRANSPORT PARAMETERS ***************

CONTROL PARAMETERS FOR INTRAGRAVEL CALCULATIONS:

ALP	CPER	CBA	VSA	BSW	BSW
HA	M	DJ	DJ	FNS	GRV
10	92	100	1	80	110

GRAIN SIZE DIAMETER OF SEDIMENT FRACTIONS (millimeters)

									DGS1
DGS1	DGS2	DGS3	DGS4	DGS5	DGS6	DGS7	DGS8	DGS9	0
0.062	0.125	0.26	1	2	4	10	26	40	250

SPECIFIC GRAVITY OF SEDIMENT FRACTIONS

									SGG1
SGG1	SGG2	SGG3	SGG4	SGG5	SGG6	SGG7	SGG8	SGG9	0
2.20	2.43	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65

INITIAL SIZE COMPOSITION OF SUBSTRATE MATERIAL (mass fraction finer than, in decimal)

										BSW
PCF1	PCF2	PCF3	PCF4	PCF5	PCF6	PCF7	PCF8	PCF9	PCF10	MIX
0.00	0.01	0.02	0.03	0.05	0.13	0.59	0.83	1.00	1.00	130
0.01	0.09	0.25	0.41	0.51	0.63	0.76	1.00	1.00	1.00	110
0.01	0.09	0.25	0.41	0.51	0.63	0.76	1.00	1.00	1.00	110

COMPOSITION OF BED MATERIAL THAT FILLS THE REDD'S DEPRESSION (mass fraction finer

PCFI	PCFI	PCFI	PCFI	PCFI	PCFIL	PCFI	PCFI	PCFI	PCFIL	
LL1	LL2	LL3	LL4	LL5	L6	LL7	LL8	LL9	L10	
0.00	0.01	0.02	0.03	0.05	0.13	0.59	0.83	1.00	1.00	110

*****************End of ReddSite.inp File *************************

Internal parameters

In addition to the user-supplied data and selection of intragravel transport parameters, the user has the option of rewriting several internal parameters. These include channel routing parameters, intragravel flow transport parameters, oxygen consumption parameters, and biological parameters. Alonso et al. (1996) cautions against altering internal parameters in management applications, until the user is familiar enough with the model. In this study, Sed_SOC was adjusted to test the sensitivity using values of 4, 8 and 11.38. A value of 11.38 was selected for all simulations.

Appendix D. Abiotic conditions predicted in SIDO within the redd

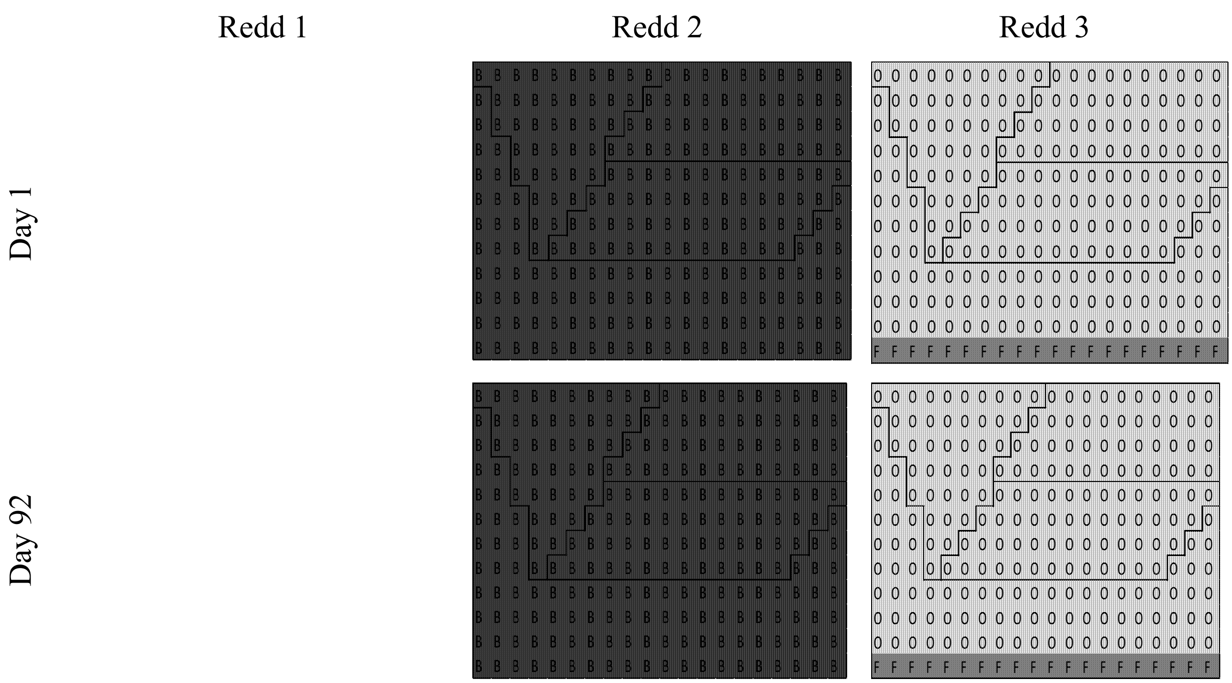


Figure D.1. Predicted infilling behaviour of fines (sand, silt, clay) predicted during the simulation for Site 1. O=Open cell (O), F=Filling cell (F), B=blocked cell (B).

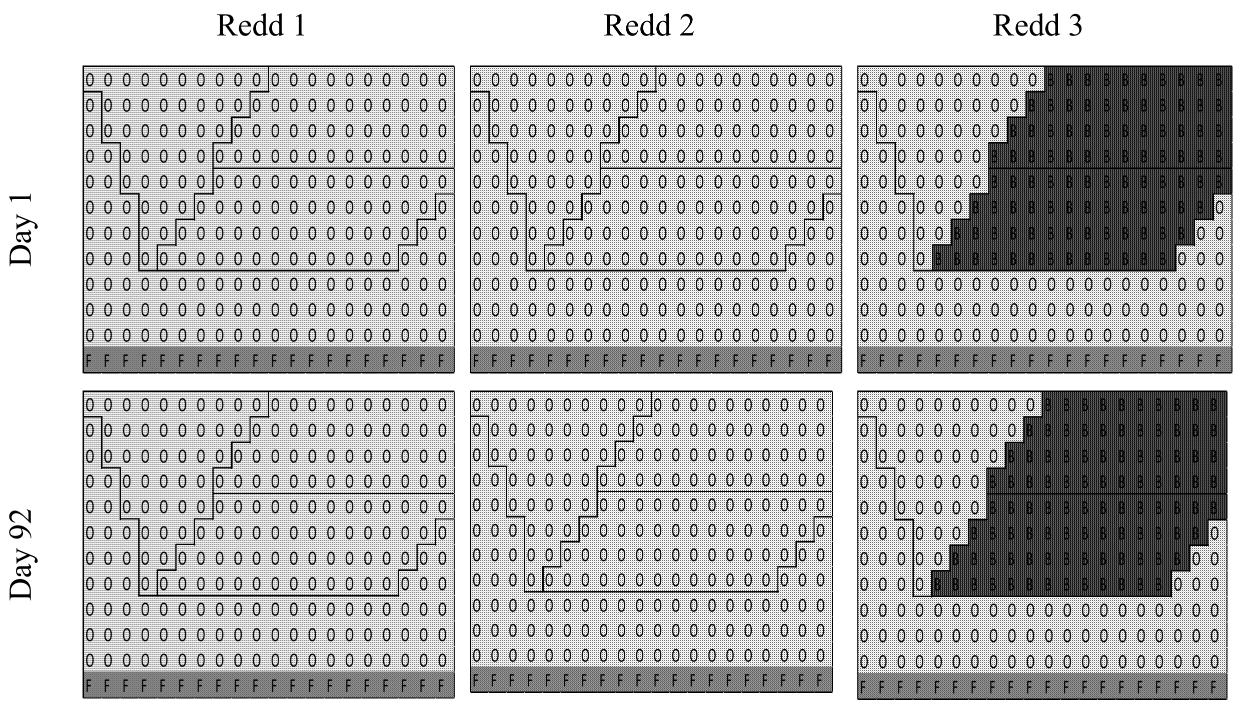


Figure D.2. Predicted infilling behaviour of fines (sand, silt, clay) predicted the simulation for Site 2. O=Open cell (O), F=Filling cell (F), B=blocked cell (B).

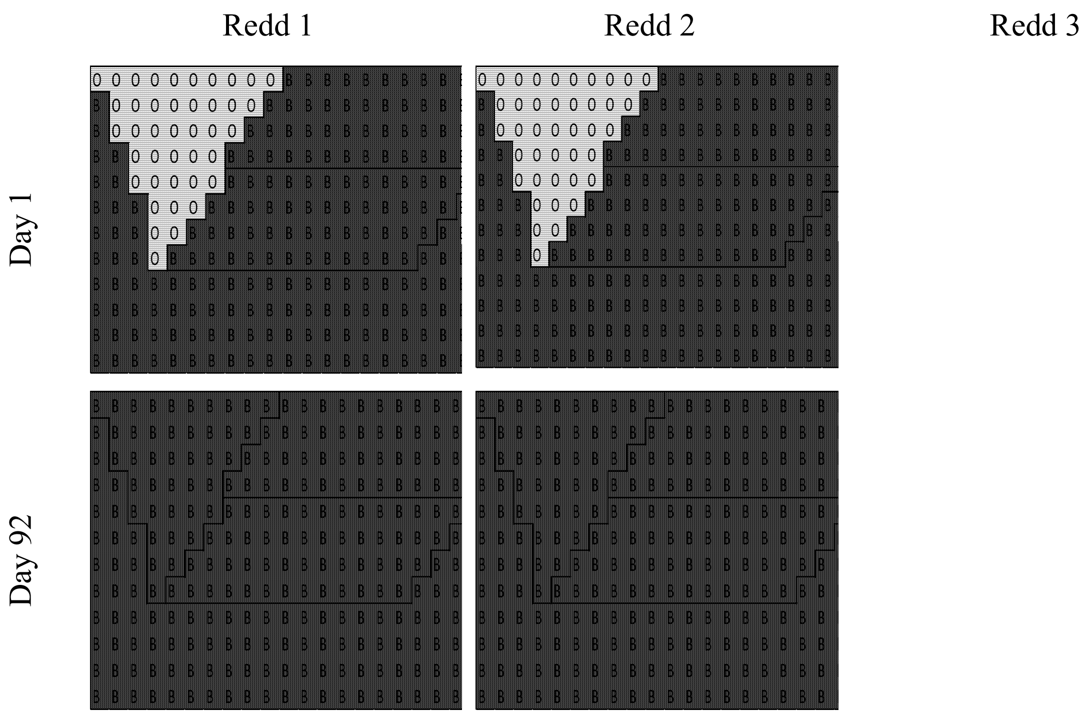


Figure D.3. Predicted infilling behaviour of fines (sand, silt, clay) predicted the simulation for Site 3. O=Open cell (O), F=Filling cell (F), B=blocked cell (B).

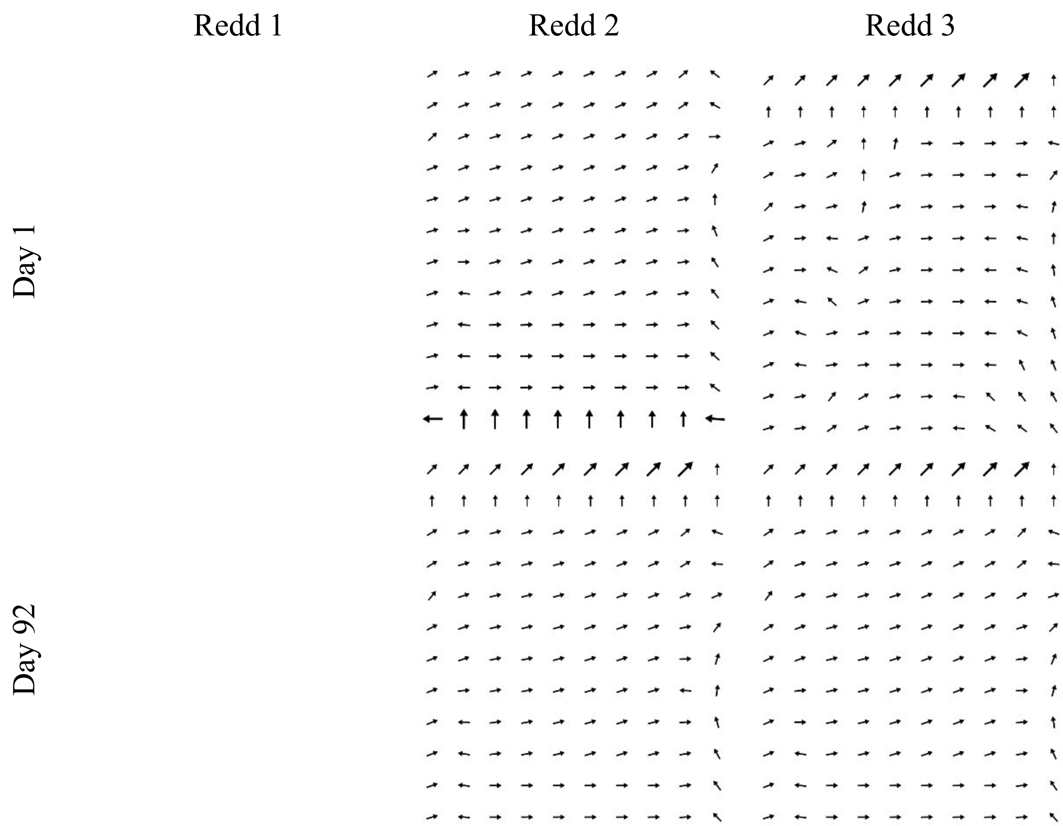


Figure D.4. Predicted directional intragravel velocities at Site 1.

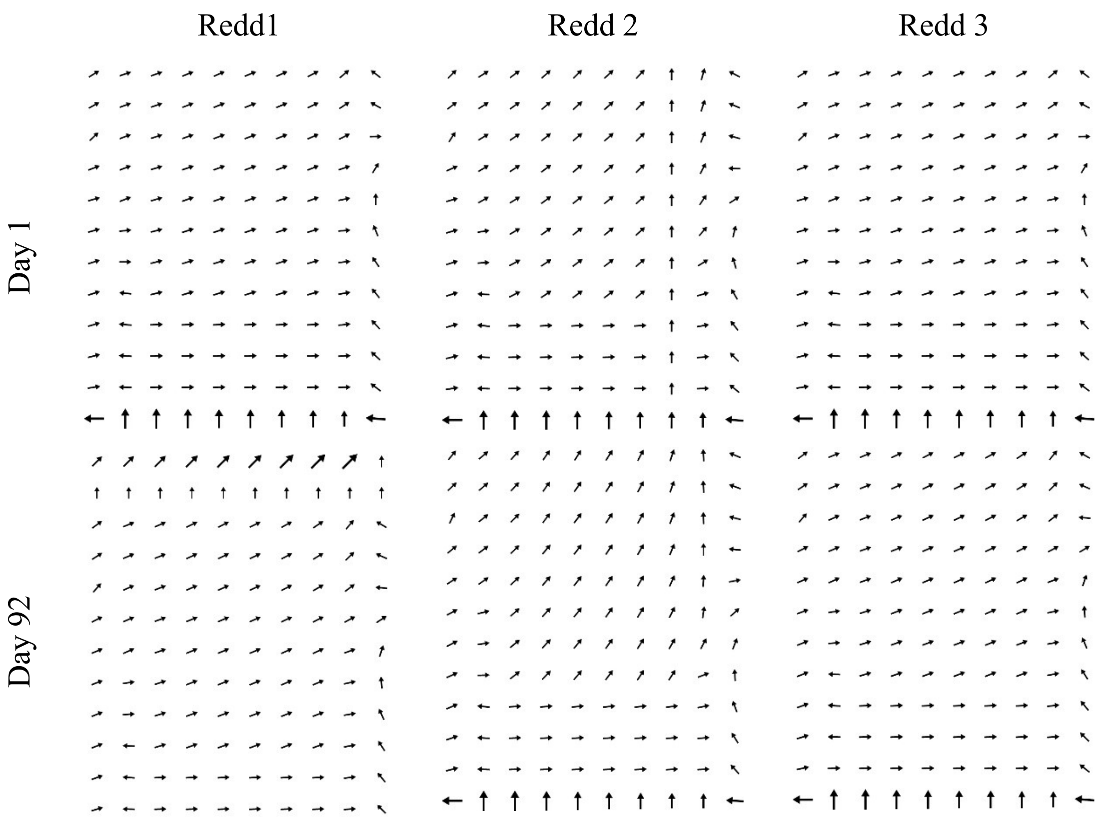


Figure D.5. Predicted directional intragravel velocities at Site 2.

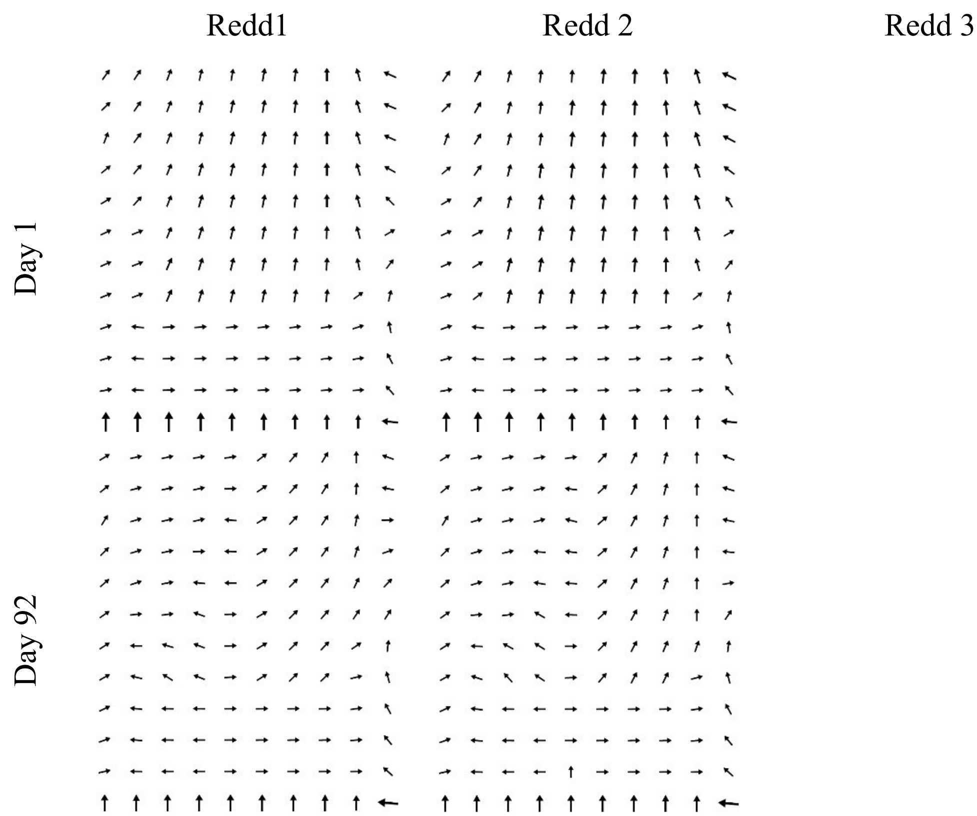


Figure D.6. Predicted directional intragravel velocities at Site 3.

Appendix E. Calculation of daily sand, silt and clay water column concentrations

Below is a method to generate concentration values for clay, silt and sand components for hydrolog.inp file of SIDO. Let x = [clay], y= [silt], z= [sand], using densities (ρ) of 2.20g/cm^3, 2.43 g/cm^3 and 2.65 g/cm^3 for clay, silt and sand respectively.

For example, using data from Site 2, Day 1:

$$100\left(\frac{x}{x+y+z}\right) = 1.02 \qquad (1)$$

$$100\left(\frac{y}{x+y+z}\right) = 31.00 \qquad (2)$$

$$100\left(\frac{z}{x+y+z}\right) = 68.57 \qquad (3)$$

$$x * \rho_{clay}\left(\left(\frac{cc}{m^3}\right) * \left(\frac{g}{cc}\right) = \left(\frac{mg}{l}\right)\right) + y * \rho_{silt} + z * \rho_{sand} = 21.85\ \frac{mg}{l} \qquad (4)$$

$$= 2.20x + 2.43y + 2.65z = 21.85 \qquad (5)$$

Using the above equations, values for x,y, and z can be solved:

$$\left(\frac{x}{y}\right) = \left(\frac{0.0102}{0.31}\right) = 0.033 \qquad (6)$$

$$\left(\frac{y}{z}\right) = \left(\frac{0.31}{0.6857}\right) = 0.452 \qquad (7)$$

Equation (6) can be substituted into equation (5)

$$2.20\ (0.033\mathrm{y}) + 2.43y + 2.65z = 21.85 \qquad (8)$$

Equation (7) can be substituted into equation (8):

$$2.20(0.033 * 0.452\mathrm{z}) + 2.43(0.452z) + 2.65z = 21.85$$

$$0.0328z + 1.098z + 2.65z = 21.85$$

$$3.781z = 21.85$$

$$z = \left(\frac{21.85}{3.78}\right) = 5.77\mathrm{ppm}$$

$$y = 0.452z = 0.452x * 5.77 = 2.61\mathrm{ppm}$$

$$x = 0.033y = 0.033 * 2.61 = 0.86\mathrm{ppm}$$