Continuous and Real-time Sedimentation Monitoring within Spawning Substrates on the Nechako River, BC

Andre Zimmermann, Principal Geomorphologist, Northwest Hydraulic Consultants, Vancouver, BC, azimmermann@nhcweb.com
Simon Gauthier-Fauteux, Geomorphologist, Northwest Hydraulic Consultants, Vancouver, BC, sgauthierfauteux@nhcweb.com
Steven McAdam, Hydroelectric Impacts Biologist and Sturgeon Specialist, BC Ministry of Land and Water Resource Stewardship, Vancouver, BC, steve.mcadam@gov.bc.ca

Introduction

The Nechako River White Sturgeon (*Acipenser transmontanus*) population has been undergoing recruitment failure since around 1967 (McAdam et al. 2005). Recruitment failure began approximately 15 years after the completion of Kenney Dam and the onset of flow regulation. There is limited evidence to suggest that recruitment failure was directly caused by the alteration of the hydrograph and reduction in peak flows. The discordance between post-regulation high flow events and the occurrence of rare, unexplained recruitment pulses in 1994/95, 2007 and 2011 (Figure 1), further highlights that recruitment does not seem to be directly linked to flow magnitude, but rather to a combination of factors and/or to indirect impacts of flow regulation. While flow regulation has undoubtably led to multiple changes in the river morphology (e.g., loss of side-channels, vegetation encroachment, etc.), studies to date have not been able to identify a direct link between the effects of flow regulation and the onset of recruitment failure.

The leading hypothesis to explain the collapse in natural recruitment is substrate change within a critical spawning reach, where sedimentation of sand within gravels and cobbles may have led to a reduction in the quality and availability of early rearing (interstitial) habitat. Interstitial voids between the gravel and cobble clasts provide refuge habitat for eggs and larvae during the incubation period, which lasts approximately 21 days, after which free-swimming larvae emerge from the substrate and drift downstream. If the interstitial spaces are filled with sand, the eggs and larvae are not able to seek refuge within the substrate, leading to premature drift, increased predation, and other negative physiological impacts (Baker et al. 2014; Boucher 2012; Boucher et al. 2014; McAdam 2011, 2012).

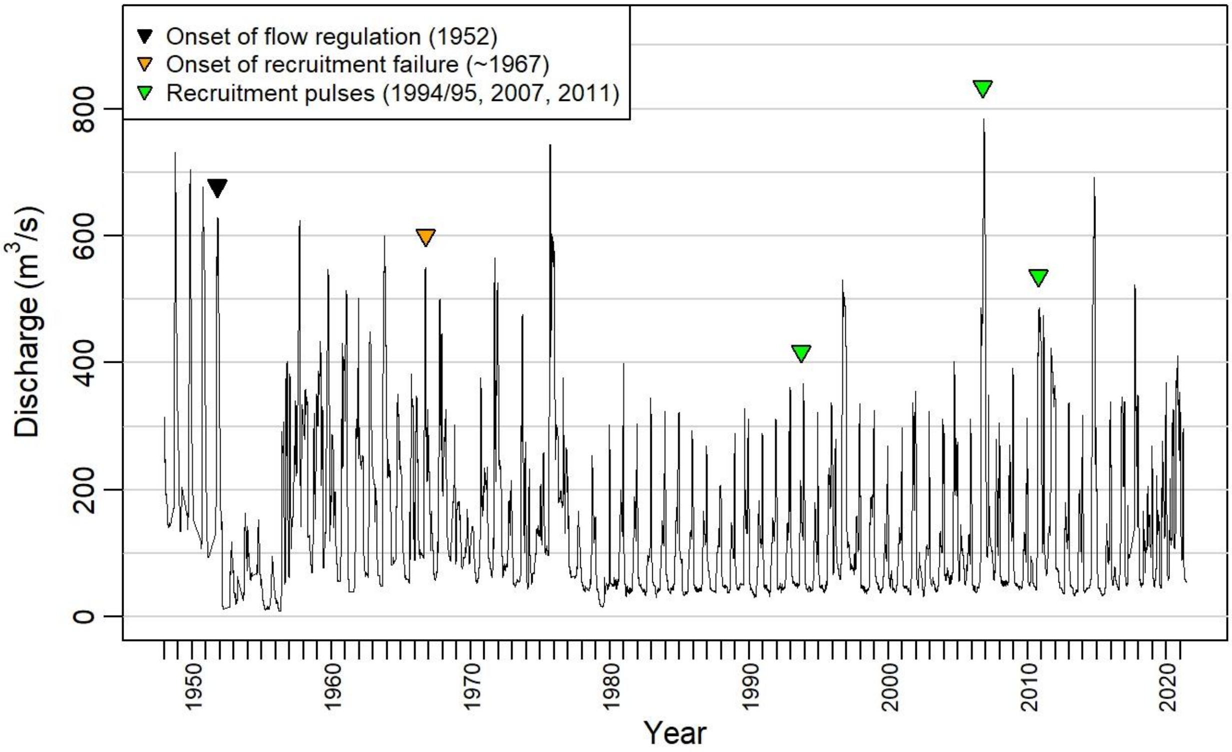

Figure 1. Key recruitment events plotted in relation to mean daily discharge at WSC gauge (08JC001) Nechako River at Vanderhoof from 1948 to present

There is a pressing need to implement habitat restoration strategies on the Nechako River to promote natural recruitment due to the limited number of remnant wild adults (< 500 fish). While hatchery inputs provide a stopgap measure against extirpation, the goal of the Nechako White Sturgeon Recovery Initiative (NWSRI) is a naturally recruiting population. While several attempts have been made to restore the quality of spawning and incubation habitat, including gravel placement in 2011 (McAdam et al. 2018; NHC 2012) and subsequent substrate remediation (i.e., “cleaning”) in 2016 (NHC 2016) and 2021 (NHC 2021), the effectiveness and longevity of these treatments have been limited in large part due to ongoing sedimentation.

This presentation will present the results of recent and ongoing work conducted as part of the NWSRI. This work was commissioned to address two key uncertainties limiting the design and implementation of effective habitat restoration within the critical spawning reach: 1) how quickly does restored spawning substrate infill with fine sediment and 2) can certain flows flush infilled fines from within the substrate, thereby restoring the interstitial space between the gravel particles. The findings of this work are intended to inform future habitat restoration measures, including both direct (e.g., gravel addition) and indirect (e.g., flow manipulation) approaches towards restoring natural recruitment.

Instrumentation to Monitor Substrate Infilling and Mobility

To improve our understanding of infilling processes on the Nechako River, temperature sensor arrays were designed to monitor changes in substrate composition based on the principals of thermal conductance. The objectives of the design were to remotely monitor changes in substrate composition in real-time, over relatively long time periods (i.e., one year or more), and across a range of flow conditions. The temperature sensor arrays were deployed in conjunction with a fixed underwater camera to allow for near-continuous, visual observations of sediment mobility and transport.

The design for the sensor arrays was based on the method for monitoring infiltration presented by Zimmermann and Lapointe (2005). This technique uses the hot wire principle to monitor changes in substrate composition, where the amount of heat removed by a fluid can be related to the fluid's velocity. Sedimentation within interstitial voids would thus be expected to reduce the inter-gravel flow velocity, resulting in both an increase in the magnitude and (under ideal conditions) the duration of the heat pulse transferred downstream. Conversely, winnowing or removal of infilled fines would allow the inter-gravel flow to move more freely, thereby decreasing the magnitude and duration of the heat pulse.

Three temperature sensor arrays were deployed within the critical spawning reach near Vanderhoof, BC, following ice-off in April of 2022 (Figure 2). The sensor arrays were deployed 40 m ("Inshore Sensor Array (Grid 1377)"), 55 m ("Middle Sensor Array (Grid 1379)"), and 75 m ("Offshore Sensor Array (Grid 1378)") offshore from the left bank of the channel, where the total channel width is approximately 130 m. Each sensor array consisted of five Campbell Scientific (CS225) temperature sensors positioned beneath and downstream of a 45-Watt U-shaped heating element mounted to a 1 m x 1 m x 0.1 m steel frame (Figure 3). Power and instrumentation cables for each grid were run back to the shore separately using 1" Liquidtite Conduit. Additional weight was added to the Liquidtite Conduit to sink the cable to the riverbed and resist motion from the flow velocity (which is generally low at this site, i.e., < 1.5 m/s). Prior to deployment, each steel frame was filled with a mixture of clean gravels to a thickness of 7-10 cm to mimic newly restored substrates (Figure 4).

The sensor arrays and data acquisition system can run off a 24 V solar powered array; however, for this install 120V AC power was available. The instrumentation was wired to a datalogger connected to a cellular modem, allowing for remote and real-time data monitoring and configuration of the instruments. Images and videos collected by the fixed underwater camera were also transmitted daily over the cellular network to allow for near real-time visual observations of natural substrates in the vicinity of the temperature sensor arrays. While the datalogger was initially configured to power each heating element for 30 minutes every hour, the heating frequency was subsequently reduced to 30 minutes every four hours due to excessive heat retention (i.e., the sensors were progressively getting warmer and not returning to baseline/ambient temperature between heating intervals once the substrate began to infill with sediment).

Figure 2. Locations where the temperature sensor arrays and fixed underwater camera were deployed within the critical spawning reach of the Nechako River in April of 2022

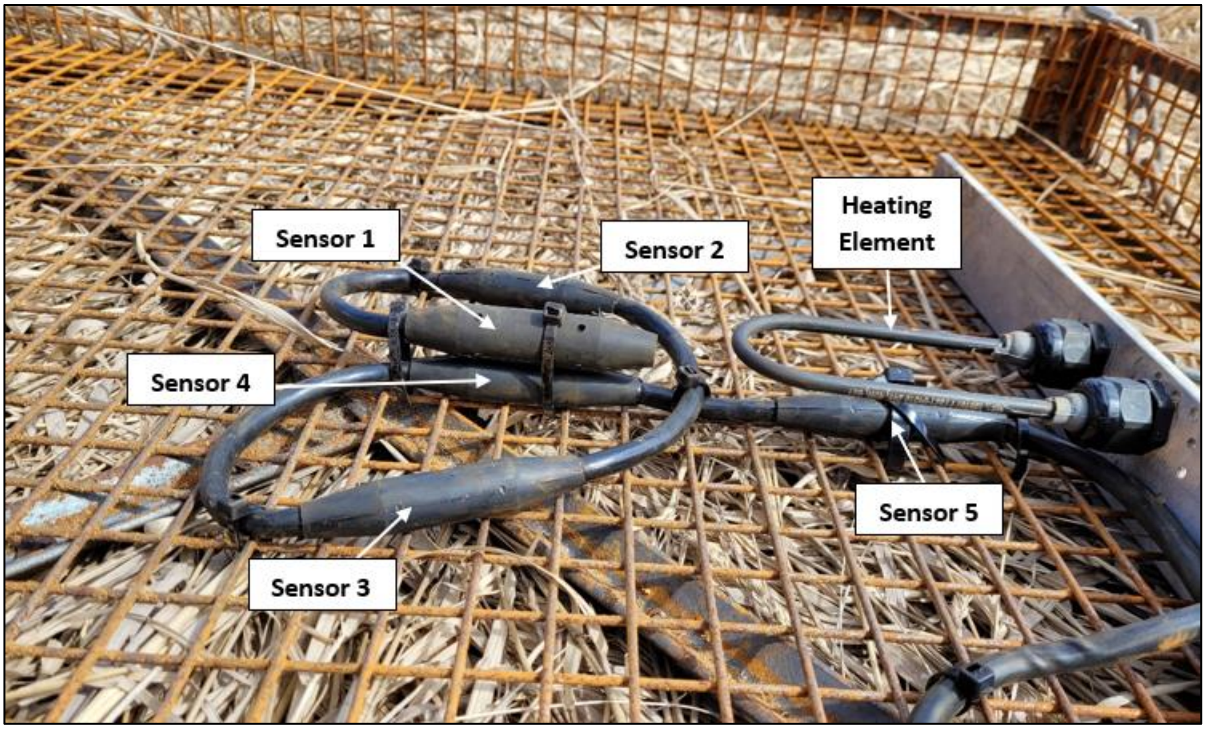

Figure 3. Configuration of the five temperature sensors in relation to the heating element (heating element positioned upstream of the sensors)

Figure 4. Temperature sensor array covered with clean gravel prior to deployment to mimic newly restored substrate

Monitoring Outcomes

The three sensor arrays installed across the width of the river showed very different rates of sediment accumulation. However, all sites ultimately infilled with fine sediment over time. The sensor array nearest to the center of the channel ("Offshore Sensor Array (Grid 1378)") showed that fine sediment began infilling the gravel substrate within 2 days of deployment, while the middle sensor array ("Middle Sensor Array (Grid 1379)") took 12 days, and the left bank sensor array ("Inshore Sensor Array (Grid 1377)") took 26 days before infilling started (Figure 5). The amount of time from when the substrate grids began to infill (i.e., first heat pulse measured by any one sensor) and at least partial infilling of the entire grid (i.e., heat pulse measured by all five sensors) for the Offshore Sensor Array (Grid 1378), Middle Sensor Array (Grid 1379), and Inshore Sensor Array (Grid 1377) was 5 days, 21 days, and 29 days, respectively (Figure 6). These results are further summarized in Table 1.

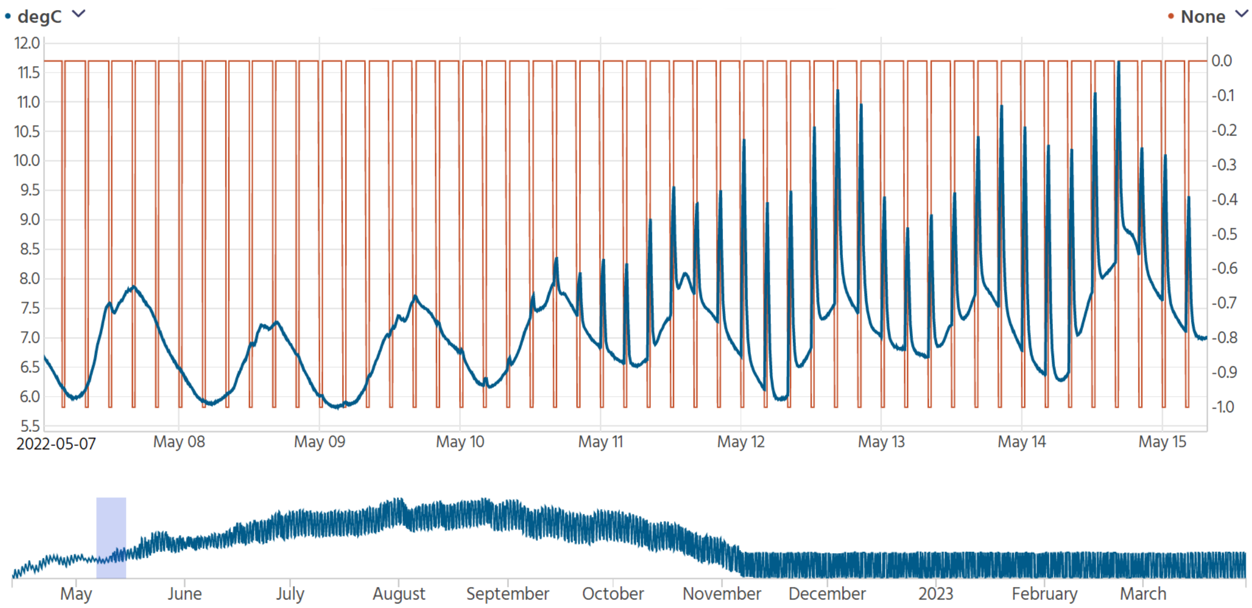

Figure 5. Sensor 5 on Inshore Sensor Array (Grid 1377) showing increased response to heating starting on May 9th, 2022; Sensor 5 shown in blue, Heater shown in orange on right axis (0 = OFF, -1 = ON). The lower panel highlights what portion of the data is shown in the upper panel within the monitoring period (May 7th – May 15th, 2022)

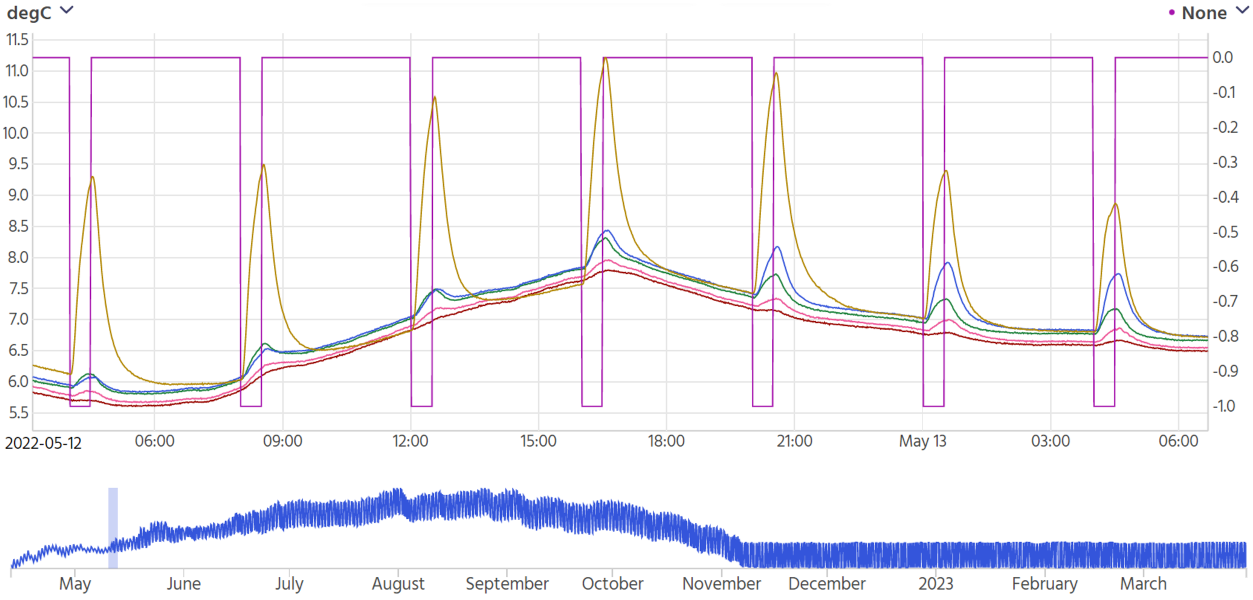

Figure 6. All five sensors on Inshore Sensor Array (Grid 1377) showing a response to heating after May 12th, 2022; Sensor 1 shown in blue, Sensor 2 shown in dark red, Sensor 3 shown in green, Sensor 4 shown in pink, Sensor 5 shown in dark yellow, and Heater shown in purple on right axis (0 = OFF, -1 = ON). The lower panel highlights what portion of the data is shown in the upper panel within the monitoring period (May 12th – 13th, 2022)

Table 1. Summary of measured heat responses for all three sensor arrays

Sensor Array	Time until infilling began (initial heat pulse measured by any one sensor)	Time until at least partial infilling of entire grid (heat pulse measured by all five sensors)	Approximate time until grids were fully infilled (heat signals stabilized)
Inshore Sensor Array (Grid 1377)	26 days	29 days	79 days
Middle Sensor Array (Grid 1379)	12 days	21 days	73 days
Offshore Sensor Array (Grid 1378)	2 days	5 days	98 days*

* This includes an unexplained disturbance to the sensor array on May 15th, 2022, which caused the heat signals to decrease temporarily, leading to longer time required for the grid to become fully infilled compared to the other sensor arrays.

The magnitudes of the heat signals measured by all sensor arrays generally increased relatively rapidly from the initial date of infilling until about mid-June to mid-July. From mid-July to present, the magnitudes of the measured heat pulses remained relatively similar, suggesting that the substrate grids had become fully infilled (Figure 7). Interestingly, an increase in river flow from 75 to 500 m^3/s, corresponding approximately to a five-year return interval flood, resulted in additional increases to sediment infiltration. The data show no indication that high flows removed sediment from within the interstices of the gravel (Figure 8), even though discharge exceeded 350 m^3/s for approximately two months between June 8 and August 8, which is a fairly typical peak flow during the post-regulation period[1].

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[1] Flow regulation on the Nechako River began in 1952 following the construction of Kenney Dam.

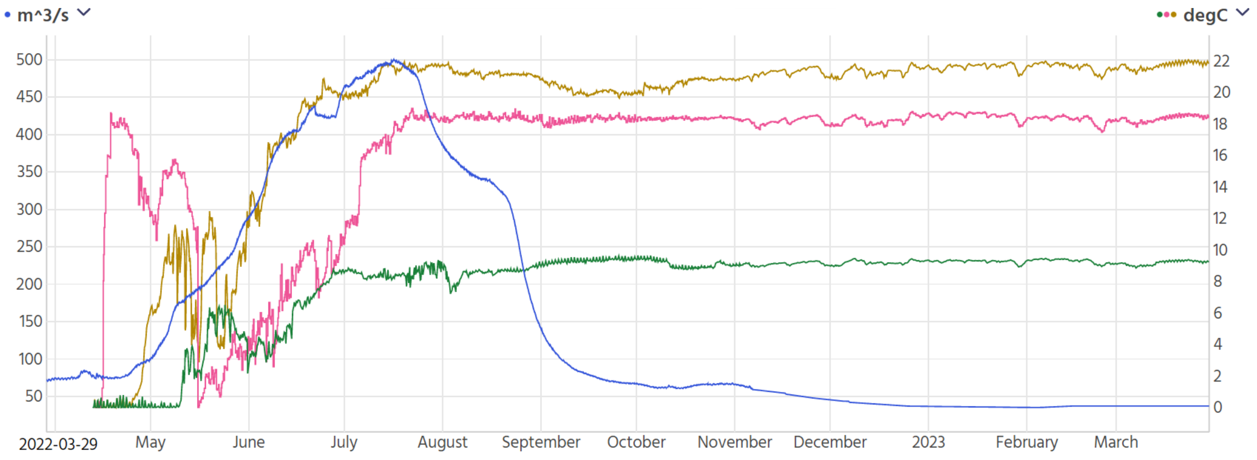

Figure 7. Heat signals measured by Sensor 5 on all three sensor arrays showing progressive increase in heating after deployment (indicative of infilling), after which the magnitudes of the heat pulses remained relatively similar to present (indicating the substrate grids are fully infilled, with no removal of fines); Inshore Sensor Array (Grid 1377) shown in green, Middle Sensor Array (Grid 1379) shown in yellow, Offshore Sensor Array (Grid 1378) shown in pink. Discharge at Vanderhoof (WSC 08JC001) shown in blue

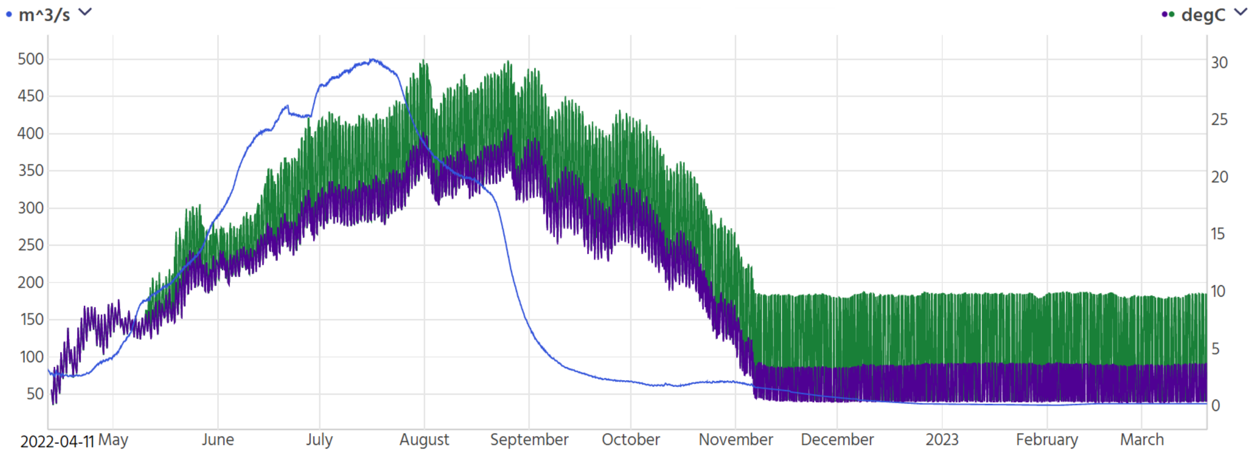

Figure 8. Data from Inshore Sensor Array (Grid 1377) showing no indication that high flows removed sediment from within the interstices of the gravel, despite reaching 500 m^3/s (approximately a five-year return interval flood) on July 16th, 2022; Sensor 1 shown in purple, Sensor 5 shown in green. Discharge at Vanderhoof (WSC 08JC001) shown in blue

The data show that the magnitudes of the heat signals measured by all sensors have remained relatively high and very consistent since early-November (Figure 7; Figure 8), which corresponds to the period of ice-formation on the Nechako River. The data show no evidence to suggest that scour or winnowing of fine sediments has occurred to date under the ice cover, but rather that the substrate has remained very stable; these findings are consistent with visual observations of the natural riverbed collected using the fixed underwater camera positioned near the sensor arrays, which shows comparatively little gravel mobility during the ice-covered period (to date) as compared to earlier periods of higher, open-water flows.

For all sensor arrays, the magnitude of the heat pulses measured by Sensor 5 (positioned directly under the heating element – see Figure 3) were greater than those measured by all other sensors on the arrays. Sensor 5 was also the first sensor to detect infilling for all arrays. Given the configuration of the heater relative to the sensors (Figure 3), the heat pulse measured by Sensor 5 is interpreted as a proxy to show the overall amount of infilling within the substrate grids given the proximity of this sensor to the heating element. By the end of the data record presented herein (December 10th, 2022), the magnitude of the heat pulse measured by Sensor 5 was highest for Middle Sensor Array (Grid 1379) (+21.5°C), followed by the Offshore Sensor Array (Grid 1378) (+18.4°C), and finally the Inshore Sensor Array (Grid 1377) (+9.3°C) (Figure 7). The interpretation that the magnitude of heating measured by Sensor 5 is indicative of the overall amount of infilling was corroborated by underwater images taken on October 3rd, 2022, showing that the Middle Sensor Array (Grid 1379) (Figure 9) and Offshore Sensor Array (Grid 1378) (Figure 10) had the greatest amount of visible sand infilling the gravel substrate, while the Inshore Sensor Array (Grid 1377) (Figure 11) had comparatively less infilled fines. The sediment infilling the sensors is interpreted to have been primarily transported as bedload because medium to coarse sand constitutes the majority of bedload sediment transported past this location (as confirmed by a large bedload sampling dataset collected between 2013-2017), and because the suspended sediment load of this river system is relatively low and composed of very fine material (monitored between 2013-2015), which is likely to remain largely in suspension throughout the study reach.

Additional information can be gleaned from the heat pulses measured by the remaining four sensors. While Sensor 5 on the Inshore Sensor Array (Grid 1377) measured the lowest heat pulse of all three arrays, the magnitudes of the heat pulses measured by the remaining four sensors on the Inshore Sensor Array (Grid 1377) were roughly equal to or higher than the corresponding sensors on the other two arrays. Closer investigation of the heating pattern on the Inshore Sensor Array (Grid 1377) shows that Sensor 5 reached peak heating first, with delayed heating of the other sensors (Figure 12). The next sensor to reach peak heating was Sensor 1 and Sensor 3, followed by Sensor 4, and lastly Sensor 2. In similar fashion, the magnitude of the heat pulse varied between the sensors, with Sensor 5 measuring the greatest heat pulse, followed by Sensor 1, Sensor 3, Sensor 4, and Sensor 2, respectively. Given the configuration of the sensors (Figure 3), these results indicate that the inter-gravel flow at this location was primarily oriented in the downstream and downstream-left directions, staying at approximately the same depth within the gravel. This heating pattern may be used to infer site-specific differences in inter-gravel and hyporheic flow conditions. In particular, the greater rise in temperature for Sensor 1 at the Inshore Sensor Array (Grid 1377) indicates that more water was moving from the heating element to the downstream sensor at this location, as compared to the two other sites.

Figure 9. Underwater photo taken of the Middle Sensor Array (Grid 1379) on October 3rd, 2022, confirming that the increased heat signal was produced by infilling of the clean gravels with fine sediment

Figure 10. Underwater photo taken of the Offshore Sensor Array (Grid 1378) on October 3rd, 2022, confirming that the increased heat signal was produced by infilling of the clean gravels with fine sediment

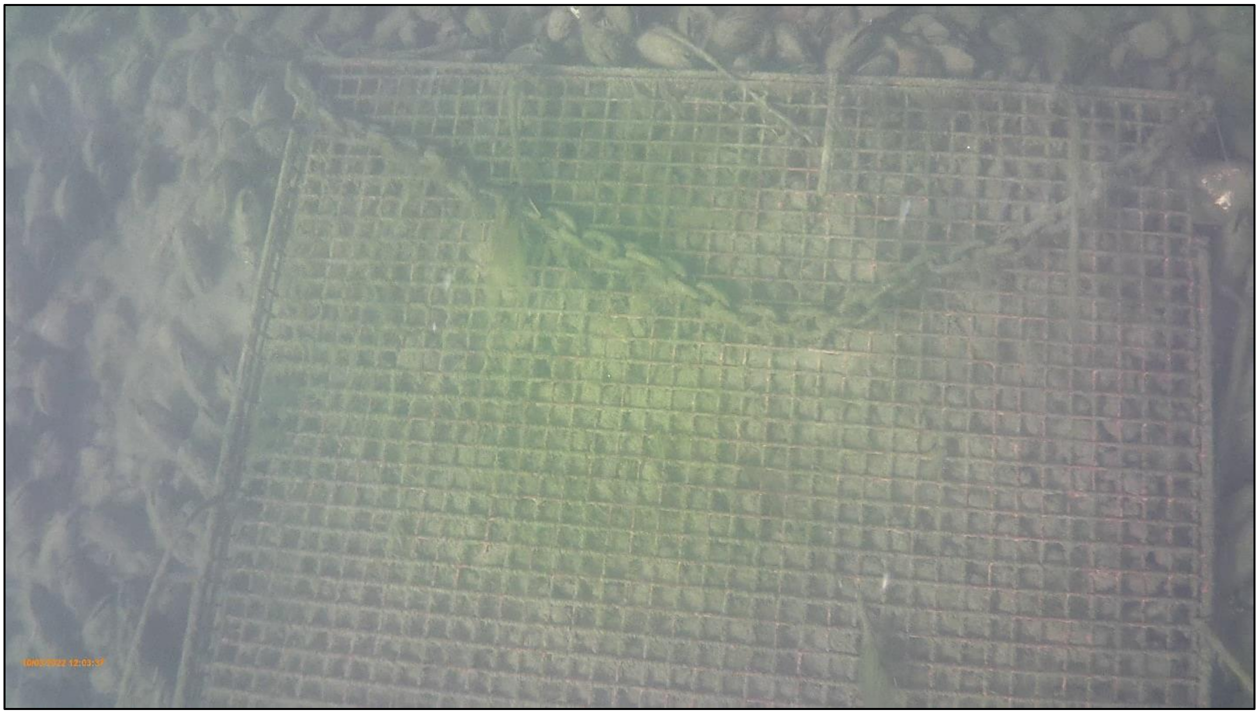

Figure 11. Underwater photo taken of the Inshore Sensor Array (Grid 1377) on October 3rd, 2022, confirming that the increased heat signal was produced by infilling of the clean gravels with fine sediment

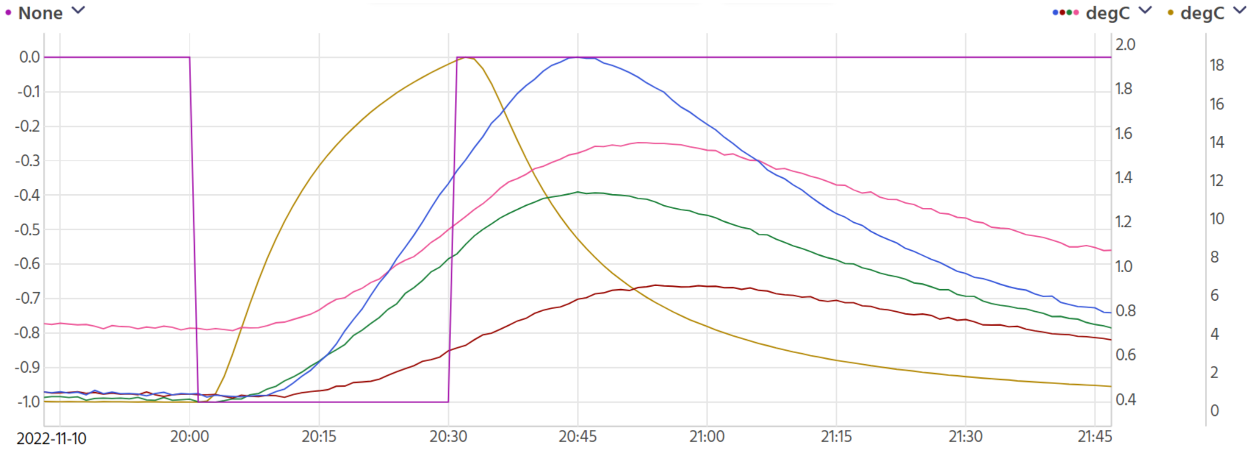

Figure 12. Comparison of the heat signal measured by the five sensors on the Inshore Sensor Array (Grid 1377) on November 10th, 2022; Sensor 1 shown in blue, Sensor 2 shown in dark red, Sensor 3 shown in green, Sensor 4 shown in pink, Sensor 5 shown in dark yellow on secondary axis, and Heater shown in purple (0 = OFF, -1 = ON)

Potential Applications and Challenges of Monitoring

The results from this study show that placing clean substrate into the river immediately before the spawning season may be of limited value as the substrate can infill within the duration of time required for incubation of eggs and larvae. Furthermore, the data suggest that high flows have not removed sediment from the interstitial substrate. Thus, additional habitat restoration measures may be required to restore the quality of spawning gravels in the absence of very large flood flows.

Results from this monitoring will help improve the collective understanding of substrate mobility at the surface of spawning gravels during lower flow conditions as well. The results will provide the first continuous monitoring record of substrate infilling and potential scour during the winter, ice-covered period, as well as during the spring break-up. It is possible that ice-effects during the spring break-up may alter local hydraulics at the sites, resulting in increased substrate mobility and (at least partial) removal of infilled fines.

Broadly speaking, this monitoring technique may be suitable for various applications given that it can be deployed, configured, and monitored remotely and in real-time. These features allow for the sensor arrays to provide value not only as tools to continuously monitor substrate conditions, but as management tools by providing real-time data to inform decision making and adaptive management strategies. Finally, this technique may provide value for a wide range of hydraulic and geomorphological studies, in particular for those concerned with sediment transport, infilling and grain mobility over a wide range of flow and seasonal conditions (e.g., ice-cover).

Another key benefit of this methodology is that it is capable of monitoring subsurface conditions within the gravels. This provides a direct indication of habitat quality at-depth within the gravel layer, which represents the habitat utilized by eggs and, even more so, larvae. While such methods have been applied to monitoring of hyporheic flow, this represents an interesting and potentially beneficial application related to fish habitat.

Potential challenges encountered with this technique include that the sensor arrays may be biased towards retaining infilled fines due to the immobility of the framework gravels contained within the grid itself (i.e., gravels cannot readily be transported out of the steel frame). Retention of fines may have been further exacerbated by a ½” steel mesh that was used to cover the Inshore Sensor Array (Grid 1377) and Middle Sensor Array (Grid 1379) to facilitate deployment (Figure 9; Figure 11). That said, the Offshore Sensor Array (Grid 1378), which was not covered by a steel mesh (Figure 10), did not show any evidence of winnowing, corroborating the finding that the gravels were not winnowed at-depth despite the relatively high flows reaching 500 m^3/s. This was further supported by observations of sediment transport and bed mobility collected using the fixed underwater camera, which showed that no appreciable mobilization of the framework gravels forming the natural riverbed occurred throughout the monitoring period. While it is not likely to have changed the overall findings of the study, the design and deployment of the sensor arrays may be improved in the future by not using a steel mesh to cover the frames and by trying to embed the frames into the riverbed (to the degree possible).

Another potential challenge encountered with this technique is accounting for the effect of vegetation growth on near-bed hydraulics, as well as sediment transport, retention, and infilling.

Vegetation growth primarily occurred on the Inshore Sensor Array (Grid 1377) and Middle Sensor Array (Grid 1379), again, due to the steel mesh used to cover the placed substrate to facilitate deployment (Figure 9; Figure 11). The potential impacts of vegetation growth on near-bed hydraulics and sediment retention may be mitigated by improving the design of the sensor arrays, as described above.

A third potential challenge associated with this monitoring technique is the difficulty in resolving the causes of inexplicable changes in the measured heat signal, such as the abrupt decrease in the heat signal measured by all sensors on Offshore Sensor Array (Grid 1378) overnight on May 15th, 2022 (see Figure 7). While a decrease in heat signal would be expected to indicate removal of infilled fines, the very abrupt change and lack of similar response on the other two sensor arrays introduces uncertainty in the interpretation of the results; note that the heat signal measured by all sensors on the Offshore Sensor Array (Grid 1378) progressively increased following the event, suggesting persistent and ongoing sedimentation continued shortly thereafter. This uncertainty emphasizes the value of visual observations, collected either concurrently or periodically, to validate the interpretation of the heat signals.

Lastly, more work is required to resolve inter-gravel flow velocities and velocity vectors between the sensor arrays, to gain additional information on inter-gravel and hyporheic flow conditions between each site.

Conclusions

This study shows that temperature sensor arrays can be used to monitor changes in substrate composition based on the principals of thermal conductance. The methodology allowed for continuous, real-time, and remote monitoring of surficial substrate composition (i.e., infilling) on the Nechako River over relatively long time periods (i.e., one year or more) and across a range of flow and seasonal conditions, including winter ice-covered periods. Results from this study are expected to inform the planning and development of future habitat restoration strategies, notably that gravel placement prior to the spawning season may have limited value given the rate at which the substrate can infill, and that the relatively high, post-regulation flows may not remove infilled sediment from within the gravel interstices; thus, additional and/or complementary habitat restoration measures may be required. While acknowledging certain challenges associated with this methodology, it nevertheless may provide value for a broad range of monitoring and management programs.

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