Revising the Basis of Sediment Management in Rivers: Incorporating Real-Time Sonar, Hydroacoustic and Hydrodynamic Field Data

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Introduction

Sediment transport and accumulation can cause serious problems for the operation of run-of-river hydroelectric developments. In general, sediment-related problems can increase maintenance and operation costs, while simultaneously reducing revenue from power generation. Sediment passing through a powerhouse can cause abrasion damage that reduces the efficiency and life of turbines, increasing the frequency of shutdowns and repairs. Sediment buildup at an intake can block flow paths and reduce the amount of water available for power generation. Consequently, there is a strong economic incentive to effectively manage the accumulation of sediment in front of intake structures and the passage of sediment through turbines. These actions maximize power generation, which increases revenue. However, the practical challenge with developing an effective sediment management strategy is the inability to physically see how sediment behaves underwater and how effective changes in plant operations are in minimizing sediment accumulation and transport.

Sediment transport processes at intakes of run-of-the-river hydroelectric plants therefore provide both a management challenge and an opportunity to examine the applicability of existing sediment management approaches and tools, and to evaluate the utility of novel monitoring techniques.

The relatively modern tools considered in this paper include continuous sonar scanning of the river bed using Dual Axis Scanning (DAS) sonars, hydrophones and acoustic backscatter sensors (ABS) that are integrated directly into the plant control network. All three of these technologies utilize hydroacoustic sensors that are less easily fouled in high sediment environments and can operate continuously to collect information when sediment is moving. Hydroacoustic methods of monitoring sediment load with an Acoustic Doppler Current Profiler (ADCP) and hydrophones have also been around for several decades; however, we are unaware of sites where these have been integrated into the plant controls and utilized for real-time sediment monitoring.

More traditional approaches to monitoring sediment transport include bedload and suspended load transport measurements, which provide an estimate of the load at a single point in time, as well as sounding surveys with a boat or raft that collect data over a limited duration in time. Traditionally these data are often used to calibrate numerical and/or physical models and the results from the numerical and physical models are used to adjust how the facility is designed and operated. The traditional approach follows a typical 'study' design where a question is posed, an approach is developed, results are compiled, and a report is written describing the results and how things can be changed to address the original problem. In contrast, the approach presented here is one of ongoing data monitoring and real-time adjustments based on the observations at site during operations.

This paper will present a case study, the Forrest Kerr Hydroelectric Project, which illustrates how modern real-time field monitoring tools including a hydrophone, ABS sediment concentration sensor, ultrasonic flow meter and dual axis scanning sonars, can be used to improve sediment management strategies. We discuss how the available tools and approaches for working with real-time operating facilities are changing, and how as a community we should be responding to these changes in order to further our understanding of sediment dynamics at hydroelectric facilities and improve their operation.

Background

The 195-MW Forrest Kerr Hydroelectric Project has a large run-of-river intake with capacity to divert 250 m^3/s for hydropower generation. The project is located in Northwest British Columbia at the confluence of the Iskut River and Forrest Kerr Creek. Both watersheds are glaciated and the reaches of both rivers upstream of the facility feature extensive gravel bed braided reaches. The hydrology at the Project is dominated by a substantial snowmelt/glacial melt freshet. Rainfall and rain-on-snow events result in the highest annual floods.

Based on field measurements of suspended sediment transport, it is estimated that 6.4 M tonnes of suspended sediment moves past the intake per year. Bedload transport modeling conducted in the 1980's suggest there is 0.8 M tonnes of bedload moving past the intake per year (DPJ&A and HGPD, 1984). Observations from site show that bedload is readily mobilized during flows that are approximately the mean annual discharge and the river remains turbid when flows are approximately half the mean annual discharge or greater. The braided reaches upstream of the intake are very mobile and not armored; they are the major source of bedload that is directly transported past the intake.

Over a two year period, which included the first year of operations, 0.75 M tonnes of sediment were deposited in the reach of Forrest Kerr Creek upstream of the project. This creek is estimated to only produce 12 to 17 % of all the sediment coming past the intake (NHC, 2014), which suggests that the total bedload may be as much as 2.5 to 5 M tonnes per year. All in all, there is a substantial amount of sediment transported past the intake each year. The grain size of the material includes the full range of sand, gravel and cobbles that are typical of braided rivers at transport capacity.

Prior to the construction of the facility, NHC undertook both physical and numerical modeling to assess intake hydraulics. Both models proved useful in helping define hydrodynamic conditions during different scenarios, including during flood conditions. However, both the numerical and, to a lesser extent, the physical model could not realistically simulate the extremely complex and stochastic nature of sediment transport processes observed in the field that have subsequently become increasingly apparent with the current field program. Furthermore, the questions that need to be answered now only became apparent once the facility was operating.

Sediment Management and Monitoring Technology

The Forrest Kerr project includes a number of unique structures for handling sediment transport with the goal of minimizing sediment entering the intake, which are shown in Figure 1 through Figure 4. The sediment management structures include:

1. **A submerged box culvert** located at the base of the sluiceway channel (see **Figure 2**). The submerged box culvert acts as a tunnel bedload excluder by passing bedload arriving at the sluiceway channel into the river reach downstream of the dam rather than into the intake. Flow through the box culvert is controlled by a radial gate and the box culvert can transport the entire transport capacity of the river for small and moderate floods depending on how it is operated.
2. **A desander** at the intake entrance that includes 8 sediment collection bays with sediment removal pipes at their base which cycle over time. Depending on the river flows, when the desander is operating, one or two of the pipes draining the sediment out of desander are opened for a few minutes and then the pipe is closed and the next pipe is opened. This cycle continues continuously. If these sediment removal pipes become blocked, there is an air purge system which clears debris and sand off the pipe openings. A photograph showing the installation of the air purge system can be seen in Figure 3. In general gravel should not enter the desander; although it has happened when the box culvert inlet becomes overwhelmed by bedload.

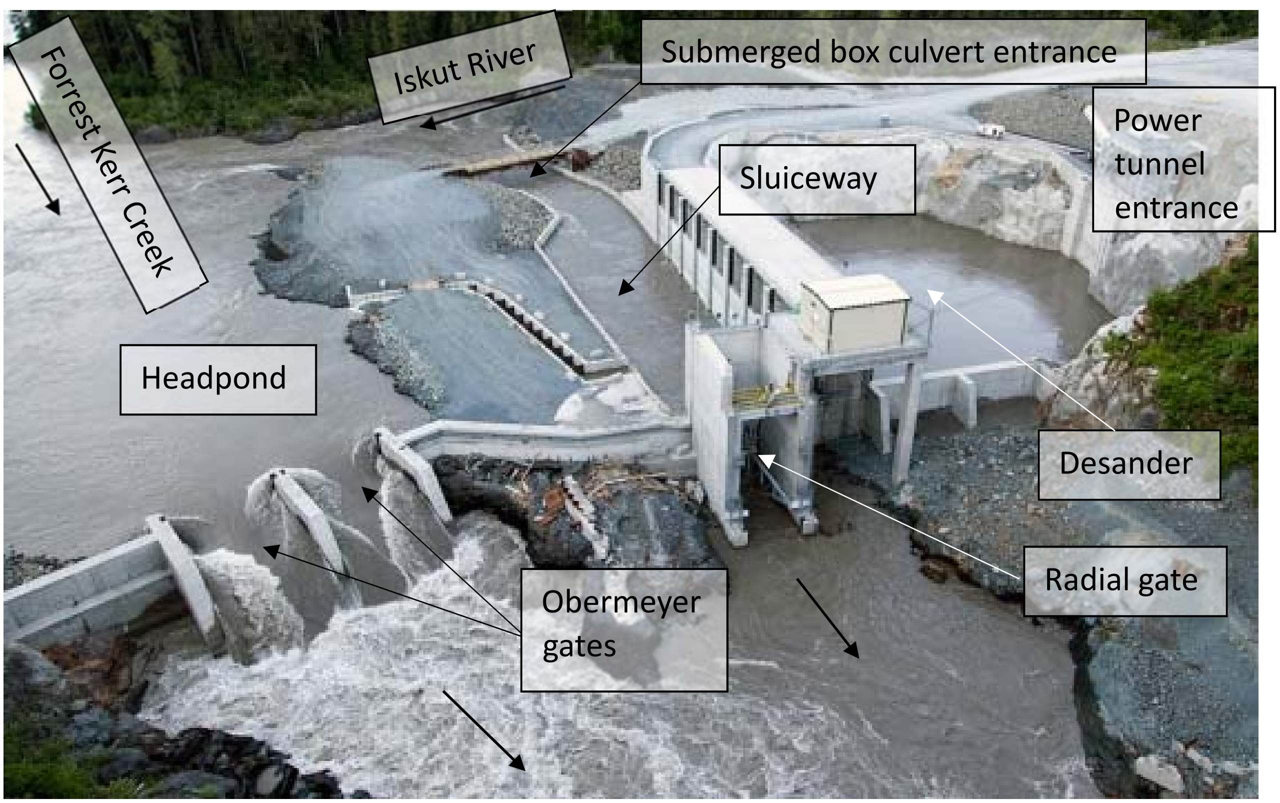

Figure 1. Aerial view of Forest Kerr run-of-river facility (box culvert on the bottom of the sluiceway is fully submerged and not visible).

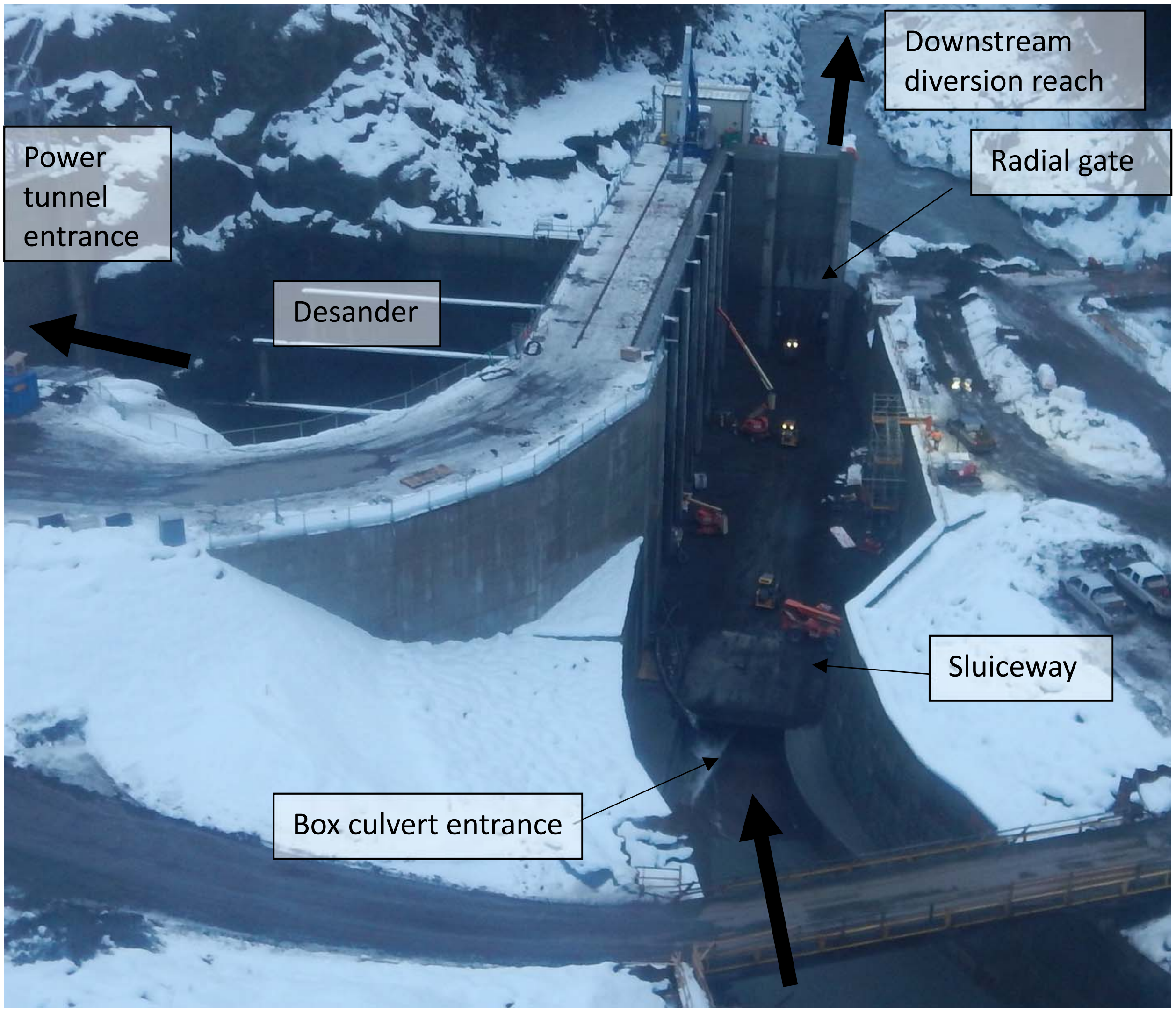

Figure 2. Intake during maintenance when the headpond has been drained. Box culvert and sluiceway are clearly visible. Large black arrows indicate direction of flow.

Figure 3. Air purge system being installed along desander sediment collection pipes. Each slot in the larger pipe is equipped with an air nozzle that blasts material off the sediment collector pipe.

To optimize sediment sluicing at the intake and monitor the desander bays to ensure they are functional, several modern real-time field monitoring instruments have been employed at the Forrest Kerr intake. These instruments are illustrated in the schematic shown in Figure 4 and include:

1. **Three Dual Axis Scanning (DAS) sonars** have been installed at the intake for real-time bathymetric monitoring (Haught and Zimmermann, 2019). The DAS sonars inform the operator on sedimentation levels at the intake every 30 minutes and enables the elevation of the bed to be tracked nearly continuously.
2. **A hydrophone** installed at the sluiceway entrance for detecting sediment motion (Tsakiris et al. 2019). The hydrophone is used to monitor bedload sediment moving into the box culvert, and consequently informs the operator whether the radial gate opening is sufficient to mobilize and transport sediment.
3. **An ABS and turbidity sensor and flow meter** have been installed in the desander to infer how much sediment is being flushed out of the desander sediment collection pipes. The ABS uses backscattered sound while the turbidity sensor uses backscattered light to infer sediment concentration. In general the ABS is most sensitive to the full range of sand sizes and coarse silt, while the turbidity sensor is most sensitive to the silt load (https://www.sequoiasci.com/article/response-of-lisst-abs-and-obs-to-log-normal-size-distributions). The flow meter uses the transit time of sound to infer flow, which indicates that sufficient water is moving through the system, or the ports along the pipes are clogged. For the purposes of this study none of the sensors have been calibrated and the relative change in the signal is used to infer changes in sediment transport. After a few years of use the sensors continue to zero well during low flow conditions when no transport is occurring.

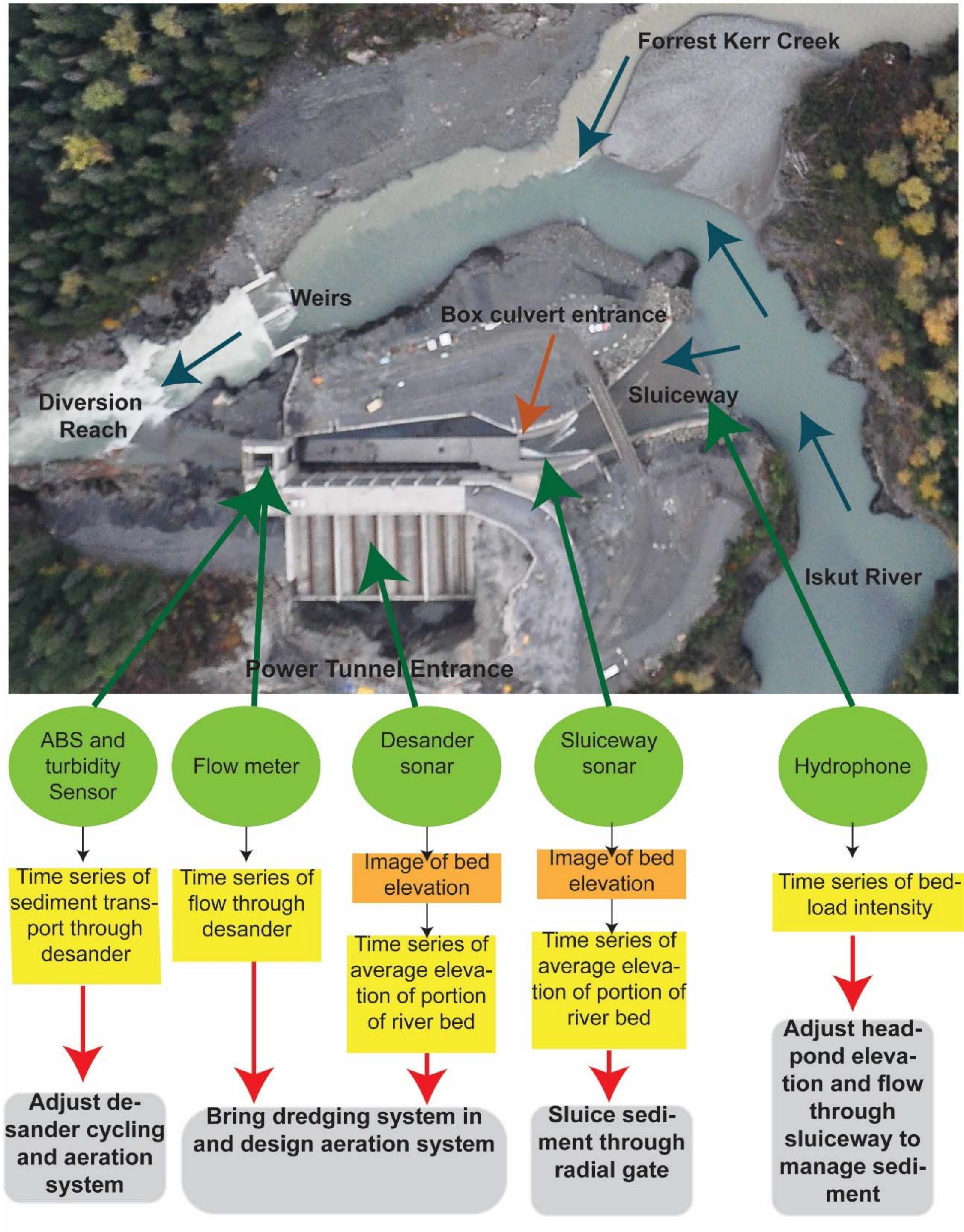

Figure 4. Schematic showing the location of the various sensors (green ovals). Orange boxes represent data plots illustrating the elevation of the entire bed surface in a single image while yellow boxes illustrate time series that can be reviewed by scientists, engineers and operators on the HMI. Grey boxes illustrate some of the changes that can occur in response to the data. Black arrows represent automatic data processing that is done to create the time series while red arrows represent interpretation by operators and scientist to make an informed decision using the data in the yellow boxes, plus information on plant flows, river flows and water levels at the intake. Blue arrows indicate the direction of river flow.

These data are supplemented by a continuous record of gate positions, flow values and water levels upstream and downstream of each flow control structure that is maintained as part of the facility. The systems that have been installed enable measurements of bed elevations, sediment transport and flow conditions which update every minute to every half an hour, depending on the parameter being monitored.

Monitoring Outcomes

Based on our experience with the system over the last few years, we have concluded that the most effective approach for managing sediment at these facilities is to work closely with operators and advise them on the optimal facility operation at a given time, based on collected field data in real-time. This approach has radically changed how sediment is managed at the Forrest Kerr facility and could have comparable benefits for other, similar facilities. Some key changes are as follows:

- During times when the river flow is sufficiently low that only the instream flow requirement (IFR) of 10 m^3/s needs to be released through the diversion reach, the box culvert is flushed with 1 to 2-minute duration bursts of 40 m^3/s every few hours to clear sediment that can be seen from the sonar to have accumulated in front of the entrance. The real-time monitoring during trials with different flow conditions revealed that continuously releasing 20 or 30 m^3/s is ineffective at moving bedload and results in substantially less energy production.
- During flood events the entrance to the box culvert is tracked closely to ensure sediment isn't building up and passing over the box culvert entrance. Monitoring is particularly challenging in large events as the water column can be 0.1 % sediment and the energy from the sonar is largely absorbed by the water.
- The hydrophone can be used to track the intensity of the sediment transport; see Figure 5. Figure 5 illustrates the period from July 8th to 10th, 2018 when the hydrophone shows that sediment has been mobilized and is being transported following a drop in the sluiceway water level that resulted in an increase in local water velocities. Burial of the hydrophone is used to indicate that sediment has accumulated at the entrance to the sluiceway. This is particularly valuable in very high sediment transport conditions, when the sonar cannot penetrate the water column.
- The ABS, turbidity sensors and flow meter on the sediment extraction pipes in the desander can indicate that a desander bay is not removing sediment and the air purge system that clears debris off the extraction pipe openings needs to be adjusted.
- The desander bays can be inspected using the sonar to see if any of the pipes are clogged and if so, where they are clogged. This can then guide dredging works, determine which air purge zone needs to be run, or for planning additional improvements to the system. Earlier scans of the desander showed sediment filled the desanders as a wave of bedload with Gilbert type deltas and were instrumental in getting the air purge system installed, which has proven to be very effective.
- The sonar has revealed that gravel sediment accumulation at the intake is more of an issue during the falling limb of the freshet than at the beginning of the freshet when flows are roughly similar. This enables more energy production in the spring when sediment inputs are lower. The sonar has also revealed that at high flows the box culvert may become overwhelmed by bedload and shutting down the intake entirely so the box culvert entrance doesn't get buried may be the best course of action.

- Data acquired from the ABS were utilized to optimize the cycle duration for the desander flushing valves and if they needed to be operated at all. This determination was based on whether a change in the transport rate through the sediment collection pipes could be detected when the desander valves were cycled.
- The sonar at the box culvert can be used to track when sediment transport is occurring past the intake. This information is critical as the stage-discharge rating curve at the downstream hydrometric gauge is likely to shift as a result of sediment deposition.

Following all aforementioned changes in the facility operation, the productivity of the plant has seen a substantial increase. The addition of the air purge system and a better understanding of sediment transport in the desander has greatly reduced the flow of sediment through the powerhouse and wear on the turbine infrastructure.

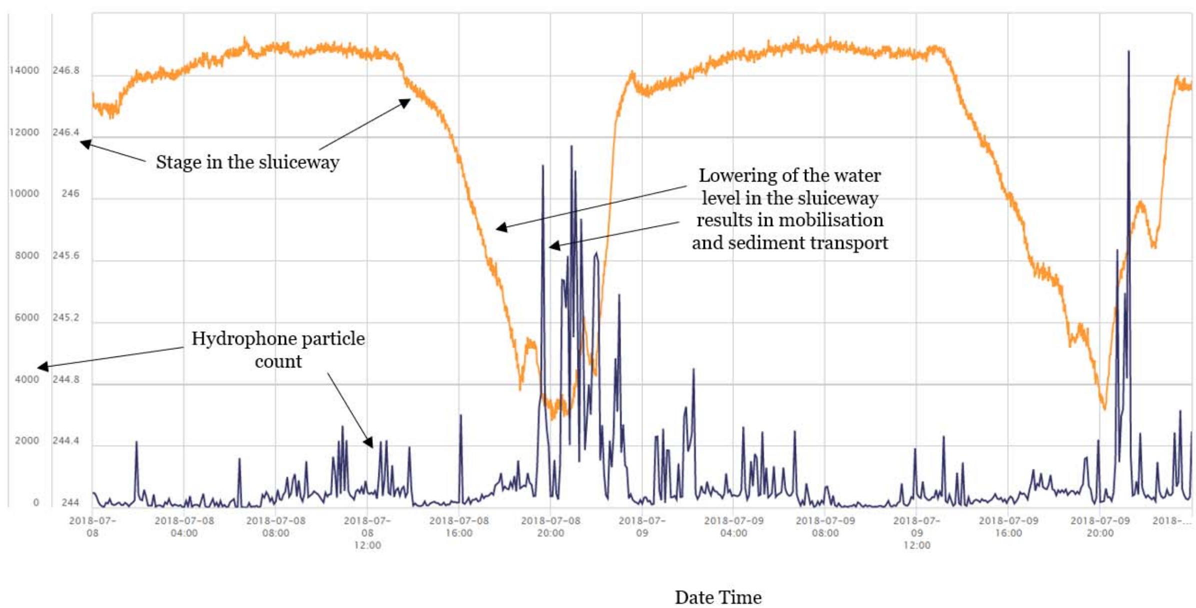

Figure 5. Sluiceway stage and hydrophone particle count between July 8th and 10th, 2018.

Excitement and Challenges of Ongoing Monitoring

The ability to monitor sediment transport in real time as described with the Forrest Kerr case study has fundamentally changed the approach to sediment management at many facilities. Historically, the approach to addressing sediment transport problems at hydropower, and particularly at existing facilities, involves some basic investigations on site, building a numerical or physical model and performing a series of simulations to assess how the problem might be addressed. At the end of the project, a report summarizing the findings and providing operational guidance is compiled.

Significant challenges with the traditional approach include:

- Bed elevation is often based on little-to-no, and often outdated, survey data. As a result, the variability of the bed elevation, especially during flood events is not captured or known, which creates a substantial issue when defining an initial bed condition. This uncertainty has an impact upon water levels and discharges.

- The grain size of the bed and amount of sediment supplied to the reach is estimated, or assumed. Further, it requires simplification of the complex and stochastic nature of sediment supply for use in a model.
- The numerical models have a range of sediment transport formulae, which incorporate a range of simplifying assumptions. Furthermore, most sediment transport formulae have been developed and are applicable on a uniform river reach scale and generally employ cross section average flow conditions, but most numerical models apply them at much smaller scale, i.e., from node to node.
- Models often require a substantial amount of time to run to steady state, causing them to lag behind real-time observations. The long model run time makes real time decision making and solving impossible, as models will likely require longer time to run than the actual event.

To overcome some of these challenges today, the work at the Forrest Kerr facility demonstrates that it is possible to instrument a facility and 'see' what is happening and how the conditions change in real time, allowing for faster response to changes in flow conditions and sediment buildup. Predicting conditions outside of normal operating conditions or evaluating a potential change in design or operational approaches, could still employ numerical or physical models, but would be better done if site data are used to understand when the bed elevations are changing, by how much they are changing and when sediment transport starts and stops. Current computational fluid dynamics (CFD) modeling for the FK facility makes use of the data from the field program to assess the possible range in bed levels during different flood events. The model is then used to test different operating scenarios (e.g. variations in Obermeyer levels and radial gate openings) to help determine the most effective strategy to minimize sedimentation at the intake during flood events.

Major challenges during the transition to direct observation of sediment transport, and in particular real-time support for sediment monitoring, include:

- Large datasets - there is a substantial amount of data to manage and sort through. To do this effectively one needs a good means of managing the data or the data will be unworkable and not useful.
- Trained operators and continuous coverage – for whatever reason the most interesting flood events seem to happen when the operators who know the site the best are on holiday. In general, you need a few people to know each site and they need to be able to pull up and review the data with minimal effort. This is hard to finance as storm events typically only last a few days, so the amount of time to on-board multiple people for the scenario of one or two key people being away is substantial.
- Complex hydraulics - the hydraulics at most of the sites are complicated and often controlled by a downstream control that can vary with time such as a sluicegate, the Obermeyer gates in the Forrest Kerr facility, as well as with the discharge through a power plant. As these factors change the sediment transport rates, having a solid knowledge of hydraulics and how they will change the flow pattern is very important for interpreting real time information from the sensors.
- Knowledge of sediment transport - a knowledge of bed forms is useful when interpreting noisy data to help assess if a feature that is possibly visible in the scans is present or if it is a signal artifact.

- Strong communication skills - the engineers and scientists need to have good communication with the operators at the facility and learn from what the operators are seeing and what the operators interpret to be going on.
- Data interpretation for informed decision making - for real time operations there is a need to train operators on how to interpret the data so they can make informed decisions on how to change operations.

To address the challenges discussed above a series of standard documentation protocols have been put in place so a wider number of individuals can understand the data flow. Automatic reports that run hourly have also been configured to summarize the key data and this enables easy data review when professionals are out of the office. Furthermore, notifications on key variables, such as the bed elevation in front of an intake have been enabled.

NHC has also started to use the data to train professionals on the pattern and processes of sediment transport at river intakes. While the data are complex, they are also extremely insightful, and can provide young professionals a chance to work with data that is not readily available elsewhere.

Conclusions

Overall, the introduction of the new technology has enabled much more information on the movement of sediment in rivers to be tracked in real time. At some locations this enables sediment to be tracked minute by minute and inform operations in real time on how much sediment is moving and where it is building up or being scoured from. The availability of such comprehensive, real-time data has fundamentally transformed how we approach the field of sediment management at these projects. From a passive consulting role of writing technical reports and static operational protocols, we have moved to a more active role that involves ongoing communications, dynamic data management and analysis, which ultimately benefits hydropower generation thorough an increase in efficiency and improved management techniques.

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