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Sediment Monitoring to Support Modeling a Reservoir Sediment Flush on a Sand-bed River in Northern Nebraska

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Abstract

The U.S. Geological Survey (USGS) in cooperation with the U.S. Army Corps of Engineers (USACE), monitored a sediment flush event from Spencer Dam located on the Niobrara River near Spencer, Nebraska, during the fall of 2014. Data collected during the flush were used to validate a one-dimensional sediment transport model developed by the USACE. The USACE surveyed 26 cross sections within the reservoir and as far as 1 kilometer (km) upstream from the reservoir pool to about 10 km downstream from the dam before and after the flushing event to measure erosion and deposition. They also collected surficial sediment samples from sandbars within the reservoir. The USGS assisted USACE in its model validation efforts by collecting sediment data before, during, and after the flush using both traditional sampling techniques and a continuous laser-diffraction particle-size analyzer. From the context of longitudinal volumetric change, the model replicated erosion in the upper half of the reservoir within 4 percent of that observed by survey data and it replicated deposition downstream from the dam within 5 percent. However, the model underpredicted the erosion of the accumulated delta sediments in the reservoir by 43 percent. The timing and magnitude of suspended sediment concentrations produced by the model compared reasonably well to the discrete suspended-sediment sample results. These results indicate cross-sectional survey data and discrete sediment data may be adequate for developing sediment flush models for reservoirs in similar well-sorted sand-bed streams.

The USGS installed a continuous particle-size analyzer immediately downstream from the dam. Although the particle-size analyzer was successful in providing a large dataset during the flushing event, based on discrete point samples, it overestimated the amount of fine particles and underrepresented the amount of coarse material. It also required a significant amount of maintenance during the flushing event because of the large sediment load and the rapid bed aggradation. The maintenance issues with the particle-size analyzer along with uncertainty in the correlation to discrete suspended-sediment samples reduced its value for model validation. However, these issues may have been specific to the flushing event at Spencer Dam, which involved a sand-bed dominated stream and a wide channel. It is foreseeable that other sediment flush models developed for different streams with dissimilar sediment gradations may benefit from similar continuous sediment data, but adequate planning and evaluation should be performed.

Introduction

The Niobrara River in northern Nebraska is a wide and shallow sand-bed river, which drains a large area of the Nebraska Sandhills ecoregion (Figure 1). In its lower reaches, the river is characterized by a sand-bed braided channel, dominated by actively migrating sandbars (Alexander et al., 2010). A hydroelectric dam (referred to as Spencer Dam [Figure 1]) built near Spencer, Nebr. (not shown in Figure 1) was retrofitted in the 1950s to manage for this sediment. Sluicing gates at Spencer Dam are lowered twice a year to allow accumulated sediments to pass downstream. In 2014, the usual spring flush was cancelled because of adverse river conditions, so the 2014 fall flush event consisted of an entire year's worth of accumulated sediment.

Figure 1. The Niobrara River near Spencer Dam in northern Nebraska

Sedimentation is a common problem for reservoir managers throughout the world. Periodic drawdown flushing is one method for managing the accumulated sediment (Lai and Shen; 1996; Wang and Hu 2009). However, the effectiveness of flushing can vary because the characteristics of each reservoir and dam system are unique. The composition of the sediment in the reservoir, the size of the reservoir, and the design of the dam are only a few of the factors that may influence the success of flushing.

The U.S. Army Corps of Engineers (USACE) has incorporated sediment transport features in HEC-RAS 5.0 (USACE 2016) that can be used to model sediment flushing events. These tools had been used for sediment management studies, but model results had never been compared to a reservoir flushing event (Gibson and Boyd 2016). In the fall of 2014, USACE identified the Spencer Dam fall sediment flush as an opportunity to evaluate the new model features in HEC-RAS 5.0. The Spencer Dam fall sediment flush also provided a way to test and incorporate the U.S. Department of Agriculture's Bank-Stability and Toe Erosion Model (BSTEM) (Gibson et al. 2015) into HEC-RAS 5.0. Final analysis of BSTEM performance is not yet complete and will not be addressed within this paper.

To validate the HEC-RAS 5.0 model, the U.S. Geological Survey (USGS) in cooperation with USACE, collected data before, during, and after the sediment flush. USACE surveyed cross sections within the reservoir pool and as far as 1 kilometer (km) upstream from the reservoir pool to about 10 km downstream from the dam. The USGS collected discrete sediment samples, as well as continuous suspended-sediment size data using an autonomous particle-size analyzer before, during, and after the flush at a location just downstream from the dam (Figure 1). USACE also collected surficial sediment particle-size samples within the reservoir before the flush.

This paper examines how sediment monitoring was used to assist USACE with model validation for the Spencer Dam sediment flush and discusses the implications for modeling and monitoring similar sediment flush events.

Description of Fall 2014 Reservoir Flush

Spencer Dam operators began lowering gates at midnight October 5, 2014. This initial drawdown was done slowly and resulted in less than 1 meter (m) of lowering in the reservoir. At 8:00 am on the morning of October 6 the operators began raising the four main Tainter gates every hour until they were fully open at about 13:20 in the afternoon. These gates dropped the reservoir pool elevation about an additional 2 m. Once these gates were open, a sluice gate, with an opening 1.5 m lower than the main gates, was opened. All these gates remained open until November 7, 2014 (Gibson and Boyd 2016).

Sediment releases began increasing as the main Tainter gates were lowered but when the sluice gate was opened, it created sudden and impactful morphological changes within the reservoir. A head cut moved rapidly upstream from the sluice gate opening and areas of sandbars left dry by the drawdown began rapidly scouring and slumping into the active channels (Figure 2). Three main channels formed within the reservoir: one along the right bank, one midchannel, and one along the left bank. After 24 hours most of the flow was concentrated in the right channel. Once the right channel became severely incised, the amount of flow and geomorphic activity in the other two channels became comparably insignificant (Gibson and Boyd 2016).

Figure 2. Photograph of the Spencer Dam reservoir during the October 2014 sediment flush looking upstream from right bank. The streamflow is moving towards the bottom right corner.

The channel downstream from the dam became extremely turbulent with moving dunes and antidunes. By the afternoon of the first day, the water appeared to take on characteristics of a slurry. The streambed in the vicinity of the continuous sampler and the Hwy 281 bridge began aggrading within hours after the first lowering of the main Tainter gates. Prior to the sediment release, the bed below the bridge was found to be primarily bedrock, but by the afternoon of the second day the bed had risen about 1.5 m because of the deposited sediment (Gibson and Boyd 2016).

Although suspended-sediment concentrations were highest for the first 48 hours after the flush, suspended-sediment concentrations remained well above pre-flush conditions even 4 weeks after the flush.

Methods

Cross-Sectional Surveys

The USACE surveyed cross sections from approximately 1 km above the reservoir pool to 10 km downstream from the dam. Twenty-six cross sections were surveyed between the reservoir pool and the first kilometer downstream from the dam. The cross sections within the reservoir pool were separated by an average spacing of 75 m. Above and below the reservoir pool, cross section spacing ranged from 0.2 km to 5 km. The cross sections were surveyed prior to the flush and cross sections downstream from the reservoir pool were surveyed immediately after the flush. However, water within the reservoir froze because of an abnormally early extreme cold period and so cross sections within the reservoir were not able to be surveyed after the flush. USACE resurveyed all cross sections during and after the spring flush of 2015 and used the data to assist in filling in the survey data gaps. In areas that were surveyed both after the fall 2014 flush and before and after the spring 2015 flush, the constructed cross sections overlapped reasonably well, which implies the morphological changes during the fall 2014 and spring 2015 flushes were similar downstream from the dam and that pre-flush cross sections were similar in the reservoir pool. Based on visual observations the morphologic changes that occurred within the reservoir pool were similar as well (Gibson and Boyd 2016).

Discrete Monitoring

USGS collected discrete suspended-sediment samples and bed-sediment samples at the Highway 281 bridge (Figure 1) as well as one site upstream from the reservoir and at two bridge locations downstream from Highway 281 (not shown in Figure 1). The focus of this paper is related to the USACE model, which only estimated suspended sediment concentrations at Hwy 281. Data and associated information for the other discrete suspended-sediment samples and bed-sediment samples collected by the USGS can be found in Schaepe and Zelt (2018) and the data can be downloaded from the USGS National Water Information System Web Interface (USGS 2016). Additionally, USACE collected 17 surficial sediment samples from sandbars along a 1-km segment within the reservoir prior to the flush.
Discrete suspended-sediment samples were collected by the USGS before, during, and after the sediment flush from the Hwy 281 bridge. USACE wanted to quantify the rapid suspended-sediment concentration changes that occurred during the beginning of the flush, so more samples were collected in the first few days of the flush; thereafter the sampling frequency was reduced. Five samples were collected the first day of the flush (October 6, 2014), six samples were collected on the second day, four samples were collected on the third day, and two samples were collected on the fourth and fifth days. Single samples were collected on day 16 and day 33 (the final day) of the sediment flush. One sample was collected before the flush on October 2 to determine background concentrations and one sample was collected on November 13 shortly after the reservoir pool was filled (November 7 through November 10) and the dam resumed regular operations (November 10).

Suspended sediment samples were collected using equal-width-increment (EWI) sampling techniques (Edwards and Glysson 1999), so that the entire stream cross section would be represented in each sample. EWI sampling was utilized over equal-discharge-weighted sampling because the rapidly changing streamflow caused by the flush made equal-discharge-weighted sampling impractical. Replicate samples were collected for 22 of the 25 samples collected at the Highway 281 bridge to quantify sample variability. Quantifying the variability between replicate sets provides information on the precision of the sample result. Replicate samples were collected concurrently meaning that at each station two bottles were filled, one for sample set A and one for sample set B. At the next station the order was switched so that one set was not always collected prior to the other. The median difference between replicate sets was 12.1 percent (Schaepe et al. 2018). Suspended-sediment concentrations were determined by the USGS Iowa sediment laboratory using standard methods (Guy 1969). Additional information about these samples and sample data can be found in Schaepe and Zelt (2018).

Several suspended-sediment point samples were collected near the intake of the continuous particle-size analyzer (see “Continuous Monitoring” section) for quality control. These samples were collected using a USGS DH-81 bottle sampler using standard USGS methods (Edwards and Glysson 1999). The samples were analyzed by laser diffraction using a LISST-Portable (Sequoia Scientific 2011a). Additional information about these samples can be found in Schaepe et al. (2018).

Continuous Monitoring

The USGS installed an on-site laser-diffraction particle-size analyzer (LDPSA)(Sequoia LISST Streamside, Sequoia Scientific 2011b) to collect continuous suspended-sediment particle-size samples during the beginning of the sediment flush when sediment concentrations were expected to change most rapidly. USGS deployed the LDPSA the week prior to the sediment flush to ensure that the instrument was working as expected and to obtain pre-flush baseline data. It was then redeployed the night before the sediment flush at the same location and operated sporadically during the first 4 days of the flush.
The LDPSA instrument collects water by pumping it from the stream and then analyzes it using laser diffraction technology. The results are given volumetrically (microliters/liter) for 32 log-spaced size classes ranging from 1.9 to 386 microns (µm) (Sequoia Scientific 2011b), although only nine of those size classes were quality-assured for this study. The LDPSA measures sediment particles using a 670-nanometer wavelength laser beam. A photodiode measures the light energy from the laser beam that passes through the water-sediment mixture. Particle-size measurements are based on the multiangle scattering pattern. The resolution of the LDPSA is 1 milligram per liter (mg/L) and this resolution can be maintained for concentrations as large as 8,000 mg/L. Additional information about laser diffraction technology can be found in Agrawal and Pottsmith (2000).

The LDPSA was installed approximately 0.4 km downstream from the dam on the right bank. Most of the components were mounted in a storage box on top of the bank, about 7.6 m above the river, and the pump was installed using a sliding rail system and set in the water about 1.2 m from the bank. Additional information on instrument components, instrument settings, and calibration data can be found in Schaepe et al. (2018).

Sediment Transport Model

The Spencer Dam flushing event was modeled using a one-dimensional (1D) HEC-RAS 5.0 unsteady sediment model. Cross-sectional survey data measured before the flush was used to define the spatial parameters of the model. An inline structure was included in the model to represent the dam, and gate operations, which were provided by Nebraska Public Power District, were input to the model as a time series (Gibson and Boyd 2016).

The Yang sediment transport function (Yang, 1973) was selected for the final model. The Copeland algorithm was used to model bed-material mixing. Model outputs of erosion and deposition volumes were not sensitive to the transport function or bed-material mixing algorithm. However, incision rates were sensitive to the transport function and the Yang transport function most effectively reproduced the rates observed during the flush (Gibson and Boyd 2016).

The model was run using 6-second time steps. Larger time steps introduced steep friction slopes, which created high shear stresses causing the bed to be unstable which led to over-prediction of erosion in the model. Larger time steps also created hydraulic instabilities. Smaller time steps did not produce a steep enough energy grade line to initiate scouring (Boyd and Gibson, 2016). Additionally, the timing of the sluice gate opening was reduced in comparison to the flushing event to improve model stability (Gibson and Boyd 2016). Additional evaluation of the model's handling of the sluice gates opening will be needed so that the model results can be considered reliable for various sluicing scenarios.

Surficial sediment samples collected before the flush were used to calibrate bed gradations. Most of these samples consisted of at least 90 percent fine-medium grain-sized sand. Model test runs indicated that it was not sensitive to sediment boundary conditions; thus, a simple equilibrium load boundary was defined at the upstream cross section (Gibson and Boyd 2016).

Performance of Sediment Monitoring Techniques

Logistical Challenges of Discrete Monitoring

Sampling conditions at the Hwy 281 bridge were difficult because of the extreme river conditions, especially during the first day and a half of the sediment flush. The initial surge of stored water and sediment, combined with the bridge constriction, made sampling conditions difficult. Stream velocities consistently exceeded 7 feet per second. The high velocities combined with the additional force from the heavy sediment load routinely dragged the sampler downstream during sampling. Large sand dunes were constantly forming and moving within the sample channel cross section. These sand dunes may have contaminated some of the suspended-sediment samples with bed material.

Logistical Challenges of Continuous Monitoring

Although the monitoring equipment location was well located for capturing the rapid changes in sediment concentrations, because of its close proximity to the dam, the flow and sediment characteristics were problematic for autonomous sampling from a fixed bank-side location. During the flush, bank material was continually eroding and falling into the river near the pump. Streambed aggradation during the first night of the flush was so substantial that the pump became fully buried in sediment and therefore could not operate. It took until early afternoon of the following day to reposition the pump and resume sampling. The stream depth near the bank was limited to around 0.5 m, which made it difficult to maintain enough distance between the pump to the streambed to ensure that bed material was not being sampled. Because of the rapid aggradation and shallow depths, the pump had to be moved several times during the flushing event.

Comparison of Continuous Sediment Sampling versus Discrete Sampling

Comparisons of LDPSA results to the results of discrete point samples collected near the LDPSA pump and discrete suspended sediment samples at the bridge indicated differences in sample composition and magnitude. The differences between the LDPSA and the discrete point samples near the pump are related to the sample intake method (pump compared to nozzled bottle sampler), because they both employ the same method of analysis (laser diffraction). The LDPSA samples had a larger percentage of fine material and lower percentage of coarse material than the discrete point samples collected near the LDPSA pump (Figure 3). Pump samplers are known to underestimate the coarse load (Edwards and Glysson 1999; Roseen et al. 2011) because the pumping force cannot overcome the momentum of the coarser material, especially for particles that are further away from the pump (Edwards and Glysson 1999). The result of this is that the LDPSA's sample had a greater proportion of fine material and a smaller proportion of coarse material than the discrete point samples collected near the pump.

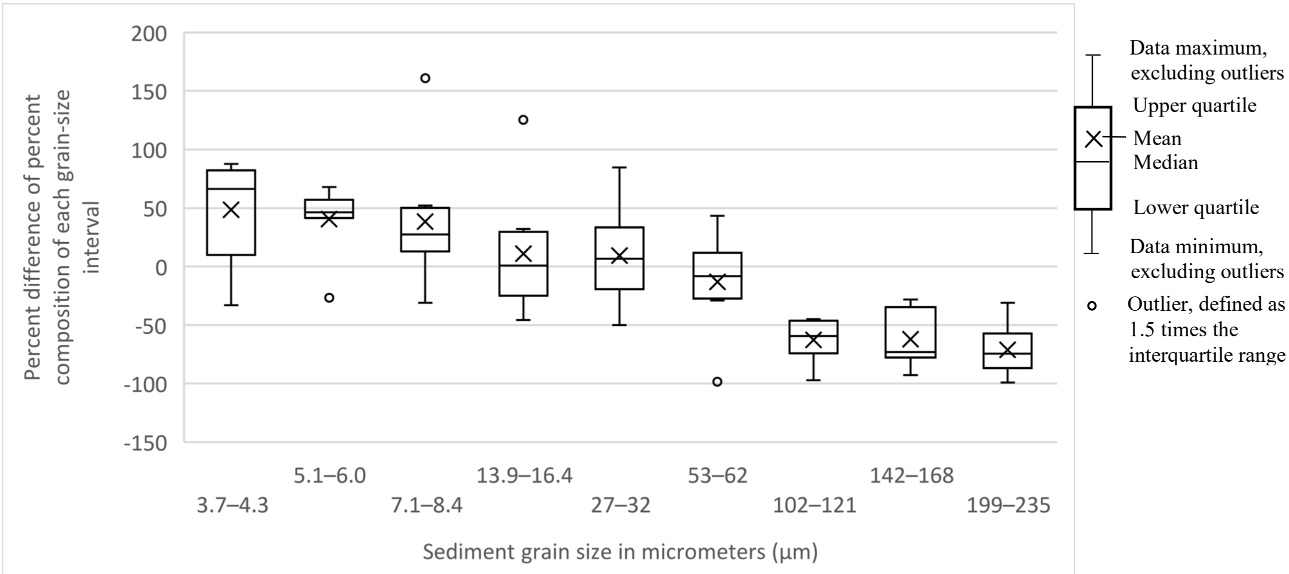

Figure 3. Comparison of measured concentrations for selected sediment grain sizes collected by LISST-Streamside (Sequoia Scientific 2011b) continuous sediment monitor and selected discrete point samples collected near the continuous sediment monitor and analyzed by LISST-Portable (Sequoia Scientific 2011a). Positive differences indicate the LISST-Streamside results were higher than those of the LISST-Portable.

Differences between LDPSA data and bridge sample results indicate that suspended-sediment concentrations near the pump were not representative of the channel cross section as a whole. A complete grain-size distribution was not determined from the LDPSA data (see Schaepe et al. 2018), but if simple interpolation is used to create a full distribution and an effective density of 1.24 grams per milliliter (calculated by Czuba et al. 2015) is assumed, then concurrent (collection times were within 15 minutes of one another) samples from LDPSA data and bridge discrete suspended-sediment sample results have a coefficient of determination of 0.05 which indicates a poor relation of the two datasets.

The concentrations measured at the bridge were substantially higher than those measured by the LDPSA. There are many factors that may have contributed to these differences. The difference in channel configuration was most likely the largest contributing factor. The cross section at the bridge was confined, which created a mostly deep and fast cross section. The channel cross section at the pump was much wider and so velocities were lower, and depths were smaller. This indicates that more sediment would be transported in suspension at the bridge site compared to the cross section at the pump (Edwards and Glysson, 1999).

As with the discrete point samples collected near the pump, the sample intake method used for the bridge sample was different than for the LDPSA samples. The bridge discrete suspended-sediment samples were collected at 10 equally spaced locations within the cross section. As a result, the bridge discrete suspended-sediment samples represented the entire water column whereas LDPSA samples only represented the volume around the pump intake. Also, the discrete suspended-sediment bridge samples were collected with an isokinetic bottle sampler; the LDPSA samples were collected by a pump.

Sediment transport model performance

Bathymetric Comparison

Overall the sediment transport model performed well in estimating scour and deposition within the reservoir and downstream from the dam. The total volume change estimated by the model in the upper half of the reservoir was within 4 percent of the surveyed volume change. The sediment deposition volume estimated by the model for the 500-m stretch of river directly downstream from the dam was within 5 percent of the surveyed volume. However, within the deltaic portion of the reservoir the model underestimated erosion volumes by 43 percent (Gibson and Boyd 2016), although some of the measured erosion may have been associated with the differences between the fall 2014 flush and the 2015 spring flush.

The performance of the model is demonstrated by a plot of a typical reservoir cross section (Figure 4). The plot shows that the model accurately estimated incision depth but failed to accurately represent the lateral erosion. This occurred because dry sediments that the model assumed to be stable became compromised when toe slopes beneath them eroded. This causes sediment in the incising bank to slump off, increasing the rate of channel expansion. Most sediment models underestimate these lateral erosional processes because they estimate erosion only at the channel-bar interface. Additional geotechnical and lateral process models are needed to accurately model these geomorphological processes (Gibson and Boyd 2016).

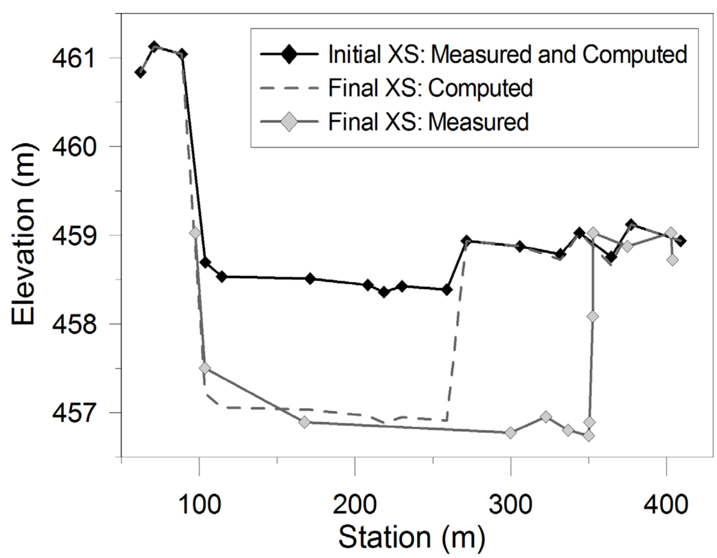

Figure 4. Measured and computed cross sections before the fall 2014 (initial XS) and after the spring 2015 flush (final XS) at a representative, mid-reservoir transect from Gibson and Boyd (2016). Vertical coordinates referenced to the North American Vertical Datum of 1988.

Suspended-Sediment Concentration Comparison

Model results for sediment concentrations were compared to the discrete suspended-sediment sample concentrations collected from the Hwy 281 bridge (Figure 5). The model computed total sediment load concentrations whereas the discrete suspended-sediment samples only included the suspended portion; therefore, the model results were expected to be higher. In a different segment of the Niobrara River, Colby and Hembree (1955) found that the suspended fraction represented an average of 51 percent of the total load. When suspended sediment concentrations were above 1,000 mg/L the average increased to 0.67. Turowski et. al (2010) summarized studies by Maddock and Borland (1950) and Lane and Borland (1951) and reported that for sand-bed streams the suspended fraction made up 74 to 91 percent of the total load for concentrations between 1,000-7,500 mg/L and 80-95 percent for concentrations greater than 7,500 mg/L. These studies indicate that for higher concentrations of suspended sediments in sand-bed streams, the suspended load should become a larger percentage of the total load. Therefore, Gibson and Boyd (2016) determined that the model estimated the timing and magnitude of the sediment load reasonably well.

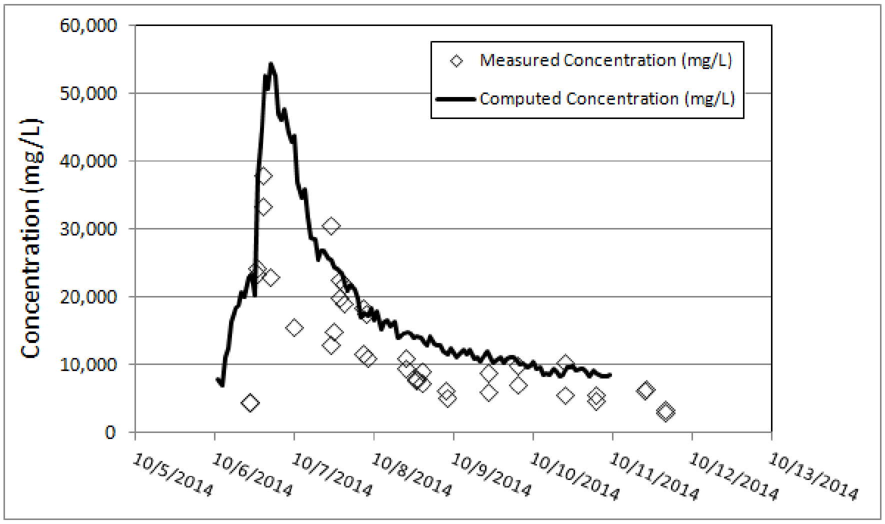

Figure 5. Suspended-sediment concentrations during the flush measured 500 m downstream from the dam and the total-sediment concentration computed at that location by HEC-RAS (Boyd and Gibson 2016)

Discussion

Continuous and discrete sediment monitoring are useful for refining and verifying sediment flush models. However, the type or types of data recommended for collection will depend on the needs of the model, site conditions, and the resources available. Preferably, knowledge about previous flushes can be used to inform monitoring decisions. In cases where no previous flushing events have been monitored, information from existing models developed for other similar flushing events may be used but greater uncertainty should be expected.

At a minimum, cross-sectional information, both upstream and downstream, would provide valuable information for the model. Surficial sediment samples collected upstream from Spencer dam also proved to be a vital component of the Spencer model and such data would provide models with a starting point for estimating the gradations of sediment that will be transported downstream from the dam. The discrete suspended-sediment samples indicated that the model adequately estimated sediment concentrations downstream from the dam. This indicates that for the Niobrara River and possibly other sand-dominated streams, sediment-size gradation information collected within the reservoir may be adequate for model calibration. For streams that have a wider range of sediment sizes, continuous suspended-sediment monitoring may be needed to identify the composition of sediment in suspension during the flush.

If it is determined that continuous suspended-sediment monitoring data will be collected during a sediment flush, it is critical to assess whether the equipment will operate effectively and to determine what type of data are needed. If previous sediment flushes have been observed, those conditions should be used to dictate selection of monitoring equipment. If no prior knowledge is available, preliminary hydrologic and sediment models based on site reconnaissance should be used to guide the monitoring design. Prior background information at a minimum should include identification of possible monitoring locations, estimates of aggradation downstream from the dam, estimation of suspended-sediment sizes, and an understanding of channel geometry.

No matter what conditions are expected, discrete suspended-sediment monitoring is necessary for validation and interpretation of continuous data (Landers et al. 2016; Czuba et al. 2015; Rasmussen et al. 2009). However, because of the extreme conditions that occur during a sediment flush, discrete monitoring may be difficult. For example, during the Spencer Dam sediment flush in fall 2014, the only safe and reasonable location for discrete monitoring was at a bridge location that was not ideal for sample collection. At this bridge location, flow was highly constricted, which introduced velocities that were higher than the maximum velocity recommended for the sampling equipment. In addition, large dunes were constantly migrating on the streambed. In deeper rivers, it may be possible to avoid such situations by using a boat. For other situations, possible alternatives may include temporary cableways, an alternate bridge location, or a wadeable cross section. The quality of discrete sample results is highly dependent on the sampling site (Edwards and Glysson 1999; Landers et al. 2016) and so it is critical a suitable location for discrete sampling is identified. The objective of the investigator should be to collect the best discrete data possible so that any continuous data that are collected can be adequately interpreted and used appropriately.

If an adequate discrete suspended-sediment monitoring site can be identified and continuous monitoring results are required, then conditions at the site should be evaluated to determine the most applicable continuous monitoring technology. For example, aggradation, such as occurred downstream from Spencer Dam, limits how instruments may be installed and used. Some instruments, such as turbidity monitors and the Sequoia LISST-SL, can be cabled from the bridge and moved up or down as necessary. Other instruments that are more fixed must be mounted on some type of sliding rail system such as was used in this study or similar to how the acoustic Doppler velocity meter (ADVM), which was used in the Clearwater and Snake Rivers in Washington and Idaho (Wood and Teasdale 2013), was mounted. However, these moveable units are not free from effects from aggradation, because sediment composition of the sample being analyzed is dependent on proximity to the bed (Edwards and Glysson 1999; Landers et al. 2016), and during times when the equipment is not attended, the distance from the instrument to the bed will change. Other possible alternatives would be to use an intake attached to a floating mount or engineering a constriction near the intake that would prevent deposition.

A determination or estimation of the gradations of sediment in suspension during a flush will help determine the most appropriate continuous monitoring equipment. If it is determined that the sediment in suspension will primarily be fine sediments, then a turbidity monitor may be used as a surrogate for suspended-sediment concentration (Rasmussen et al. 2009; Uhrich and Bragg 2003). However, in a sediment flush, the types of turbidity monitors that can be used may be limited because the concentrations may exceed the upper limits of the equipment's capabilities. ADVMs have also been shown to adequately estimate suspended-sediment concentrations in fine-sediment dominated streams (Landers et al. 2016) and are still useful during periods of high concentrations.

In streams where sediments in suspension are a mixture of fine and coarse material then multi-frequency ADVMs and laser diffraction technology (such as LISST instruments) are preferable to turbidity monitors for estimating suspended-sediment concentrations (Landers et al. 2016; Topping et al. 2015; Czuba et al. 2015). These technologies also can be used to estimate suspended-sediment size (Landing et al. 2016; Czuba et al. 2015) whereas turbidity monitors cannot.

Variability of suspended-sediment within a cross section has a large effect on the quality of continuously monitored data. This is especially true during a sediment flush when changes are occurring quickly. Channel geometry can either contribute to the variability or limit it. In the case of Spencer Dam, the constriction of the bridge combined with the bedrock bed constrained the initial flush of water so that flow increases were mainly noticeable as an increase in stream velocity. These increases along with the initial pulse of sediment created a cross section dominated by suspended sediment. As the flush went on, the bed aggraded so that the water rose above existing gravel and sandbar constrictions and then widened and began to form bars and side channels. Once this occurred, most of the sediment in suspension was in the center of the channel. Monitoring of a previous flush may have provided information as to the best location to place a continuous monitor that would have accounted for these cross-section deviations, but because of the nature of sand-bed streams it would not necessarily respond the same way during a subsequent flush. Only comparative analysis of continuous data to discrete cross-sectional data could determine how well the data corresponded.

To avoid issues related to changes in cross-sectional suspended-sediment variability, if possible, a cross section should be selected that is relatively narrow with high banks so that the majority of sediment remains in suspension during the flush. If an ADVM is used, the channel should be straight for at least 5 to 10 channel widths both upstream and downstream from the monitoring location, and the ADVM should be adequately placed upstream or downstream from obstructions (such as bridge piers) and be far enough upstream or downstream from the discrete sampling location to avoid acoustic interference (Landing et al. 2016). Even if the grain-size distribution across the cross section remains constant, the distribution of grain sizes may change with time, which can affect acoustic attenuation (Topping and Wright 2016). This will add to the analysis time related to ADVM post-processing.

As is indicated by most of this section, monitoring sediment during a sediment flush presents challenges, especially for continuous monitoring. Because of this, the needs of the study should be carefully weighed against safety, the probability of obtaining quality data, and the resources available. Each sediment flush modeling project is unique and complex, and thus requires careful planning and preparation. It is ultimately the responsibility of the investigators to decide the data needs of their model and determine if those data can be collected, safely, practically, and within cost constraints.

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