USGS-WWDC Water Research Program Project Report

Project Title: **Sediment and Fisheries: An Assessment to Inform Sediment Management Practices at Wyoming Dams**

Prepared by Ashleigh Pilkerton, Annika Walters, Frank Rahel

Principle Investigators

Annika Walters, Associate Professor/ Research Ecologist, U.S. Geological Survey, Wyoming Cooperative Fish & Wildlife Research Unit, Zoology and Physiology, University of Wyoming, annika.walters@uwyo.edu, 307-766-5473

Frank Rahel, Professor, Zoology and Physiology, University of Wyoming, frahel@uwyo.edu, 307-766-4212

Lindsay Patterson, Supervisor, Surface Water Standards, Wyoming Department of Environmental Quality, Water Quality Division, Lindsay.Patterson@wyo.gov, 307-777-7079

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Abstract

Effective sediment criteria must consider natural temporal and spatial variation in sediment, reflect the requirements of the biological communities they are meant to protect, and be attainable for the system. Our research addresses multiple considerations for managing sediment at dams to best protect fisheries and provides a suite of data, results, and models that can be implemented and customized to inform future sediment management activities worldwide. We contribute knowledge and a set of operational tools to predict and quantify the biological effects of sediment flushing operations and provide evidence that dam operators can effectively minimize the effects of sediment flushing operations to protect downstream aquatic life. We conducted a series of experimental sediment releases at Willwood Dam and monitored downstream water column and streambed conditions in salmonid spawning habitat to understand the effects of dam sediment management on fisheries. We found spawning habitat conditions directly reflect dam operations and identified three monitoring techniques that best predict the rate of fine sediment deposition during experimental sediment releases (discharge, depth integrated suspended sediment concentration and lagged acoustic backscatter suspended sediment concentration) and hyporheic dissolved oxygen concentrations (the rate of fine sediment deposition). Additionally, we conducted a literature review to catalog the effects of suspended sediment on fishes to update models for predicting severity of ill effects on combinations of fish life history, life stage, taxonomic group and sediment particle size. This work provides a compilation of the current state of knowledge on fish responses to sediment and address limitations with the Newcombe and Jensen (1996) severity index currently used in developing operating recommendations for sediment management worldwide. The updated severity index paired with a strong understanding of the biological and geomorphic effects of sediment releases gleaned through our fieldwork will provide guidance for addressing current challenges at Willwood Dam and statewide. This research will enhance the ability of managers to select monitoring metrics that are best suited for quantifying the impact of sediment releases from dams and their impact on fisheries. Our research will assist in evaluating Wyoming's water quality criteria for suspended sediment and turbidity. This work will have direct implications for a number of state and federal agencies charged with managing water quality, fisheries, and water storage including Wyoming Department of Environmental Quality, Wyoming Game and Fish Department, and the United States Bureau of Reclamation.

Publications and Presentations

Multiple presentations, reports and journal manuscripts have resulted from this project. Two manuscripts are in preparation. The first provides an updated understanding of fish responses to the concentration of suspended sediments, and duration, frequency, and timing of exposure and identifies which fish species, life stages, and time periods are most sensitive to sediment releases. The second includes the findings of our efforts to evaluate the relationships between approaches that measure sediment releases from dams (e.g., water column suspended sediment, turbidity, sediment deposition in sensitive habitats) and their relevance to fisheries.

Publications and Reports

1. Pilkerton, A., L. Patterson, J. Alexander, J. Burckhardt, F. Rahel, A.W. Walters. May 2022. Sediment and Fisheries: An Assessment to Inform Sediment Management Practices at Wyoming Dams. Report to Willwood Dam Working Group 2.
2. Pilkerton, A., L. Patterson, J. Alexander, J. Burckhardt, F. Rahel, A.W. Walters. *In Prep*. Understanding the Biological Effects of Controlled Sediment Flushing Operations on Salmonid Spawning Habitat. Target Journal: River Research and Applications
3. Pilkerton, A., S. McCullough, F. Rahel, A.W. Walters. *In Prep.* Re-evaluating Channel Suspended Sediment and Fisheries – An Update to Newcombe and Jensen's Quantitative Assessment of Risk and Impact. Report to Willwood Dam Working Group 2.
4. Pilkerton, A., S. McCullough, F. Rahel, A.W. Walters. *In Prep.* An Updated Quantitative Assessment of Risk and Impact between Suspended Sediment and Fish. Target Journal: North American Journal of Fisheries Management.

Presentations

1. Pilkerton, A., A. Walters, F. Rahel, and L. Patterson. 2022. Modeling the Biological Impacts of Sediment Flushing Flows on Spawning Habitat. Monitoring and Modeling Effects of Aquatic Barriers on River Ecosystems, Joint Aquatic Sciences Meeting.
2. Pilkerton, A., A. Walters. 2022. Clear as Mud: Predicting the Impacts of Controlled Sediment Flushing Operations on Spawning Habitat. Wyoming Cooperative Fish and Wildlife Annual Meeting.
3. Pilkerton, A., A. Walters, F. Rahel, and L. Patterson. 2022. Understanding the Biological Impacts of Sediment Flushing Flows on Spawning Habitat: A case study of Willwood Dam, WY. CO/WY American Fisheries Society Meeting 2022.
4. Pilkerton, A., A. Walters, F. Rahel, and L. Patterson. 2022. A Case Study to Understanding the Biological Impacts of Sediment Flushing Flows on Spawning Habitat, Willwood Dam, WY. Program in Ecology Student Symposium.
5. Pilkerton, A., A. Walters, F. Rahel, and L. Patterson. 2021. Sediment and Fisheries: An Assessment to Inform Sediment Management Practices at Wyoming Dams. University of Wyoming, Brown Bag Seminar.
6. Pilkerton, A., A. Walters, F. Rahel, and L. Patterson. 2021. Modeling Surrogate Metrics for Fine Sediment Deposition Impacts in Suitable Salmonid Spawning Habitat. Society of Freshwater Sciences Annual Meeting 2021.
7. Pilkerton, A., A. Walters. 2021. Sediment and Fisheries: An Assessment to Inform Sediment Management Practices at Wyoming Dams. Wyoming Cooperative Fish and Wildlife Annual Meeting.
8. Pilkerton, A., A. Walters, F. Rahel, and L. Patterson. 2021. Modeling Surrogate Metrics for Fine Sediment Deposition Impacts in Suitable Salmonid Spawning Habitat, Willwood Dam, WY. Colorado-Wyoming Chapter of the American Fisheries Society Annual Meeting 2021.
9. Pilkerton A. Updates to Sediment and Fisheries: An Assessment to Inform Sediment Management at Wyoming Dams. Presented to: Wyoming Department of Environmental Quality Willwood Dam / Shoshone River Work Group; September 2020; Virtual.
10. Pilkerton, A., A. Walters, F. Rahel, and L. Patterson. 2020. Sediment and Fisheries: An Assessment to Inform Sediment Management Practices at Wyoming Dams. Society for Freshwater Sciences/Association for the Sciences of Limnology and Oceanography Joint Meeting.
11. Pilkerton, A., A. Walters. 2020. Sediment and Fisheries: An Assessment to Inform Sediment Management Practices at Wyoming Dams. Wyoming Cooperative Fish and Wildlife Annual Meeting.
12. Pilkerton, A., A. Walters, F. Rahel, and L. Patterson. 2020. Sediment and Fisheries: Quantifying Impacts of Sediment Releases from Willwood Dam. Colorado-Wyoming Chapter of the American Fisheries Society Annual Meeting 2020.

13. Pilkerton, A. 2020. Water Quality Techniques to Quantify Sediment Deposition in Suitable Spawning Habitat. Willwood Dam Working Group 2 – Wyoming Department of Environmental Quality.
14. *Forthcoming*: Pilkerton, A., A. Walters, F. Rahel, and L. Patterson. December 2022. Sediment and Fisheries: An Assessment to Inform Sediment Management Practices at Wyoming Dams. Wyoming Water Forum.

Student Support Information

The funded project supported training and mentorship of five students, four undergraduate students, and one graduate student.

- **Kayli Newkirk (Clore)** earned Bachelor of Science degrees in Zoology, and Wildlife and Fisheries Biology and Management from the University of Wyoming. Kayli was funded through the project to be trained in field collection of pebble counts and freeze core samples in addition to helping with laboratory sample processing including loss on ignition techniques, suspended sediment concentration filtration and weighing. Additionally, she assisted with literature reviews and data extraction. Kayli's laboratory and fieldwork experience aided her in securing technician positions with the Wyoming Game and Fish Department, and most recently, as a Biological Science Technician with the U.S. Forest Service, Medicine Bow – Routt National Forests and Thunder Basin National Grassland.

- **Braxton Newkirk** earned a Bachelor of Science degree in Wildlife and Fisheries Biology and Management from the University of Wyoming. Braxton fulfilled internship credit requirements for his degree by assisting with field sample collections and laboratory sample processing including processing suspended sediment concentration samples and assisting with loss on ignition methods. Following his involvement with this project, Braxton worked as a Fisheries Technician for the Wyoming Cooperative Fish and Wildlife Research Unit and recently started a M.S. program at the University of Nebraska, Lincoln with the Nebraska Cooperative Fish and Wildlife Research Unit under Dr. Jonathan Spurgeon.

- **Darby McMartin** is an undergraduate student at the University of Wyoming studying Wildlife and Fisheries Biology and Management. Darby was funded to assist with literature review processes including identifying literature of interest, extracting data triplicates and helping with collected data using WebPlotDigitizer for severity of ill effects models. As a result of her involvement with this research, Darby is working on an independent research project and will be presenting her research at Undergraduate Research Day or a similar forum. Darby expects to graduate from the University of Wyoming in December 2022.

- **Sara McCullough** earned her Bachelors in Science in Geology from the University of Wyoming. As an undergraduate student and post-baccalaureate student, Sara was funded to assist with multiple aspects of this project. Initially, Sara assisted with field and laboratory work including collection of freeze core samples and pebble counts where she refined skills developed through her undergraduate degree and developed confidence in field based studies of geomorphology and sediment transport. Additionally, Sara spearheaded techniques to process sediment infiltration bag and time integrated suspended sediment samples for grain size analysis in collaboration with the Wyoming Sediment Petrology Lab. More recently, Sara assisted with the literature review process including extracting data from literature of interest and with the refinement of the severity of ill effects metrics (Newcombe and Jensen 1996). As a result of the skills and expertise developed through this project, Sara is working on an independent project to analyze sediment particle size variation as a function of timing of sediment flushing events using samples collected during this research. Sara is currently a Masters student at the University of Wyoming in the Department of Geology and Geophysics.

- **Ashleigh Pilkerton**, is a PhD graduate student mentored by Dr. Annika Walters and Dr. Frank Rahel at the University of Wyoming in the Program in Ecology and Evolution with the Wyoming Cooperative Fish and Wildlife Research Unit and Department of Zoology and Physiology. Ashleigh developed all research plans, conducted field work, analyzed data and prepared research summaries for this project. This research comprises the first two chapters of her dissertation and funding through this project covered associated field and laboratory costs in addition to covering her tuition and fees.

Conferences Attended

Results from this research were presented through several scientific symposia and conferences including:

- Joint Aquatic Sciences Meeting 2022, Session on Monitoring and Modeling Effects of Aquatic Barriers on River Ecosystems

- Wyoming Cooperative Fish and Wildlife Research Unit Annual Meeting (2020, 2021 and 2022)
- CO/WY American Fisheries Society Meeting (2020, 2021 and 2022)
- Program in Ecology Student Symposium 2022
- Society of Freshwater Sciences Annual Meeting 2021
- Society for Freshwater Sciences/Association for the Sciences of Limnology and Oceanography Joint Meeting 2020
- *Forthcoming:* Wyoming Water Forum December 2022

Notable Awards and Achievements

- Ashleigh Pilkerton received the following awards and honors for her research associated with this project:
    - Best Student Paper Award, 2nd Place, CO/WY American Fisheries Society Annual Meeting, 2022
    - Associated Students University of Wyoming Conference Funding Scholarship, May 2022
    - Honorable Mention in the 2021 National Science Foundation Graduate Research Fellowship Program
    - American Fisheries Society Ron Remmick Memorial Scholarship, University of Wyoming Department of Zoology and Physiology, Spring 2021
    - Vern Bressler Fisheries Fund Scholarship, University of Wyoming Department of Zoology and Physiology, Spring 2021
    - Associated Students University of Wyoming Conference Funding Scholarship, May 2020
    - Vern Bressler Fisheries Fund Scholarship, University of Wyoming Department of Zoology and Physiology, Spring 2020
- Dr. Annika Walters received the following grants:
    - USGS Supplemental Funds - FY2021
    - USGS Supplemental Funds - FY2022

Progress

This project combines literature review with field work to assess the relationship between sediment and fisheries. The resulting findings address three objectives through two separate research endeavors:

1. Update our understanding of fish responses to the concentration of suspended sediments, and duration, frequency, and timing of exposure.
2. Determine which fish species, life stages, and time periods are most sensitive to sediment releases.
3. Evaluate the relationships between approaches that measure sediment releases from dams (e.g., water column suspended sediment, turbidity, sediment deposition in sensitive habitats) and their relevance to fisheries.

An overview of the approach for addressing Objectives 1 and 2 are included below titled: "***An Updated Quantitative Assessment of Risk and Impact between Suspended Sediment and Fish***". Final results for this section are pending additional model validation. Results from Objective 3 are included under the research summary titled: "***Understanding the effects of dam sediment management on salmonid spawning habitat***".

An Updated Quantitative Assessment of Risk and Impact between Suspended Sediment and Fish

Based on: Newcombe and Jensen (1996), Channel Suspended Sediment and Fisheries: A Synthesis for Quantitative Assessment of Risk and Impact

1. Objectives

Newcombe and Jensen's (1996) work provides a strong foundation for determining threshold effects and exposure limits of suspended sediment in streams and estuaries on fish. The meta-analysis of 80 published reports resulted in the development of six empirical equations that calculate the severity of ill effects (SEV) of suspended sediment exposure to various life stages and taxonomic groups. The severity of ill effect value serves as an index to inform the degree of impact of the suspended sediment concentration and exposure on fishes and ranges from 0, "no impact" to 14, "80-100% mortality". Higher SEV values indicate a lethal impact on fishes while lower values are classified into behavioral, sublethal and paralethal impacts. SEVs calculated from suspended sediment concentration (SSC, mg/L) and exposure duration (ED, hours), are available for six combinations of life history, life stage, taxonomic group and sediment particle size. However, this work is over 25 years old and is difficult to apply to low sediment concentrations and younger age classes (e.g., eggs and juveniles). While the equations do account for predominant particle size, sediment concentration, and duration of exposure to suspended sediment, other factors of known importance, such as timing and frequency of exposure, degree of sediment deposition, and sediment particle size and distribution, are not factored into the equations. To address this, we synthesized existing literature, including studies in Newcombe and Jensen (1996), and new studies to the present to update the severity index. We focused on key components of a sediment release including sediment concentration, and duration, frequency.

The objectives of this work were to

1. Update our understanding of fish responses to the concentration of suspended sediments, and duration, frequency, and timing of exposure
2. Determine which fish species, life stages, and time periods are most sensitive to sediment releases
3. Address limitations of Newcombe and Jensen (1996) to add models addressing effects of low sediment and impact on younger age classes (eggs, juveniles)

Our work provides a compilation of the current state of knowledge of fish responses to sediment that will assist in assessing the sensitivity of Wyoming fish to sediment and developing operating recommendations for sediment management. The updated severity of ill effects models documented here will allow managers to make informed decisions and set regulatory thresholds to help ensure the amount and timing of sediment releases are reflective of ecological requirements.

2. Methods

We began our investigation using papers referenced by Newcombe and Jensen (1996) and conducted a comprehensive literature review to extract data triplicates, consisting of (i) suspended sediment concentration, (ii) duration of exposure, and (iii) severity of ill effect for fishes as described by Newcombe and Jensen (1996). Currently, data triplicates for 62 of the resources cited by Newcombe and Jensen are included in our dataset. A systematic backward literature review was conducted for all references listed in Appendix A (Newcombe and Jensen 1996). The ''snowball'' method of using the most recent works to find relevant articles cited in them provided additional articles.

We used several keywords to find relevant articles on the Web of Science and Google Scholar including *suspended sediment and fish, suspended sediment concentration and fish,* and *suspended sediment concentration and salmonids* published between 1995 - 2021. Our search was not exhaustive as there were more than ~74,200 results on Google Scholar. The articles selected during this search were refined through three steps. First, an initial screening was applied to determine if a given study was relevant based on the title and abstract. Given that many of the earliest studies pertaining to the effects of suspended sediment on fish were published in theses or conference proceedings, publication types were not limited to only peer-reviewed journal articles. Second, because the purpose of the literature review was to supplement Newcombe and Jensen's work with data published since 1996, studies that described experiments investigating suspended sediment studies on fish were of interest. Studies that conducted in-vitro experiments, such as experiments on gill tissue only, were excluded as they do not directly contribute to the understanding of whole body fish response. The title, abstract and if needed, the full text of the article were evaluated to determine whether the article was included or excluded prior to downloading it. Given the discrepancy between suspended sediment concentration and turbidity measurements, articles collected after the initial evaluation of literature cited by Newcombe and Jensen and articles identified during the backwards search of these articles that reported turbidity without a conversion for suspended sediment concentration (mg/L) were categorized separately and not processed. Per analysis requirements in Newcombe and Jensen's (1996) work, only articles containing information on three components of the data triplet (suspended sediment concentration, length of exposure to sediment, and nature of the effect) were included. The remaining articles were considered for further analysis during the final stage during which we categorized them as high priority (data triplicate was readily available), mid-priority (some information was available for data triplicates), low-priority (data triplicate not available, but research or literature review was relevant to overall effort) or miscellaneous (research focused on other components of the effect of suspended sediment on aquatic ecosystems, i.e. macrophytes, macroinvertebrates, logging, etc.). We read articles that met the criteria for 'high-priority" in detail and extracted all relevant data. Data points were manually extracted from figures using WebPlotDigitizer (Rohatgi 2020). References cited in each article were used as a secondary source of literature analysis and were initially screened using the title and processed using the three step process described here.

We used a concept matrix to record desired data from each article and compile a database for subsequent analysis of the severity of ill effects. All data were converted to appropriate units (i.e. days to hours) and notes were made to describe data quality or concerns regarding the applicability of the study. The following attributes for each article were recorded:

1. Author(s) and Publication Date
2. Fish Species Common Name
3. Fish Species Scientific Name
4. Fish Taxon Classification (S = salmonids, N = nonsalmonids)
5. Natural History (FW = freshwater and anadromous, ES = estuarine)
6. Life Stage (adult, juvenile, larvae, egg)
7. Suspended sediment exposure concentration (mg/L, some NTU or JTU)
8. Duration of exposure (hours)
9. Mean suspended sediment particle size (um)
10. Suspended sediment particle type (very fine (<15 um), fine (15-74 um), medium to fine (75-149 um), medium to coarse (150-290 um), coarse (180-740 um), bentonite clay, calcium sulfate, coal washery solids, diatomaceous earth, drilling mud (nontoxic), fire clay, fuller's clay, volcanic ash, wood fibers, other)
11. Sediment classification size (fine or coarse)
12. Subjective severity of ill effect ranking
13. Objective severity of ill effect ranking (if cited in Appendix A)
14. Description of severity of ill effect
15. Subjective severity of ill effect ranking
16. Mortality Rate (%)
17. Control Mortality Rate (%)
18. Significant Result (Y/N, as defined by authors)
19. Water temperature (C)
20. Water dissolved oxygen levels (mg/L)
21. Water dissolved oxygen levels (% saturation)
22. Sample Size (n)
23. Comments
24. Questions/Concerns
25. Potential exclusion of paper (Y/N)
26. Included in Newcombe and Jensen's (1996) Appendix A (Y/N)

Subjective severity of ill effects were assigned using Table 1 "Scale of the Severity of Ill Effect" from Newcombe and Jensen (1996). As descriptions of effect were encountered that were not included in Table 1 (Newcombe and Jensen 1996), the effect was an updated severity of ill effect table. Newcombe and Jensen (1996) state the severity of ill effect (z) is delineated semiquantitatively along a 15-point scale on which is superimposed four effects categories: no effect; behavioral effects; sublethal effects, and lethal consequences (which included a range of paralethal effects such as reduced growth rate, reduced fish density, reduced fish population size, and habitat damage).

2.1 | Model Formulation and Analysis

We used the expanded database to update the empirical equations from Newcombe and Jensen (1996) and developed additional models for attribute categories combinations omitted in their work. These additional data groupings arose from combinations of four attributes based on taxonomic group, life stage, life history, and particle size of suspended sediment, as defined by Newcombe and Jensen (1996).

We evaluated the six data groups for which Newcombe and Jensen developed models using the same model classifications and data groupings. Additionally, we developed a matrix to identify other potential data groups based on combinations of the four attributes. 32 potential models for the new data groups were identified however, 8 models were removed as the *Salmonid* taxonomic group was always classified under the *Freshwater and Anadromous* life history and thus the combination of *Salmonid* taxonomic group and *Estuarine* life history combinations were omitted. The remaining 24 new data groups were evaluated and modeled using the same methods as Newcombe and Jensen's six model data groupings.

Regression analyses for each data group were conducted as described in Newcombe and Jensen (1996) using R (R Core Team 2022). For each data group, the subjective severity of ill effect (SEV) was regressed on the natural log transformed suspended sediment dose (exposure duration [ED, h] and suspended sediment concentration [mg SS/L]). The linear regressions fitted for each group had the form:

$$SEV = a + b(\ln(ED)) + c(\ln\,(mg\;SS/L)$$

where *a* is the intercept and *b* and *c* are slope coefficients for the natural log transformation of exposure duration (ED, h) and suspended sediment concentration (mg SS/L).

The equations from the regression analysis become predictive models of the form:

$$z = a + b(\ln\,(x)) + c(\ln\,((y))$$

z is the calculated severity of ill effect (SEV), *x* is the estimate of exposure duration (hours), *y* is the concentration of the predominant suspended sediment (mg SS/L), *a* is the intercept, and *b* and *c* are slope coefficients. The resulting predictive models are numbered to correspond with the previously described data groups.

3. Results

We are in the process of validating our models and results are forthcoming. Please contact the authors directly for additional information.

4. Significance

Our meta-analysis of 127 articles on fish response to suspended sediment will yield updated empirical equations for understanding the effects of suspended sediment in fishes and predicting fish population dynamics. We believe the expansion of the data used for model development with respect to lower suspended sediment concentrations and younger age classes solidifies the applicability of this work in a wide array of fluvial systems and reduces previous application limitations. Further, this research will provide severity of ill effect calculation matrixes for managers to effectively assess suspended sediment associated risks and impacts in riverine systems in the field.

One major gap in the work of Newcombe and Jensen (1996) was the lack of data available for the youngest age classes including eggs and young juveniles. As a result, Newcombe and Jensen had to pool data triplicates for these life stages, which potentially masked important susceptibility thresholds for each life stage. We developed dose-response profiles for each developmental stage that will be particularly useful for managers concerned with younger life stages. Our updated dose-response models will provide a managerially relevant classification tool to help synthesize physical indicators with biological response within the broader context of stream health. The revised SEV models will be suitable for assessing the impacts of varying sediment concentrations on fishes and provide methods for quantitative impact assessment. The updated information on the sensitivity of various fish species, life history stages, and time periods allows managers to assess each system independently and will assist managers in making informed decisions and setting regulatory thresholds to help ensure the amount and timing of sediment releases are reflective of ecological requirements. With respect to Wyoming fishes, our work allows managers to develop an understanding of key temporal windows and sediment thresholds to most effectively pair sediment flushing events and regulatory thresholds whilst protecting downstream aquatic biota.

Understanding the effects of dam sediment management on salmonid spawning habitat
Ashleigh Pilkerton, Lindsay Patterson, Jason Alexander, Jason Burckhardt, Frank Rahel, Annika Walters

1. Objectives

Our research explores the relationship between dam operations and downstream sediment dynamics in the context of riverine fisheries management with the goal of providing managers with the tools and information to address these challenges (see Conceptual Diagram included below). We sought to understand how an experimental release of sediment contrasts with normal drawdown operations, the impacts of these operations on the youngest life stages of fish, including eggs and embryos, and to quantify the seasonal impact of dam operations on downstream spawning habitat. This research addresses four main objectives to facilitate sediment management actions at dams:

1. Assess the effects of sediment releases from dams on hyporheic dissolved oxygen and fine sediment deposition in brown trout spawning habitat.
2. Evaluate the capacity of real-time, near real-time, and laboratory water column sediment metrics to predict the effects of sediment releases from dams and other seasonal dam operations on hyporheic dissolved oxygen and fine sediment deposition in brown trout spawning habitat.
3. Evaluate the capacity of temporal sampling to quantify the influence of dam operations on sediment deposition and accumulation in downstream brown trout spawning habitat and evaluate relevancy of metrics;
4. Compare and contrast approaches that measure sediment releases from dams.

2. Methods

Our study consisted of two major sampling efforts: A) temporal sampling, and B) experimental sediment releases during the fall drawdown, with several metrics monitored continuously. Study sites were longitudinally spaced downstream of Willwood Dam in locations characteristic of brown trout spawning habitat with desired hydraulic and sedimentological parameters including relatively shallow overlying water depths during the spawning months and a distinct pool-riffle transition zone. A longitudinal component was included to quantify the variation in downstream effects. Sampling occurred in delineated sites that were no more than half the width of the river. This allowed field personnel to safely work in the main stem of the river whilst sampling a range of spawning habitat from bank to near river center.

Temporal sampling occurred during three distinct time periods including early March (prior to the spring sluice), August (during the irrigation season, after the spring sluice and high flow, prior to the fall pool draw down) and early December (after the fall drawdown) at all three sites from August 2019 to August 2021 (n = 7 sampling events, see Conceptual Figure). The goal of this sampling was to understand the spatiotemporal dynamics of sediment within the system in the context of dam operations and evaluate which metrics are best for similar sampling regimes. Sampling metrics included streambed sediment freeze core samples, modified Wolman pebble counts, turbidity grab samples and depth integrated suspended sediment concentration (Table 1).

Data collected during the fall drawdown experimental sediment releases included water column metrics (continuous turbidity monitoring, depth integrated suspended sediment samples, time integrated suspended sediment samples (2019 only), water temperature and dissolved oxygen concentration) and substrate metrics (sediment infiltration bags, hyporheic dissolved oxygen) for each experimental sediment release event (Table 1). Additional water column data was available from USGS gaging station 06284010—Shoshone River below Willwood Dam, including turbidity (FNU), acoustic backscatter suspended sediment concentration (LISST-ABS, mg/L), and discharge (cfs) (U.S. Geological Survey, 2021, Data inventory page for site 06284010—Shoshone River below Willwood Dam, near Powell, Wyoming: U.S. Geological Survey web page, accessed December 12, 2019 and September 14, 2021, at https://waterdata.usgs.gov/nwis/inventory/?site_no= 06284010). Three monitoring sites were surveyed along the study reach during 2019 and at two monitoring sites during 2020; Site B was excluded in 2020 experimental sediment flushing event sampling due to limited field personnel and slightly different geomorphological characteristics that did not reflect pool-riffle transition spawning habitat as well as Sites A and C.

We ran multiple linear regression models to predict the rate of fine sediment deposition or hyporheic dissolved oxygen for each experimental sediment release as a function of water column metrics. The response variables included A) the average percent fine sediment deposited (mass of fine sediment < 2 mm deposited divided by the total mass of sediment in the bag) in each sediment infiltration bag, per site and experimental sediment release time period, and B) average daily hyporheic dissolved oxygen per site, experimental sediment release time period, and site at 15 cm below the streambed surface. Model covariates included turbidity (USGS, FNU), discharge (USGS, cfs), a variable representing the sand fraction of the water column suspended sediment (either LISST-ABS data (USGS, mg/L), sand fraction of suspended sediment concentration from depth integrated water samples (mg/L), or total suspended sediment concentration from depth integrated water samples (mg/L)) and a lagged component (discharge or LISST-ABS data (USGS)). The variables representing the sand fraction of the water column suspended sediment were highly correlated (Pearson correlation coefficient >0.70) but there was interest in understanding which metric had the highest predictive power so global models were developed for each metric separately (Table 2). The lag variables were used to account for conditions observed in the past and were calculated by taking the average conditions of the prior 72-hours (i.e. the previous 72 hour period would be the lagged component of current 72 hour period). This allowed for predictions of the next period to account for past values of the same series. For example, a lagged effect was included to capture the potential for sediment deposition via saltation, or the movement of sediment deposited earlier upstream along the substrate. Rate of fine sediment deposition and stream dissolved oxygen were included as covariates for hyporheic dissolved oxygen models. No data was omitted in the model analysis. Data was categorized for each experimental sediment release as either a sediment mobilization event or non-sediment mobilization event, corresponding to either fall 2019 or fall 2020, respectively. All analyses were run in Program R (R Core Team 2022).

An Akaike Information Criterion approach corrected for small sample sizes (AICc) was used to compare the global models predicting either the rate of fine sediment deposition or hyporheic dissolved oxygen. Per this criterion, the best model is the one with the lowest AIC value (Helsel et al. 2020). Model fits were inspected for x-variable significance and overall model fit, and variance inflation factors were calculated. Final models were inspected for model significance, size of variance in parameter slopes and confirmed to match theory.

Top models were categorized by the real-time availability of the data into three groups: A) real-time data (data immediately available from sensors such as turbidity, discharge or LISST-ABS data), B) near real-time (real-time data that was computed such as calculating the lagged value of LISST-ABS data), and c) physical samples, such as depth integrated suspended sediment concentration samples or sediment infiltration bag samples that require laboratory analyses.

3. Principle Findings

3.1 | Temporal Sediment Dynamics

Temporal sampling was conducted using modified Wolman pebble counts and freeze core substrate samples below the dam after each distinct dam operational phase to understand the sediment dynamics within the system. Surface and subsurface composition trends, as measured by modified Wolman pebble counts and freeze core substrate samples, respectively, generally exhibited similar temporal changes with an overall decrease in the percent of fine sediment on the surface and within the streambed substrate of spawning areas during the study period (2019-2021, Figure 1 & 2). The magnitude of decrease was most pronounced in the substrate percentage of fine sediment observed in the freeze core substrate samples in downstream locations (Figure 2). Generally, each sampling site exhibited similar temporal changes in the substrate sediment percentages of fine sediment and gravels (Figure 2). An increase in the percentage of fine material (<2 mm) was observed during the post drawdown sampling events (December) across all sites, with the largest proportion of the streambed surface being composed of fines at Site A while Site B had the greatest proportion of fine material within the streambed substrate (Figure 2). The proportion of fines in the streambed surface and substrate composition was similar for both sample metrics although the magnitudes differed with pebble counts indicating a lesser percentage of fines composing the substrate (Figure 1).

Modified Wolman pebble count results indicate the percentage of the spawning area surface occupied by fine sediment and gravel varied temporally with an observed increase in the average proportion of fine sediment (<2 mm) on the streambed surface after the fall drawdown period during both sample years, compared to the other sampling events (Figure 1). The magnitude of the differences in average streambed surface composition trends across years reflects the differing fall drawdown objectives (experimental sediment release versus typical sediment release during the fall drawdown). The increase in the average proportion of fine material on the streambed surface observed during December 2019 corresponds to the experimental sediment release events of fall 2019 and to a lesser extent, was observed after normal dam operations when sediment was not intentionally released. Interestingly, an increase in the average percentage of fine material (<2 mm) observed in the modified Wolman pebble count data during the normal fall drawdown dam operations was attributed to a precipitation event resulting in sediment mobilization and subsequent sediment deposition; this is not reflected to the same magnitude in the freeze core fine sediment composition percentage. The average percentage of fine sediment observed during pebble counts dropped substantially following the winter maintenance phase (March) and late in the irrigation season (August) during 2021 (Figure 1); this can be attributed to a sediment sluicing event followed by a bed-mobilizing pulse of freshwater.

Similar temporal trends were observed in the freeze core samples. After the experimental sediment releases (fall 2019), nearly half of the substrate (47.14%) on average was composed of fine sediment (<2 mm, Figure 1 & 3). The average percentage of fine sediment present in the substrate decreased over the winter maintenance phase (March 2020) and remained low through the end of irrigation season (August 2020). A small increase in the average percentage of fine material was observed after the normal fall drawdown dam operations (December 2020), and declined through the end of the study (August 2021). This decrease is also attributable to the spring 2021 sediment sluicing event followed by a bed-mobilizing pulse of freshwater. The decrease in the average percentage of fine material in the substrate indicates the freshwater flush effectively mobilized the bed and extricated infiltrated sediment. Further, the increase in the percentage of gravel during these time periods was similar in magnitude to that observed for the decrease of fines.

Sequential temporal sampling events revealed a 'wave' of fine sediment being transported downstream (Figure 4). Following the experimental sediment release events, an increase in the percent fines observed on the substrate surface of 5.39% was observed at Site A (from 23.85% to 29.25%). During the following sampling event, the percent of fine material at Site A decreased by 11.65%, however there was an observed increase in the percent fines at Site B of 4.94% (from 31.25% to 36.19%) with a distance of ~0.615 river mile between sites. The subsequent sampling event indicated a decrease of 12.19% fines observed on the substrate surface at Site B (from 36.19% to 24.00%), while the percent of fine material on the substrate surface at Site C increased by 15.53% (from 9.71% to 25.24%) with a distance of ~2.76 river miles between sites. Given each subsequent increase in the percent of fine sediment on the streambed surface was not accompanied by an increase at the upstream site (but rather by a decrease at the upstream site), it is inferred that sediment deposited during the experimental sediment release events was slowly transported downstream. This implies that although substrate metrics may not immediately capture the direct influence of sediment releases from dams, the impacts of sediment deposited as a result of these dam operations can have important implications for spawning habitat in the following months.

3.2 | Experimental Sediment Release Sampling: Fine Sediment Deposition and Hyporheic Dissolved Oxygen Models

During 2019 and 2020, two distinctly different fall drawdown dam operational approaches were conducted to understand the impacts of varying sediment releases on downstream aquatic habitat, targeting sensitive spawning habitat, and resulted in differing conditions within the streambed substrate and water column (Figure 5). As a result of the observed water column conditions, varying effects on rates of fine sediment deposition (Figure 6) and hyporheic dissolved oxygen (Figure 7) were observed. The experimental sediment releases resulted in a range of 0.67% to 10.35% fine sediment by weight observed in the sediment infiltration bags, while the normal fall drawdown dam operations resulted in a maximum of 1.53% fine material by weight in the sediment infiltration bags. During experimental sediment release events, hyporheic dissolved oxygen (15 cm below streambed surface) ranged from 0.27 to 9.21 mg/L while hyporheic dissolved oxygen during normal fall drawdown operations ranged from 8.34 to 13.66 mg/L. The relationship between hyporheic dissolved oxygen and the rate of fine sediment deposition differed between dam operations with a stronger negative relationship observed during experimental sediment release events (Figure 8).

We used multilinear regression modeling analysis to assess the correlation between monitoring metrics and the rate of fine sediment deposition. Our results indicated there were significant differences between the predictive capacity of model covariates and upon comparison of global models to one another, we found that LISST-ABS data and it's computed lagged value are an important predictors of the rate of fine sediment deposition during normal fall drawdown dam operations and experimental sediment release events, respectively (Table 3). This implies that deposition from the water columns is the main driver of sediment accruing in spawning habitat during normal fall drawdown operations while the combination of water column suspended sediment concentration and saltation play an important role in the amount of fine sediment that is depositing in spawning habitat during sediment releases.

Top models predicting the rates of fine sediment deposition varied depending on the dam operations. During normal fall drawdown dam operations where little sediment was mobilized, LISST-ABS observations were the best predictor of the rate of fine sediment deposition. The second and third top models included the sediment load (metric tons/day) and the total suspended sediment concentration, respectively. Comparison of models using AICc approach indicated these top three models are indistinguishable and is visualized with respect to the real-time nature of the model covariates (Figure 9). During experimental sediment release events with large sediment loads, discharge, depth integrated suspended sediment concentration and lagged LISST-ABS observations were the best predictors of the rate of fine sediment deposition. The second and third top models included discharge, LISST-ABS, and either the computed lagged value of LISST-ABS or turbidity, respectively. Similarly, the top three models had ΔAICc of less than 2.0 indicating the top models are indistinguishable from one another with respect to predictive capacity

A general model predicting the rate of fine sediment deposition across all observations, including both experimental sediment release events and normal fall drawdown dam operations, indicated that discharge, depth integrated suspended sediment concentration and lagged LISST-ABS observations were the best predictors of the rate of fine sediment deposition. The second and third top models included discharge, the lagged component of LISST-ABS, and either LISST-ABS or turbidity and depth integrated suspended sediment concentration, respectively.

Similarly, we used multilinear regression modeling analyses to assess the correlation between monitoring metrics and the hyporheic dissolved oxygen at 15 cm below the streambed surface. We found significant differences between the predictive capacity of model covariates; upon comparison of global models to one another, we found that inclusion of the rate of fine sediment deposition and the stream dissolved oxygen were important components in predicting hyporheic dissolved oxygen during experimental sediment release events (Table 3) with models visualized with respect to the real-time nature of the model covariates (Figure 10).

Top models predicting the rates of hyporheic dissolved oxygen differed by dam operations. During normal fall drawdown dam operations, stream dissolved oxygen levels were the best predictor of hyporheic dissolved oxygen at 15 cm below the streambed surface. The inclusion of the organic component of the percent of fine sediment deposited in the second top model was found to have similar predictive capacity from an AICc approach. The third top model was comprised of the rate of fine sediment deposition and stream dissolved oxygen (Figure 10). During experimental sediment release events, the rate of fine sediment deposition was the best predictor of hyporheic dissolved oxygen at 15 cm below the streambed surface. The second and third top models included the rate of fine sediment deposition and stream dissolved oxygen, or the total suspended sediment concentration, respectively.

A general model predicting the hyporheic dissolved oxygen across all dam operations (experimental sediment releases and normal fall drawdown operations) indicated the rate of fine sediment deposition and stream dissolved oxygen were the best predictor of hyporheic dissolved oxygen at 15 cm. The second top model included the rate of fine sediment deposition while the third top models included discharge, the lagged component of LISST-ABS, stream dissolved oxygen and depth integrated suspended sediment concentration. Additional models evaluating the covariates of turbidity, discharge, or the combination of these two commonly monitored metrics, indicated these metrics have limited capacity to predict hyporheic dissolved oxygen during experimental sediment flushing events.

3.3 | Comparison of Approaches the Measure Sediment Releases from Dams

A Pearson correlation analysis of the explanatory variables used on the models above indicated many variables were highly correlated (> 0.70, Figure 11). The total depth integrated suspended sediment concentration samples were highly correlated with LISST-ABS (0.87), the rate of fine sediment deposition (0.85), and the sand fraction of the depth integrated suspended sediment concentration (0.92). The LISST-ABS data was also correlated with the sand fraction of the depth integrated suspended sediment concentration (0.79) and the rate of fine sediment deposition (0.82). Further, the rate of fine sediment deposition was highly correlated with discharge (0.73) and the sand fraction of the depth integrated suspended sediment concentration (0.77).

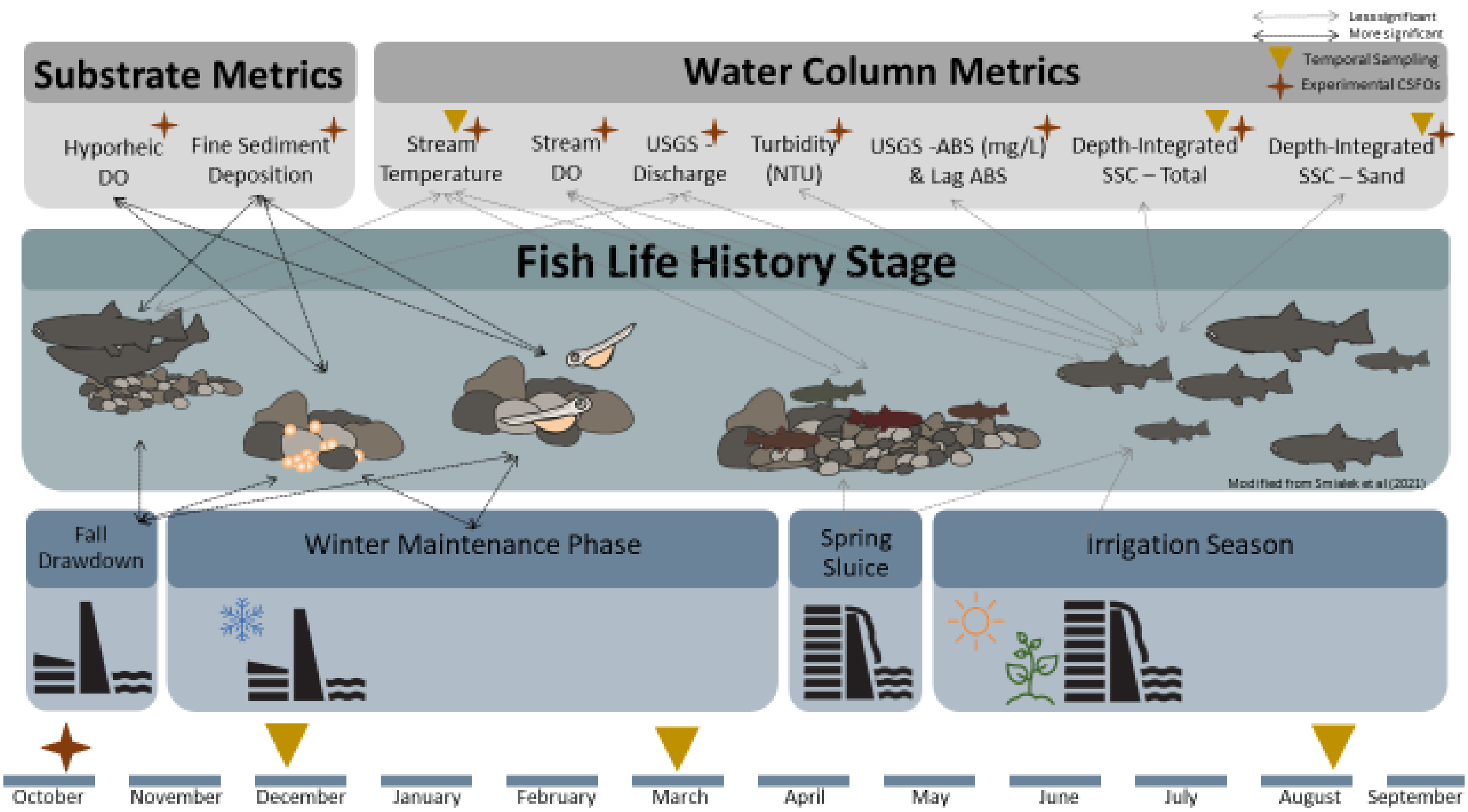
Hyporheic dissolved oxygen was strongly negatively correlated with the rate of fine sediment deposition (-0.83) and negatively correlated with many other variables including discharge (-0.67), LISST-ABS (-0.65), total depth-integrated suspended sediment concentration (-0.67), computed lagged LISST-ABS (-0.53) and the sand component of the depth integrated suspended sediment concentration (-0.56).

Turbidity was not highly correlated with any variables and was slightly negatively correlated with the lagged component of acoustic backscatter suspended sediment concentration (-0.21) and both hyporheic- and stream dissolved oxygen (-0.43 and -0.54, respectively). These correlation values indicate that there are alternative metrics that could provide similar water quality and hyporheic zone monitoring capabilities in exchange for an accepted decrease in predictive capacity.

4. Significance

Our research illuminates the direct and indirect influence of dam operations on downstream spawning habitat. We establish an important understanding of the effects of sediment mobilization from behind dams at different timescales and capture the direct influence of dam operations on spawning habitat using real time and near real time metrics. Our work demonstrates that both surface and subsurface channel substrates of the Shoshone River below Willwood Dam respond dramatically to changes in dam operations and modeling results indicates which metrics are most appropriate for predicting the associated changes in hyporheic dissolved oxygen and rates of fine sediment deposition, two critical environmental conditions for spawning fish and egg and embryo development. From an ecological perspective, this work also indicates that it is possible to both protect downstream aquatic life and meet the needs of dam operators through intentional sediment release events provided maximum suspended sediment thresholds are reflective of the downstream fishery and water column sediment conditions are monitored in real time.

Our work provides insight into temporal and spatial variability of effects associated with sediment release events and the potential for dam operators to minimize risks to downstream aquatic biota in real-time. We present the results of three years of spatiotemporal monitoring and provide more precise quantitative clarification of the impact of sediment release events on spawning habitat and downstream fisheries. Our research addresses several important components of managing sediment at dams with fisheries in mind. The models we provide here can be evaluated and customized to reflect the geological and biological components of the system and help managers developed effective sediment criteria and monitoring plans within their operational capacity. Importantly, we provide decision making tools to help inform managers of the biological effects of sediment flushing operations and provide evidence that dam operators can effectively minimize the effects of sediment flushing operations to protect downstream aquatic life.



Conceptual Diagram

Table 1. Environmental variable parameters, methods, data source and relevancy.

Sample Purpose	Parameter	Reporting Units (RU)	Sampling Methods / SOP	Sample Depth from Water Surface	Analytical method
Water Column Metrics					
Experimental CSFO	Dissolved Oxygen (DO, instantaneous, water column)	mg/L; % saturation	See SOP for *Dissolved Oxygen (DO)*	50% water depth	ASTM D 885-05 / SM 4500-O-G / EPA 360.1
Continuous	Temperature, Water (instantaneous)	ºC	See SOP for *Temperature, Water*	50% water depth	SM 2550-B
Experimental CSFO	Temperature, Water (continuous)	ºC	See SOP for *Temperature, Water* and *Temperature Logger Calibration and Placement - Wadeable Streams and Rivers*	150 cm above streambed	SM 2550-B
Experimental CSFO & Temporal Sampling	Suspended Sediment Concentration (depth-integrated)	mg/L	DH-48 isokinetic sampler, depth-integrated, single vertical (Edwards and Glysson, 1988)	Entire vertical profile	Filtration, Drying Oven and Volatile Solids (Dodge & Lambing, 2006; ASTM D 3977B); Sand-Fine Split (Dodge & Lambing, 2006; Guy, 1969)
Experimental CSFO & Temporal Sampling	Suspended Sediment Concentration (point-integrated)	mg/L	DH-48 isokinetic sampler, point-integrated (10%, 20%, 30%, 50%, 90% water depth) (Edwards and Glysson, 1988)	10%, 20%, 30%, 50%, 90% water depth	Filtration, Drying Oven and Volatile Solids (Dodge & Lambing, 2006; ASTM D 3977B); Sand-Fine Split (Dodge & Lambing, 2006; Guy, 1969)
Experimental CSFO	Time-integrated Suspended Sediment Concentration	mg/L	Walling Tube (Phillips et al, 2000)	Time integrated, continuous	Evaporation, Drying Oven and Volatile Solids (Dodge & Lambing, 2006; ASTM D 3977A); Sand-Fine Split (Dodge & Lambing, 2006; Guy, 1969)
Experimental CSFO & Temporal Sampling	Turbidity	NTU	See SOP for *Turbidity*	Grab	SM2130-B: Nephelometric Method (APHA, 1999)
Experimental CSFO	Turbidity (continuous)	NTU	OBS-3+ Campbell Scientific, per manufacture guidelines	Continuous, 15 cm above streambed	None, FM
Experimental CSFO	Water Depth, Total	m			N/A
Substrate Metrics					
Temporal Sampling	Freeze Core Substrate Composition	Phi scale	Sediment Substrate Freeze Cores (adapted from Stocker and Williams, 1972(Stocker & Dudley	Substrate, 100%	ASTM C136-01 Sieve Analysis of Fine and Coarse Aggregates

Sample Purpose	Parameter	Reporting Units (RU)	Sampling Methods / SOP	Sample Depth from Water Surface	Analytical method
Water Column Metrics					
			Williams, 1972)(Wolman, 1954)), liquid nitrogen		
Temporal Sampling	Pebble Count	N/A, Wentworth Scale	Modified Wolman Pebble Count (Wolman, 1954)	Substrate, 100%	None, FM
Experimental CSFO	Substrate Sediment Infiltration	mg	Sediment Infiltration Bags (adapted from Lisle & Eads, 1991)	Substrate	Evaporation, Drying Oven and Volatile Solids (Dodge & Lambing, 2006; ASTM D 3977A); Grain Size Analysis (Sediment Petrology Lab)
Experimental CSFO	Hyporheic Dissolved Oxygen (DO, instantaneous)	mg/L; % saturation	See SOP for *Dissolved Oxygen (DO)*	Designated intervals (0, 5, 10, 15, 20, 25, 30 cm below streambed)	ASTM D 885-05 / SM 4500-O-G / EPA 360.1

Table 2. Global model formulas for rate of fine sediment deposition and hyporheic dissolved oxygen.

Model	Global Model Formula
Rate of Fine Sediment Deposition (%)	ABS_SSC_mgL_USGS + Discharge_cfs_USGS + Turbidity_FNU_USGS + Lag_Discharge_cfs_USGS ,
	Sand_SSC_mgL + Discharge_cfs_USGS + Turbidity_FNU_USGS+ Lag_Discharge_cfs_USGS
	Total_SSC_mgL + Discharge_cfs_USGS + Turbidity_FNU_USGS + Lag_Discharge_cfs_USGS ,
	~ ABS_SSC_mgL_USGS + Discharge_cfs_USGS + Turbidity_FNU_USGS + Lag_ABS_SSC_mgL_USGS
	sed_load_metricTonDay + Lag_Sed_Load_metricTonDay
	sed_load_metricTonDay + Lag_ABS_SSC_mgL_USGS
	Discharge_cfs_USGS + Turbidity_FNU_USGS

Model	Global Model Formula
Hyporheic Dissolved Oxygen (mg/L)	FSD_Percent_Fines + Stream_DO_mgL
	FSD_Organic_Percent_Fines + Stream_DO_mgL
	Discharge_cfs_USGS + Lag_ABS_SSC_mgL_USGS + Total_SSC_mgL + Stream_DO_mgL
	Turbidity_FNU_USGS + Discharge_cfs_USGS

Table 3. Results from the most-supported multilinear regression models for the rates of fine sediment deposition and hyporheic dissolved oxygen including model structure, AICc, ΔAICc, weight and R2 values. Table includes three model categories including general models (all data averaged), non-sediment mobilization experimental CSFOs (fall 2020) and sediment mobilization experimental CSFOs (fall 2019).

Model	Model Structure	AICc	ΔAICc	wi	R^2
FSD Rate - General	Discharge + Lag ABS SSC + Total SSC	86.68	0.00	0.61	0.9371
	ABS SSC + Discharge + Lag ABS SSC	89.04	2.37	0.19	0.9321
	Discharge + Lag ABS SSC + Total SSC + Turbidity	89.34	2.67	0.16	0.9380
	ABS SSC + Discharge + Lag ABS SSC + Turbidity	92.14	5.47	0.04	0.9321
	Discharge + Sand SSC	102.33	15.65	0.00	0.8858
	Discharge + Lag Discharge + Sand SSC	104.41	17.74	0.00	0.8886
	ABS SSC + Discharge + Turbidity	105.04	18.36	0.00	0.8863
	Discharge + Sand SSC + Turbidity	105.05	18.37	0.00	0.8863
	ABS SSC + Discharge	105.82	19.14	0.00	0.8721
	Discharge	143.24	56.57	0.00	0.5343
	Discharge + Turbidity	145.61	58.93	0.00	0.5385
Model	**Model Structure**	**AICc**	**ΔAICc**	**w_i**	**R^2**
FSD Rate – Non-mobilization Events	ABS SSC	7.51	0.00	0.24	0.6787
	Sediment Load	7.54	0.04	0.24	0.6663
	Total SSC	9.42	1.92	0.09	0.7174
	Turbidity FNU	10.99	3.49	0.13	0.0600
	Discharge + Total SSC	11.57	4.06	0.03	0.8553
	Lag ABS SSC + Sediment Load	12.64	5.13	0.01	0.7263
	Lag Sediment Load + Sediment Load	12.64	5.13	0.01	0.7305
	ABS SSC + Lag ABS SSC	12.76	5.25	0.01	0.7262
	Discharge + Turbidity	13.24	5.73	0.04	0.5385
	Discharge	14.57	7.07	0.02	0.5343
Model	**Model Structure**	**AICc**	**ΔAICc**	**w_i**	**R^2**
FSD Rate – Sediment Mobilization Events	Discharge + Lag ABS SSC + Total SSC	68.97	0.00	0.25	0.9371
	ABS SSC + Discharge + Lag ABS SSC	70.26	1.29	0.13	0.9321
	ABS SSC + Discharge + Turbidty	70.86	1.90	0.19	0.8863
	ABS SSC + Turbidity	71.26	2.30	0.16	0.6809
	Discharge + Lag ABS SSC + Total SSC + Turbidity	72.19	3.22	0.05	0.9380
	Total SSC + Turbidity	72.64	3.67	0.08	0.7188
	ABS SSC + Lag ABS SSC + Turbidity	72.67	3.71	0.04	0.7563
	ABS SSC + Discharge + Turbidity	73.47	4.50	0.03	0.7122
	Turbidity FNU	98.12	29.16	0.00	0.0600
	Discharge + Turbidity	100.88	31.92	0.00	0.5385

Model	Model Structure	AICc	ΔAICc	w_i	R^2
Hyporheic DO - General	FSD + Stream DO	136.89	0.00	0.79	0.7374
	FSD	139.74	2.86	0.19	0.6863
	Discharge + Lag ABS SSC + Stream DO + Total SSC	146.36	9.48	0.01	0.7059
	Discharge + Lag ABS SSC + Total SSC	148.02	11.14	0.00	0.6570
	Discharge + Lag ABS SSC + Stream DO	148.07	11.18	0.00	0.6566
	Discharge + Lag ABS SSC	148.97	12.08	0.00	0.6123
	Lag ABS SSC + Stream DO + Total SSC	149.05	12.17	0.00	0.6455
	Discharge + Total SSC	149.36	12.47	0.00	0.6074
	Discharge	157.13	20.25	0.00	0.4504
	Discharge + Turbidity	158.09	21.20	0.00	0.4796
Model	**Model Structure**	**AICc**	**ΔAICc**	**w_i**	**R^2**
	Stream DO	26.59	0.00	0.75	0.8603

Hyporheic DO – Non-mobilization Events	FSD Organic + Stream DO	27.42	0.83	0.17	0.9167
	FSD + Stream DO	30.11	3.53	0.04	0.8909
	Stream DO + Total SSC	32.01	5.43	0.02	0.8681
	Discharge + Stream DO	32.47	5.88	0.01	0.8619
	Lag ABS SSC + Stream DO	32.59	6.00	0.01	0.8603
	Discharge	45.22	18.64	0.00	0.0995
	Turbidity	45.24	18.66	0.00	0.0976
Model	**Model Structure**	**AICc**	**ΔAICc**	**w_i**	**R^2**
Hyporheic DO – Sediment Mobilization Events	FSD	96.56	0.00	0.60	0.4397
	FSD + Stream DO	99.31	2.75	0.15	0.4486
	Total SSC	101.74	5.18	0.05	0.2829
	FSD Organic	102.86	6.30	0.03	0.2435
	Lag ABS SSC + Total SSC	102.98	6.42	0.02	0.3433
	Lag ABS SSC	103.15	6.59	0.02	0.2330
	FSD Organic + Stream DO	103.37	6.81	0.02	0.3309
	Turbidity	106.09	9.54	0.01	0.1176
	Discharge	108.26	11.71	0.00	0.0215
	Discharge + Turbidity	109.18	12.62	0.00	0.1177

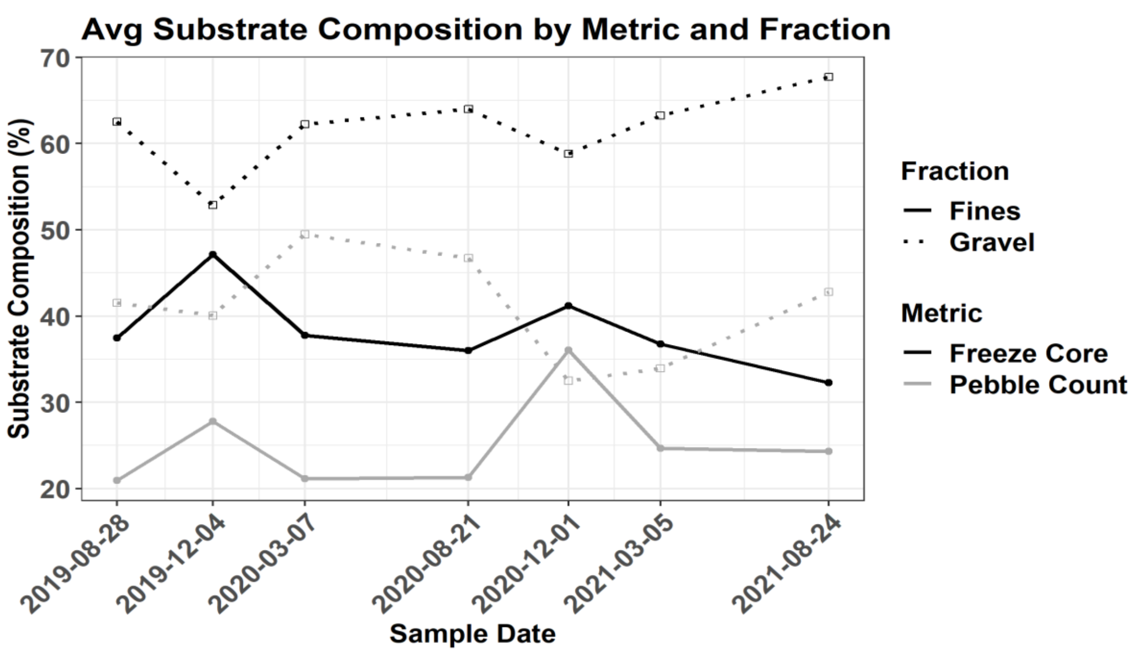


Figure 1. Temporal trends in mean percentages of fine sediment (<2 mm in diameter, solid line) and gravel (2 – 64 mm, dashed line) of streambed substrate, as measured by Freeze Core (black) samples, and streambed surface, and Wolman Pebble Counts (grey) across all sites. An increase in the percent fine material (<2 mm) was observed during the post drawdown sampling events (December). The proportion of fines in the streambed surface and substrate composition was similar for both metrics although the magnitudes differed with pebble counts indicating a lesser percentage of the substrate composition being derived from fine sediment (<2 mm).

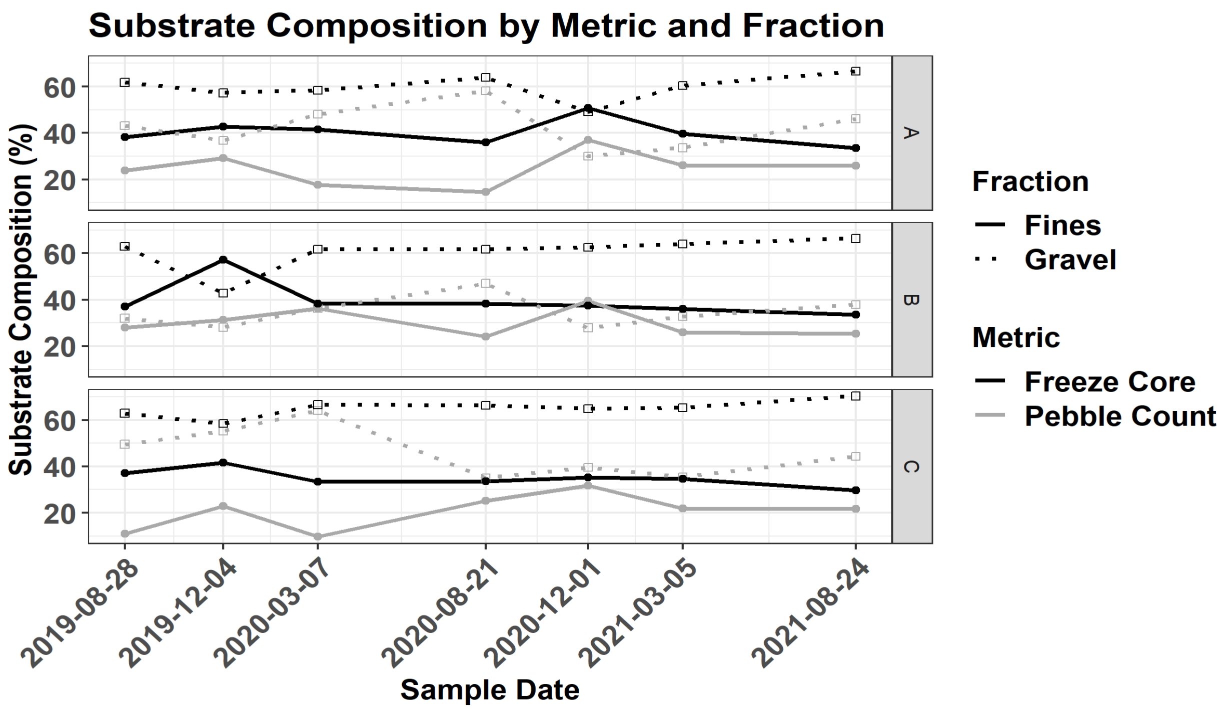


Figure 2. Temporal trends in the size composition of surface (pebble counts, grey) and subsurface (freeze cores, black) spawning habitat as represented by the percentages of fine sediment (<2 mm in diameter, solid line) and gravel (2 – 64 mm, dashed line) of streambed substrate at three sampling sites. An increase in the percent fine material (<2 mm) was observed during the post drawdown sampling events (December) across all sites, but more pronounced at Site A. The proportion of fines in the streambed surface and substrate composition was similar for both sample metrics although the magnitudes differed with pebble counts indicating a lesser percentage of the substrate composition being derived from fine material (<2 mm).

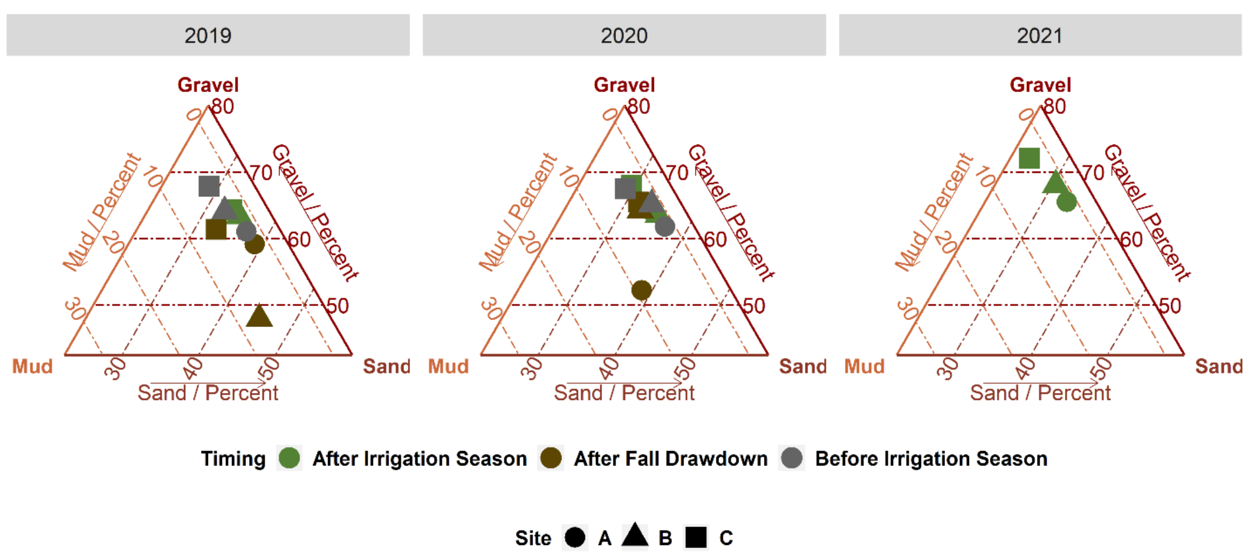


Figure 3. Ternary plot indicating the composition of the freeze core substrate samples by temporal sampling event timing. The proximity of the symbols to the apex of the triangle is proportional to the averaged potential contribution of each composition size class of the freeze core sample including mud (bottom left), sand (bottom right) and gravel (top). Sample location is represented by the following shape: circle = Site A, triangle = Site B, square = Site C. Timing of sampling event is represented by the following colors: green = after irrigation season (August), brown = after fall drawdown period (December), and grey = after winter maintenance phase and prior to next irrigation season (March).

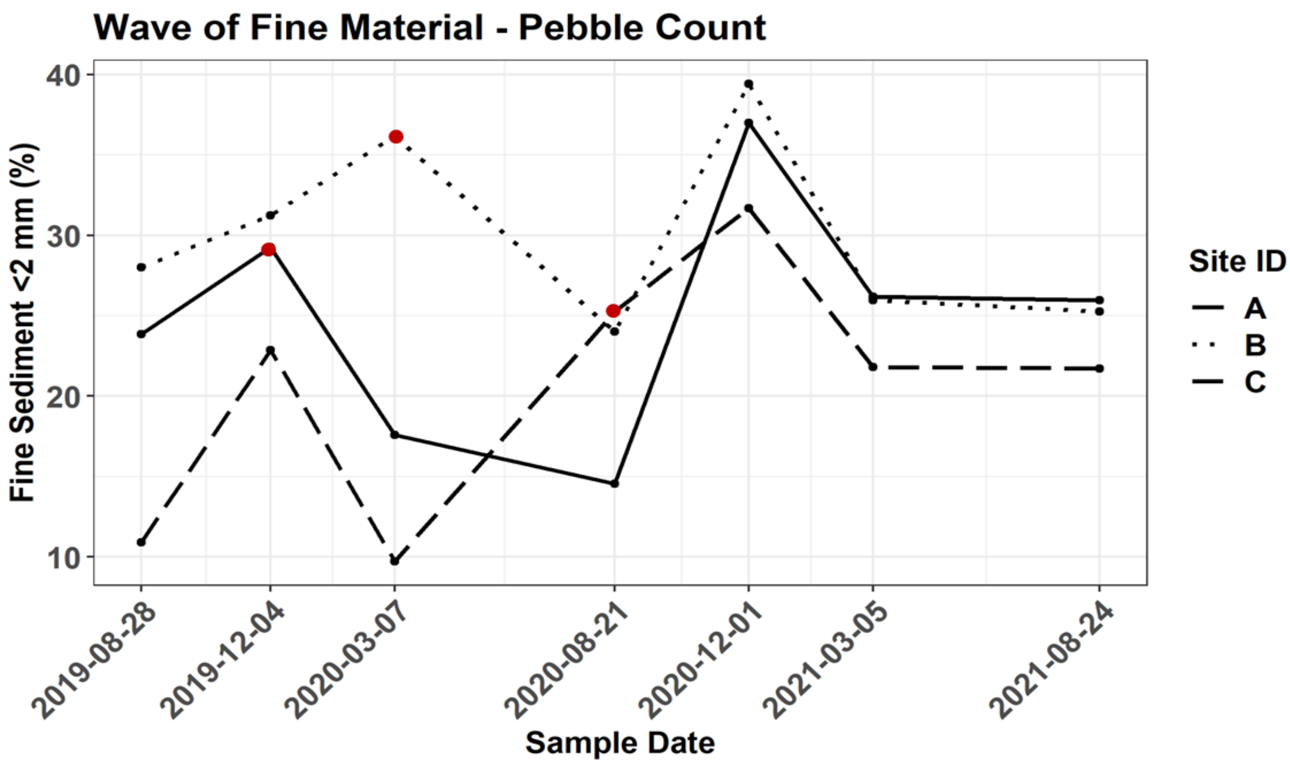


Figure 4. Temporal trends in the percentage of fine sediment (<2 mm) on the substrate surface as observed by pebble counts across all sites (A = sold line, B = small dash line, C = large dash line). An increase in the percentage of fine sediment present at Site A after the sediment mobilization experimental CSFOs was observed to be moving downstream over the next two sampling periods (red points) described in table below.
The percent fine sediment observed is indicated in each row followed by change in percent fine sediment in parentheses. Red text highlights the positive increase in the percent of fine material observed on the streambed surface corresponding to the ‘wave’ of fine sediment moving downstream. This is supported by the subsequent decrease in the percentage of fine sediment in the subsequent sampling event.

	8/28/2019	**12/4/2019**	**3/7/2020**	**8/21/2020**
Site A	23.85%	29.25% (**+5.39%**)	17.59% (-11.65%)	14.56% (-3.03%)
Site B	28.00%	31.25% (+3.25%)	36.19% (**+4.94%**)	24.00% (-12.19%)
Site C	10.89%	22.86% (+11.97%)	9.71% (-13.15%)	25.24% (**+15.53%**)

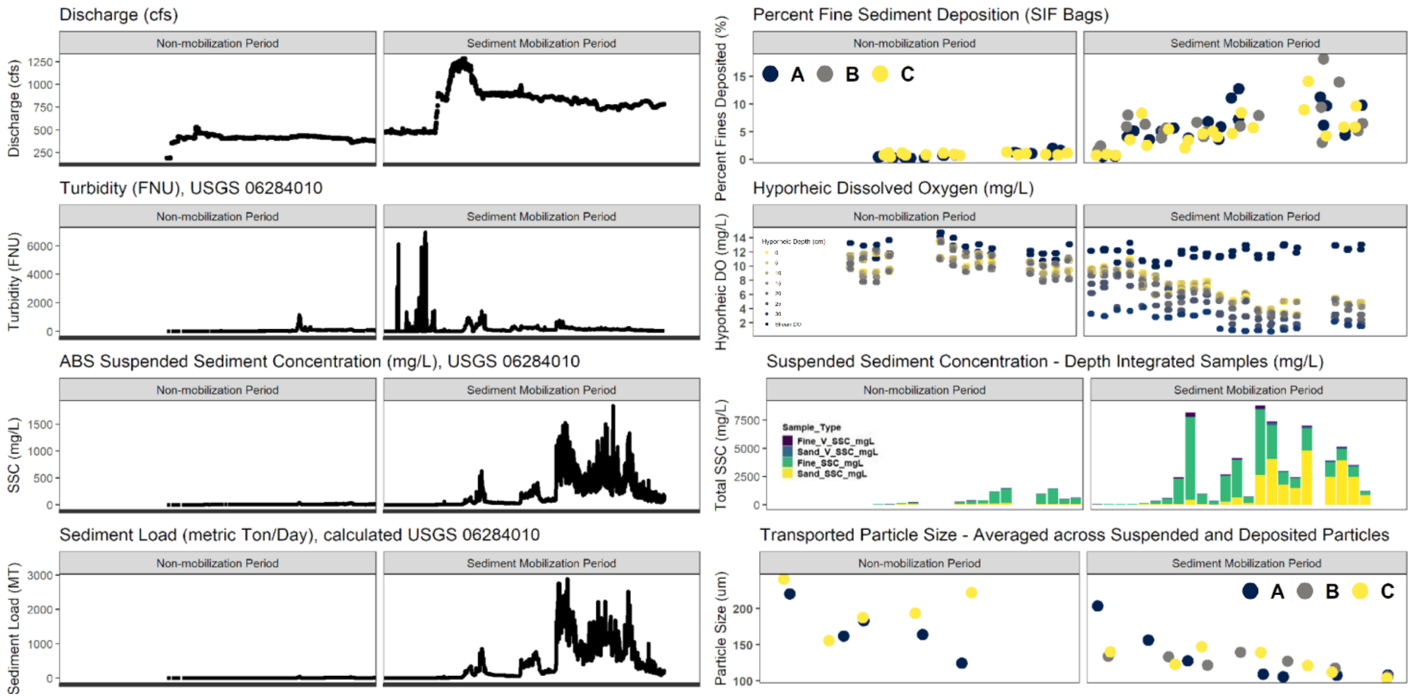


Figure 5. Environmental time series by experiment controlled sediment flushing operation including experimental controlled sediment flushing operations with low sediment loads (non-mobilization periods, 2020 fall drawdown period) and high sediment loads (sediment mobilization periods, 2019 fall drawdown period).

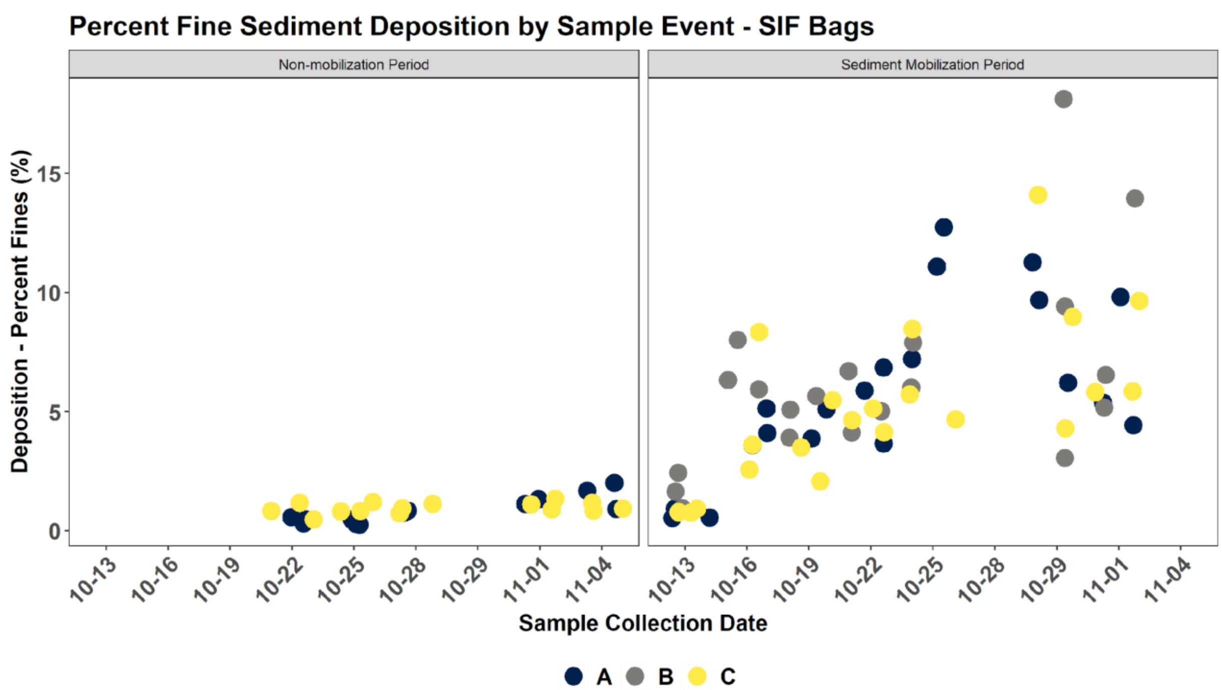


Figure 6. Average percent fine material (<2 mm) deposited in sediment infiltration bag samples by site (n = 3/site). Colors represent site as follows: blue = Site A, grey = Site B, yellow = Site C. Panels reflect non-sediment mobilization experiment CSFOs (left, 2020 fall drawdown period) and sediment mobilization experimental CSFOs (right, 2019 fall drawdown period).

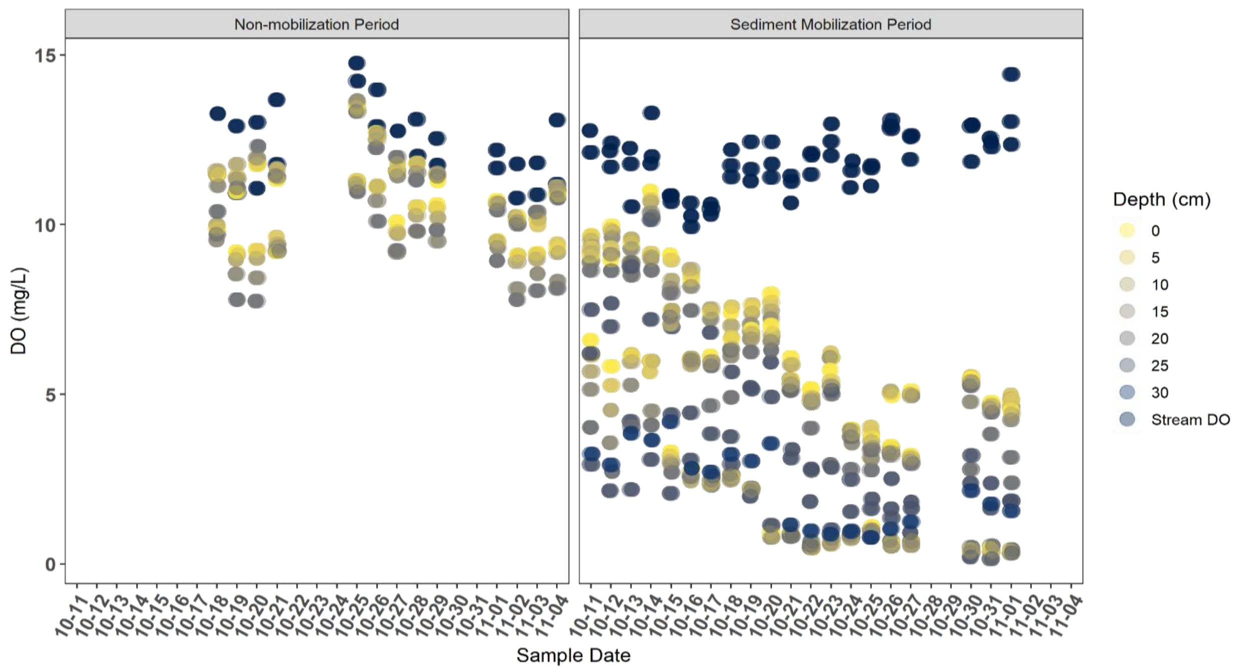


Figure 7. Average hyporheic dissolved oxygen (mg/L) observed in standpipes (n = 5/site) during non-sediment mobilization experimental CSFOs (fall 2020) and sediment mobilization experimental CSFOs (fall 2019 drawdown) averaged across. Color represents the hyporheic depth below the streambed surface (surface = yellow to 30 cm = dark blue) with stream dissolved oxygen represented in the darkest color.

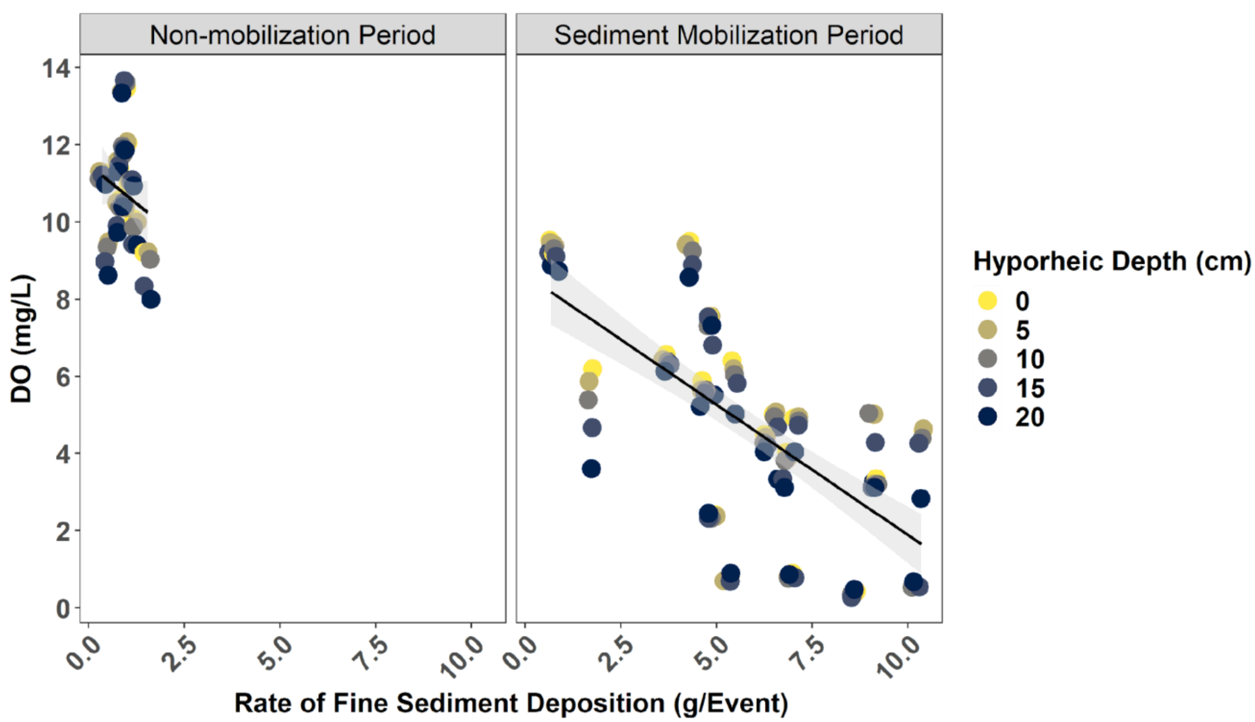


Figure 8. Relationship between hyporheic dissolved oxygen (mg/L) and rate of fine sediment deposition (grams/sampling event) by hyporheic depth. Color represents the hyporheic depth from surface (yellow) to 30 cm below streambed surface (dark blue). Panels representing sampling from experimental controlled sediment flushing operations during low sediment load conditions (left, non-mobilization period) and large sediment load conditions (right, sediment mobilization period).

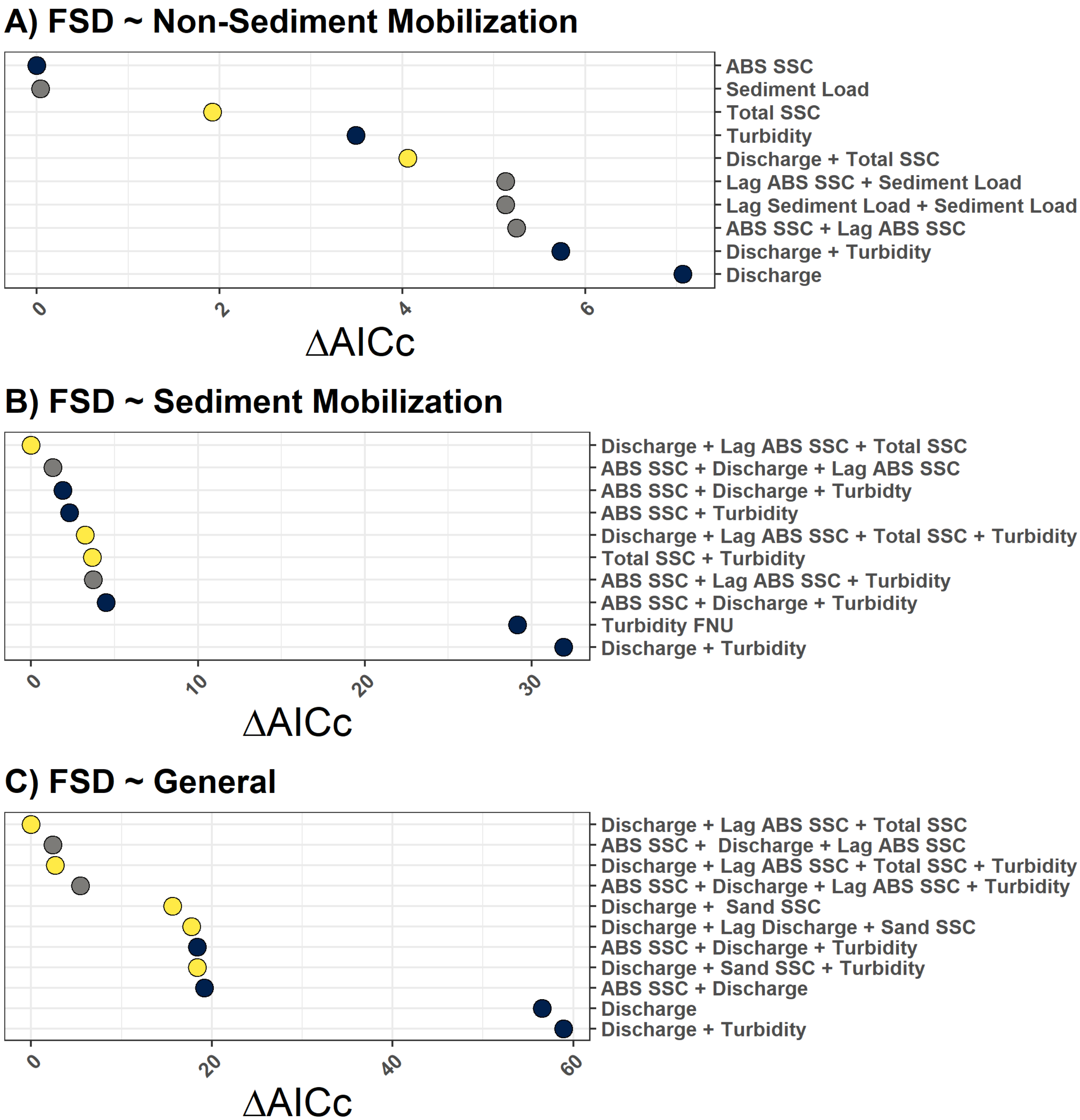


Figure 9. Top multilinear regression model results by AICc for rate of fine sediment deposition (%) including A) general models (all data combined), B) rate of fine sediment deposition during low sediment load experimental controllsed sediment flushing operations (non-mobilization period), and C) rate of fine sediment deposition during high sediment load experimental controllsed sediment flushing operations (sediment mobilization period). Color represents data availability including: blue = real time availability, grey = near real time (i.e. computed lagged value) and yellow = physical sample required. Model results for covatiates of discharge and turbidity are included for comparison.

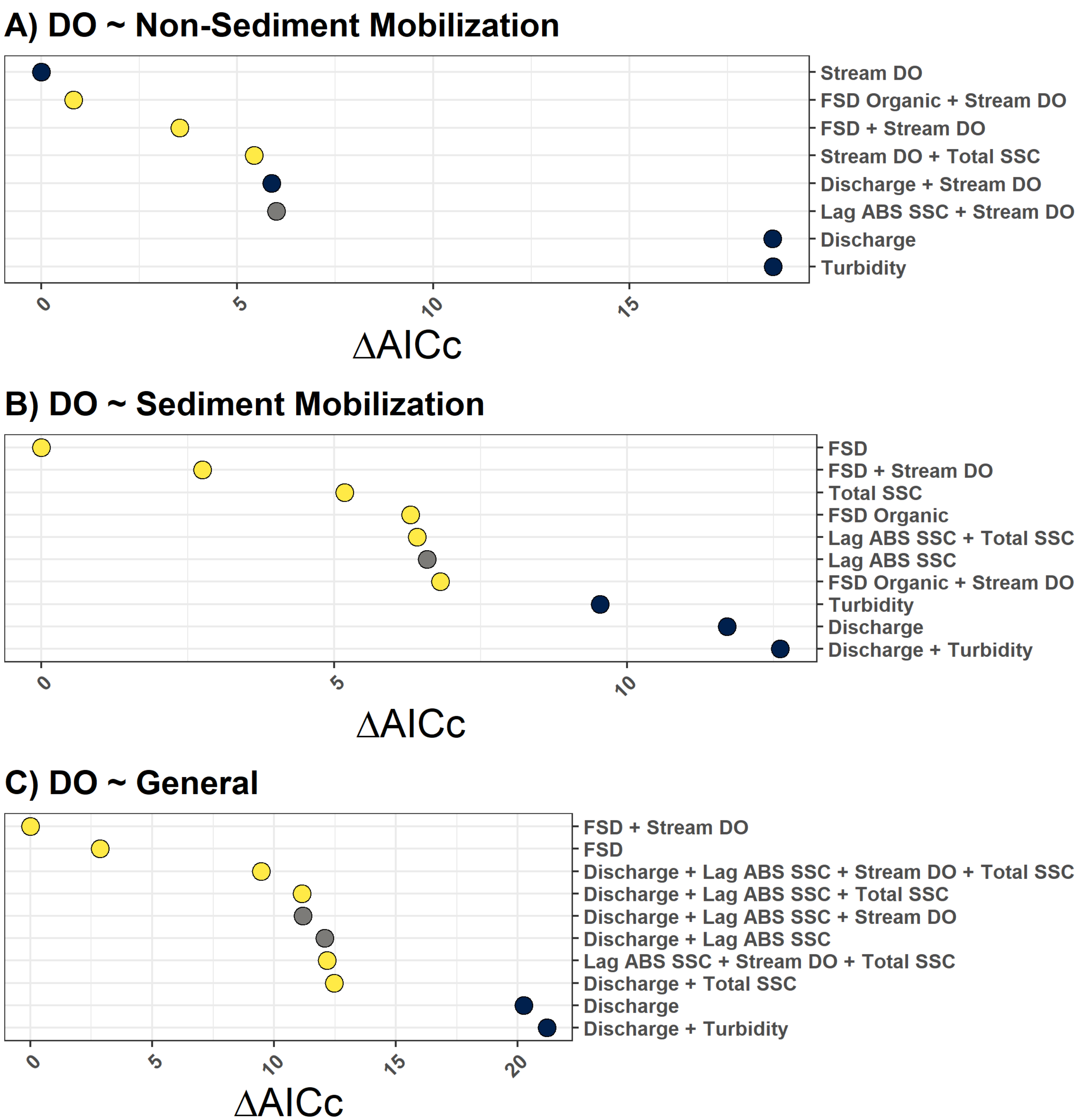


Figure 10. Top multilinear regression model results by AICc for hyporheic dissolved oxygen (mg/L) including A) general models (all data combined), B) hyporheic dissolved oxygen during high sediment load experimental controllsed sediment flushing operations (sediment mobilization period), and C) hyporheic dissolved oxygen during low sediment load experimental controlled sediment flushing operations (non-mobilization period). Color represents data availability including: blue = real time availability, grey = near real time (i.e. computed lagged value) and yellow = physical sample required. Model results for covatiates of discharge and turbidity are included for comparison.

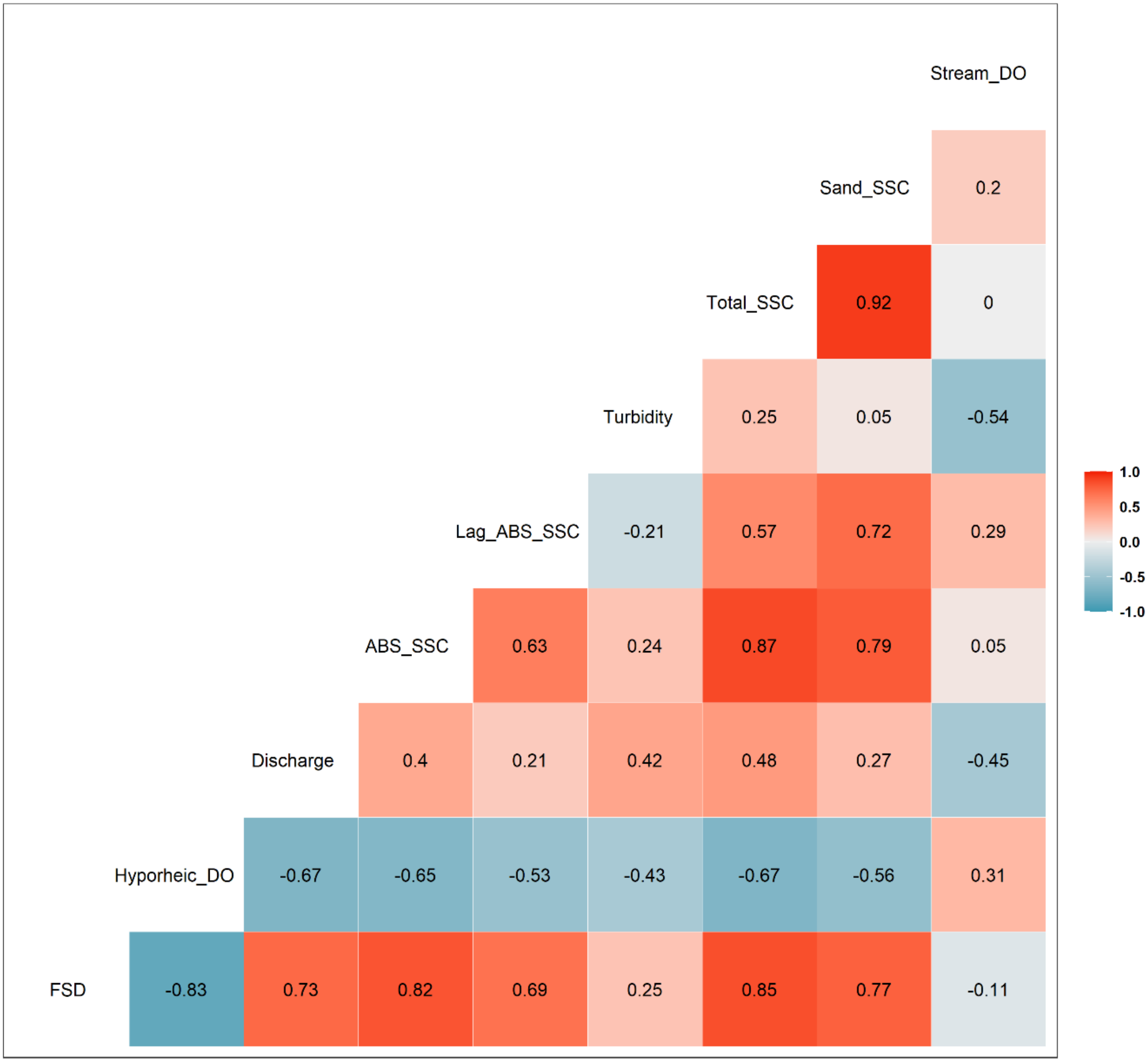


Figure 11. Pearson correlation results between environmental variables observed during experimental controlled sediment flushing operations. Numbers represent coefficient values and color indicates positive (red) and negative (blue) correlation values.

References

Helsel, D. R., R. M. Hirsch, K. R. Ryberg, S. A. Archfield, and E. J. Gilroy. 2020. Statistical methods in water resources: U.S. Geological Survey Techniques and Methods. Page chapter A3, 458 p book 4. U.S. Geological Survey.

Newcombe, C. P., and J. O. T. Jensen. 1996. Channel Suspended Sediment and Fisheries: A Synthesis for Quantitative Assessment of Risk and Impact. North American Journal of Fisheries Management 16(4):693–727. Wiley.

R Core Team. 2022. R: A Language and Environment for Statistical Computing. Vienna, Austria.

Rohatgi, A. 2020. WebPlotDigitizer (Version 4.3).