Grand Canyon Monitoring and Research Center

Sediment Transport Modeling Review Workshop

Review Panel Report

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U.S. Geological Survey Field Center
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FINAL REPORT OF THE EXTERNAL REVIEW PANEL, SEDIMENT TRANSPORT MODELING REVIEW WORKSHOP

WORKSHOP DATES: February 15–16, 2007

MEETING LOCATION: USGS Pacific Science Center, 400 Natural Bridges Drive, Santa Cruz, CA 95060

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1. OVERVIEW

Construction of Glen Canyon Dam in 1963 has resulted in drastic reduction of sediment supply to the Colorado River ecosystem (CRE) in Glen Canyon National Recreation Area and Grand Canyon National Park (GC). The ensuing sediment-depleted regulated flows affected many of the natural resources vital to the riparian ecosystem. Of particular concern in this report is the substantial erosion of sand bars and sandy beach habitat that has taken place throughout Grand Canyon (Wright and others, 2005).

The Glen Canyon Environmental Studies (GCES) were established in 1982 in order to determine the long-term impact of river regulation on the CRE. The GCES was the precursor to the present Grand Canyon Monitoring and Research Center (GCMRC) which serves as the science provider to the Glen Canyon Dam Adaptive Management Program (GCDAMP), a Federally chartered advisory committee to the Secretary of the Department of the Interior. One of the most important and unanswered strategic science questions facing the GCDAMP is if there is "a 'Flow-Only' operation (non sediment augmentation) that will rebuild and maintain sandbar habitats over decadal time scales" (Wright 2007, Melis and others, 2007; Melis and others, 2006). In 2006, the Protocols Evaluation Panel (PEP-SEDS III) convened in Flagstaff, AZ, as part of an ongoing peer review of the monitoring and research efforts carried out by the GCMRC (Wohl and others, 2006). PEP-SEDS III was charged with appraising current research activities and long-term monitoring of physical resources below Glen Canyon Dam, and to provide recommendations for future work.

As a result and follow-up of the part of the PEP-SEDS III recommendations related to the modeling program, the GCMRC organized a Sediment Transport Modeling Review Workshop in February 2007. This report summarizes the recommendations of the review panel assembled for the workshop concerning four aspects of the GCMRC's sediment modeling program: the coarse sediment modeling program, the fine sediment modeling program, the multi-dimensional modeling efforts, and the sandbar stability modeling program. In particular, the panel is charged to provide recommendations "toward developing a modeling approach for simulating the fate of sandbars over decadal time scales for various dam operational scenarios" (Wright, 2007).

2. OVERALL RESEARCH PROGRAM

A clear statement of the research objectives, anticipated products, and required data and models should be formulated to guide the research and ensure that all of the components are well integrated. This panel reaffirms the PEP-SEDS III panel recommendation (Wohl and others, 2006) for the development of a unified vision for the overall research program that incorporates the different research components and that places them within the broader scope of the physical resources program..

3. COARSE SEDIMENT TRANSPORT MODELING PROGRAM

The geomorphology of the CRE in the GC is generally dominated by the coarse sediment (cobbles and boulders), and particularly by the debris fans originated at distinct points along the steep topography encircling the river corridor (Melis, 1997). These dominant geomorphic features define the step-eddy-pool morphology in the CRE that controls fine sediment (principally sand) distribution and storage. The coarse sediment modeling program is, therefore, a tool to investigate the long-term evolution of the CRE longitudinal profile.

Preliminary Studies

The current coarse sediment transport program, as presented by Chris Magirl, has depended on one-dimensional (1D) GSTARS and HEC models and calibrated cross sections (i.e., cross section profiles that were adjusted to provide agreement between simulated and measured backwater profiles). The channel roughness – represented by a Manning's *n* – was maintained constant during this approach. This is contrary to the normal practice of calibrating models in which the best estimate or interpolation of the cross-section is obtained and then the roughness used as the calibration coefficient. However the approach by Dr. Magirl was adopted because the roughness at the reach scale was expected to show little variation and the entire bathymetry was based on just a few cross-sections that were available at the time this modeling was conducted.

This program is focused on the fate of coarse sediment in the Colorado River, where "coarse" refers to cobbles and larger-sized particles. For this purpose, the current research efforts to refine and build upon past accomplishments and knowledge discovery should continue. The objective of the coarse-sediment modeling is to improve our understanding of how the river evolves in response to delivery and transport of debris fans. The model could be used as a management tool to investigate "what-if" scenarios involving new debris fans; the magnitude and duration of effects on river navigation and resources associated with postulated new debris fans could help in formulating management responses. It is also envisaged that the program yields tools for predicting the hydraulics of the rapid and pool system (e.g., how the hydraulic controls modify with different flood conditions), and the response of geomorphic features controlled by coarse sediments to synthetic (man-made) floods.

The 1D flow modeling program appears to have reached a stage in which it could continue to be refined and better calibrated, but it is unlikely that there will be any significant new developments. There is the question of whether there is an advantage in using a full unsteady model (such as the one of Wiele and Smith, 1996) instead of the step backwater model used so far, but this point is not critical for the questions addressed to date. Instead, it is more important to broaden the scope of the program to include more detailed modeling to the smaller scales, i.e., multi-dimensional modeling around individual debris fans.

In addition to the previous studies of Dr. Magirl, some future application of the one-dimensional model might include:

- Simulation of flood wave propagation through the entire canyon;
- Setting local boundary conditions for local higher order models of sub-reaches or specific features of concern; and

- Water quality and temperature modeling through the entire Canyon or as boundary conditions for local models.

Mobility of Very Large Particles and Influence on Local Bed Conditions

The science plan to determine the mobility of very large particles under different hydraulic conditions should continue. The current state-of-the-art of sediment transport modeling has very limited information about the transport of large boulders, and usually that information pertains only to rip-rap stability, rather than to rates of transport. This work should be expanded and applied in the future to include modeling the wear, abrasion, and communition of very large particles because the slow degradation of very large particles (or lack of it) will affect the long-term evolution of river morphology. Further investigations are also warranted to determine the effect of these very large particles on local transport of adjacent large particles. In particular, it would be important to understand under what conditions these very large roughness elements act to recruit other large and intermediate particles and when the local flow field acts to repel or transport intermediate particles.

Debris Fans

The data collection of flow and turbulence near debris fans should also continue. This data is needed to understand the flow characteristics near areas where strong turbulence is generated and/or dissipated—e.g. relations between velocity, depth, roughness and channel geometry. Turbulence has a direct impact on sediment resuspension and transport, which constitutes necessary information for the fine sediment transport modeling program. Particle Image Velocimetry (PIV) is a technique that could perhaps provide good flow estimates in the CR and should be considered in the current research program. This issue has important management implications. Following a tributary 'blow-out', how long will an alluvial fan persist under certain flow conditions and is intervention necessary to avoid unacceptable risks to life? Both the large particle mobility and flow and turbulence measurement programs should be designed to gather information required to develop a multidimensional model of debris fan creation and subsequent long-term response. This effort should be coordinated with the fine sediment and multi-dimensional programs described next.

Summary

For the objectives of the coarse modeling study, the adopted approach has served a useful purpose. The model was developed during a time of poor spatial coverage of channel bathymetry. The two primary calibration parameters used were Manning's *n* (the roughness) and channel cross-section. In this application the Manning's *n* was held constant and the channel area varied to match water surface profiles. The problem associated with varying the area rather than *n* is that it is difficult to use the model in a predictive mode at discharges other than the calibrated conditions. Experience in the CRE and other systems allow rough estimates of how the resistance will vary at different discharges and this relationship can be calibrated with water surface elevation surveys or velocity profiles. Technologies have improved rapidly in the past few years so that it is now possible to obtain detailed bathymetric data (a complete coverage of the GC bathymetry is expected in the coming months). Further, the technologies will be available to measure typical roughness elements allowing more accurate representation of spatial variation in resistance. Thus further refinement of this model should be considered using channel bathymetric surveys and in the light of the integrated modeling framework described in Section 7.

4. FINE SEDIMENT TRANSPORT MODELING PROGRAM

An Innovative and Experimental Approach

Recent fine sediment modeling efforts by the GCMRC comprise the work of Wiele and others (2007, hereinafter WWG). The objective of the WWG model is to provide a practical management tool to allow the Bureau of Reclamation to design future artificial floods with a goal of maximizing bar creation. This initiative started with a conceptual model that identified a framework of the primary processes that influence the transport and deposition of fine sediment in a sediment depleted system. The review committee recognized the value of this approach and it is intended by WWG that the algorithm for each of these processes could be refined or calibrated as more field data becomes available in future years.

From a management perspective a 1D model may be the most feasible and practical approach. The WWG model uses a simple 1D reach-averaged description of the river processes, but includes several novel components. These are 1) the influence of coarse particles on interstitial and bed sand storage; 2) adjustment of near-bed suspended-sand concentrations when sand transport occurs over a boulder bed; 3) provision for sand storage in eddy deposits and parameterization of the exchange of sand between eddy deposits and the main channel; and 4) a characterization of channel geometry that incorporates reach-averaged properties, including the distribution of pools. In this approach, pools are defined as sub-reaches with depths more than a standard deviation greater than the mean depth. Efforts to calibrate the model using the 2004 beach habitat building flow (BHBF) test data were also reported by Scott Wright.

The relative simplicity of the WWG model makes it easy to evaluate model response to varying inputs and model sensitivity to varying coefficients. In this way, it is a tool for understanding the sand storage response to fluctuations in water and sediment supply. A disadvantage to this simplified approach is that at least some of the model coefficients must be set by empirical calibration with a (limited) data set (rather than being set by theory, laboratory data, or detailed modeling). This means that the model, in its present formulation, is best used as a diagnostic tool that identifies the relative importance of different processes. Currently, it does not have reliable predictive capability beyond the range of calibration experience. The recent calibration efforts by Scott Wright indicate that the WWG model can be tuned to match some observational data, but his best results were achieved with unrealistically high values for the bed roughness coefficient. These high values are not surprising because they indicate that the model lumps several physical processes into the roughness coefficient and the high value compensates for the over-simplified 1D and reach-averaged assumptions.

We view the present version of the WWG model as a proof of concept: it indicates that the parameterizations of sand storage in a boulder bed and sand storage in eddy deposits are useful and provide reasonable results in the context of a simplified model domain. Future research should be directed toward evaluating and improving the model. A few suggestions are provided below.

Next Steps

Sensitivity studies should be performed, and the calibration effort should be continued. Tests should be performed with the calibrated model and objective measures of the model performance should be developed using data that were not used for calibration, such as the 1996 controlled flood test (first test of the BHBF concept) and the 1965 channel cleaning flow release. These performance measures should be established from the perspective of the appropriate accuracy to address the questions being posed by the managers of the CRE.

The most essential and easily attained model improvement is to continue and complete the calibration of the model and validate each of the conceptual components. A one-dimensional model contains many assumptions so accurate specification of physical parameters does not necessarily result in accurate results. Thus, calibration is essential and the GCES Program is blessed with a wealth of data for calibration and validation. The pool geometries used in the model should be considered in the calibration process because these seem to be the least certain component. Validation provides a measure of the confidence that can be placed in the predictive ability of the model and demonstrates the uncertainty of the model to scientists and managers. This is a necessary step in developing management decisions that depend on model predictions.

Another relatively easy and fast way to improve the WWG model is to refine the reaches and to use a more accurate and detailed description of the eddy systems along the river. This work only involves the refinement of the statistical analysis presented in WWG and would require no re-programming of the code (no reparameterization of the eddy systems are required at this stage).

A further refinement of the fine sediment modeling program might be achieved by abandoning the reach-averaging approach of the WWG model and adopting a 1D model with shorter reaches and more detailed cross sections—similar to the approach followed by the coarse sediment program. At the earliest stage of this process, the pool and eddy storage approach would remain similar to that of the WWG model. A further step to this effort, which this review panel recommends, is to better integrate the fine and coarse sediment programs. It seems that the coarse modeling efforts run parallel to the fine sediment modeling efforts and there are no attempts to integrate both programs (i.e., the presentations by Chris Magirl and Peter Wilcock had no intersection or cross-referencing).

Finally, there is the need to evaluate the algorithms that model the pool and eddy storage/scour processes. The present algorithms in WWG were derived using a 2D, single particle-size model. However, recent research indicates that sorting and gradation in a sand bar are important factors for long term simulation. Furthermore, there is no strong evidence that a 2D model is sufficient to capture accurately the sand exchange processes of interest—i.e., there is no definitive study that indicates what level of model dimensionality and complexity is necessary for these circumstances.

Evaluation of the WWG sand exchange algorithms can be accomplished by the use of laboratory experiments, field monitoring campaigns that target the flow structure and sediment transport, and/or by using multi-dimensional models that accurately capture the physics of the processes—such as followed by WWG. The use of multi-dimensional models for this purpose is addressed in the next section.

5. MULTI-DIMENSIONAL MODELING

Within the scope of the present workshop review meeting, the primary motivation for a multi-dimensional modeling plan stems from the need to validate and improve the WWG model. Of particular concern is the algorithmic approach followed to describe the interaction between the conveyance of sediment by the river's main channel and the role played by the eddy and pool systems in sediment storage. WWG used a 2D model to reach the current form of the parameters used by the algorithms. Unfortunately, the degree of complexity needed by a model to capture, with sufficient accuracy, the processes incorporated in WWG is unknown. Therefore there is no evidence that a 2D depth-averaged model is adequate for the task.

The panel recommends that an evaluation of 2D, pseudo-3D and 3D models, using single and multiple grain-sizes, be conducted in order to determine a suitable computational platform to carry out simulations of eddy/bar sediment exchange under different hydraulic conditions. Rather than developing new models, the emphasis should be placed into existing models, especially those that are easily accessible by the GCMRC and that have good technical support. During this evaluation it is suggested that nesting of models or other approaches that will allow extensive reaches to be simulated, but with local fine mesh resolution capturing one or two eddy features. This approach would allow guidance for the grid size necessary to simulate the exchange between the main flow and eddies, as well as the magnitude of expected errors in the coarser grid.

A critical issue is the availability of appropriate experimental data for the purpose at hand. Existing data sets must be re-evaluated to determine if they are appropriate for multi-dimensional model validation. Additional field work and laboratory experiments may have to be undertaken. Consideration should be given to classifying the typical sand bars and selecting a series of test sites that cover the range of bar types (perhaps 3 or 4 sites) rather than all 10 considered by WWG. These sand bar/eddy complex sites could then be instrumented under different hydraulic conditions. Measurement stations would be set above and below an eddy/bar complex specially chosen for the experiment, allowing a detailed local mass balance to be performed. Specifically the key assumptions of the conceptual model should be verified. As an example, one important assumption is that the eddies scour on the rising limb of the hydrograph, whereas eddy deposition occurs on a more continuous basis (section 2.4 of WWG). This should be proven with field data to ensure that the significant changes in pool morphology do not occur on a more episodic basis.

The GCMRC, however, should not leap too quickly into a new data collection campaign without a detailed assessment of the existing database. Prior to collecting new eddy data, a multi-dimensional model should be used to perform some initial simulations that would be used to help design a measurement study. The collected data would then be used to refine the model.

Finally, multi-dimensional modeling activities have been undertaken by GCMRC, but they have been limited mostly to two-dimensional models, such as the one of Wiele and others (1996). Current multi-dimensional modeling efforts using a three-dimensional model with large eddy simulation (LES) turbulence was presented by Mark Schmeeckle. 3D LES modeling has the potential to provide numerical simulations with the finest degree of detail that is currently practical—and possible—for the flows and channel dimensions in the GC. Current efforts should continue, perhaps with emphasis to bring down computational cost (i.e. CPU time) using techniques such as parallelization of the code. Also, what are the differences between the code being developed and other existing codes? Is a new code needed? Is the cost/benefit ratio best served by a new code or by application of an existing code? One possible way forward is to collect the field data and then invite different modeling teams to simulate the bar building and erosion process. The purpose would not be to select the perfect model, but rather to develop a community dialogue and evaluate the importance of different processes that are or are not captured in the algorithms. This would then facilitate improvement of the transfer functions in WWG.

6. SANDBAR STABILITY

The emphasis of the GCMRC program has been on bar building with less effort placed on bar erosion and flow management to preserve built bars. It is unclear what the relative contribution of bank caving and subsequent mass slumping is in the overall sand bar erosion process. In order to provide accurate predictions of sand bar losses and long term forecast of sand storage, the importance of this erosion mechanism in the GC system must be better understood. Methods of approach to achieve this goal are *in situ* measurements, laboratory experiments, and numerical modeling. Local measurements have the potential to provide the most relevant data and should be pursued when possible.

Past difficulties encountered when instrumenting sand bars during high releases from the Glen Canyon Dam indicate that obtaining data during future BHBF tests may be difficult. However, this panel recommends that the subject be revisited by the GCMRC, at least from a feasibility point of view. A suitable and representative sand bar should be identified for instrument placement, and data should be collected at different discharges. The particular data of interest here concerns the slumping of sand due to bank collapse, modes of failure, and relative importance of mass wasting (due to bank caving) when compared to basal toe erosion. However, the collection of this type of data should be coordinated and synchronized with the other data collection efforts suggested in previous parts of this report.

The numerical modeling efforts, currently represented by the work of Brent Travis and Mark Schmeeckle of Arizona State University showed considerable promise and should continue. This work may provide the answer sought, but it must be further refined and validated using experimental data. Laboratory experiments may have to be performed to support the numerical modeling program. Future model development should be focused into two aspects. The first is to be able to answer the question whether or not erosion due to bank failure is a significant process when compared to toe scour. The second, if it is determined that bank failure is important, is then to provide a quantitative way to predict bank erosion for different BHBF tests (i.e., different discharges and flow ramping profiles). In the second stage of the work, attention must be given to the integration of the bank model with the other sediment transport modeling efforts sponsored by the GCMRC.

Before the present modeling work of Travis and Schmeeckle is adopted as part of the science program for bank erosion and channel morphological evolution prediction, it must be placed within the current state-of-the-science. There is extensive work on bank erosion processes—including geotechnical failure, interaction with water table level variations and with vegetation, cohesive sediment effects, etc.—and it is unclear if new models are needed. There must be a concerted effort to review existing models and assess their suitability for application to the conditions in the GC. Before potentially investing in the development of new models, a process that is expensive and takes a long time, a solid justification that new software is needed must be made.

7. MODEL INTEGRATION

The research team has identified numerous sediment issues and developed a suite of models to further the fundamental understanding of sediment processes through Grand Canyon and to assist in management decisions. In the future, there will undoubtedly be other geomorphic and sediment questions that have not been considered yet. It is recommended that some thought is given to an integrated modeling system that would be flexible and allow researchers and scientists to support the GCMRC efforts over the coming decade that would have flexibility for different models or new algorithm development within existing models. Clearly major steps have already been made in establishing databases and GIS coverage. However, it was unclear how the various models might be developed to interface and enhance one another in the future. One possible structure of an integrated modeling system is:

1. Include tributary/alluvial fan inputs;

2. Set-up a one-dimensional model of the entire reach. The objectives are, among others, to evaluate large scale channel controls, to determine the possible migration of channel controls and to provide sediment inflow and hydrodynamic boundary conditions for more detailed local models. This model could also be used to help address other concerns that include aquatic habitat, temperature and water quality;

3. Incorporate the reach-averaged sediment model described in section 4 above.

4. Set-up detailed 3-d or pseudo 3-d models of specific features of interest, such as bar-pool-eddy combinations.

This model structure could be integrated with data and information flow between the different scales. For example, item #4 could lead to improvements of item #3, item #1 improves item #2, item #2 would set boundary conditions for items #3 and 4, etc.

8. CONCLUDING REMARKS

One of the most important and unanswered strategic science questions facing the GCDAMP is:

> *Will any 'Flow-Only' operation (non sediment augmentation) rebuild and maintain sandbar habitats over decadal time scales? (Wright, 2007, Melis and others, 2006).*

For this purpose, a review workshop was organized and this review panel was charged with providing a road map for a numerical modeling program that can be useful to the GCMRC for the next few years. This program has the objective to improve the GCMRC's current capability for predicting the long-term fate of sand in GC under the various operational strategies for Glen Canyon Dam. The following points summarize the recommendations presented in the previous sections.

1. Formulate an integrated research plan that anticipates future research and management needs, and ensures that the modeling and monitoring components are complementary.

2. Further calibrate and test the WWG model in its present form in order to determine its immediate applicability to situations of interest. Through sensitivity and uncertainty analyses, quantify the level of confidence that can be placed in the model for management decisions.

3. Gradually revise and refine the ansatz used by WWG. This should be undertaken in stages, starting by refining the level of discretization, then by increasing the complexity of the modeling techniques used. Continue this process until significant improvements are no longer cost effective.

4. The GC is a very difficult location to conduct field work due to accessibility, permit restrictions and the very difficult field conditions. All of the USGS teams are to be commended for their professional approach and adoption of new experimental equipment (for example, the Pitot tube from New Zealand). Given the high profile research and testing conditions, the Review Panel recommends that the GCMRC is encouraged to continue this innovative work and that the resources are made available to understand the detailed flow structures.

5. Use data and multi-dimensional modeling tools (2D and 3D) to improve the understanding of the sediment exchange in eddy and bar systems. Rather than developing new multi-dimensional models, the emphasis should be placed into existing modeling tools, especially those that are easily accessible by the GCMRC and that have good technical support. The primary use of data will mostly likely be that of numerical model calibration and validation. A preliminary model should be used to optimize design of a data collection study.

6. Revisit the existing data, from the point of view of the multi-dimensional modeling effort, and determine the need to complement it with field measurements and laboratory experiments. Detailed local experiments and observations of sand bar deposition and erosion are likely to be needed to guide the development of a useful bar-scale model.

7. Analyze the uncertainty of the model predictions following the uncertainty of input (lack of data, measurement error, stochastic conditions) and of the algorithm assumptions and approximations. A probabilistic approach, in which the effect of uncertainties in input data and model algorithms on the predictions can be computed, is considered relevant for evaluating the value of the predictions.

The panel recognizes that the WWG model constitutes a significant step towards the development of a management tool to answer some of the critical GCDAMP science questions. The work plan outlined in the previous sections has the objective of honing the approach used in WWG, to bring it to a stage where its predictions can be reliable and accurate enough for the management purposes that it is intended for, to reduce and quantify remaining uncertainty. There may be parallel complementary models used. For example the WWG may be employed as the practical management tool for decision making and more complex higher dimension models could be used for reducing uncertainties in WWG by refining the constituent algorithms over time and to address particular local complexities.

This review panel stresses the need for the development of a whole-system view to guide future modeling efforts. There are different management questions that most likely will require different model needs—i.e., different resolution levels, diverse time and spatial scales, etc. Anticipating future needs at an early stage enables the development of a unified approach in which models may complement and communicate with each other. This may result in significant economy of resources later. For example, a few pertinent questions are:

1. Are there any efforts to interface other models (e.g., the temperature modeling efforts currently under way) with the models developed for the geomorphology studies?

2. How can the effects of vegetation be incorporated in the modeling effort? Vegetation has significant impact in hydraulic and aeolian erosion.

3. How will the hydraulic/sediment transport models interact with water quality, habitat, and ecology models in the future?

Some of these questions require the modeling program to anticipate and seek integration with other program activities and to address issues in other disciplines.

Finally, the GCMRC should be commended on the breadth of expertise that has contributed to the program so far from across agencies and academia such as John Hopkins University. The problems being addressed are very complex and the consequences associated with management decisions are high. This inclusive philosophy is consistent with the *Community Science* approaches adopted by the National Science Foundation in the development of Environmental

Observatories such as LTER, the WATERs Network (CUASHI and CLEANER) and NEON and it is recommended that this approach be continued.

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APPENDIX

Strategic Science Questions

Strategic Science Questions developed cooperatively by scientists and managers as a result of the Knowledge Assessment Workshops in 2005. (Source: Wohl and others, 2006.)

4.1 Physical Resources

4.1.1 Is there a “Flow-Only” (non sediment augmentation) operation that will restore and maintain sandbar habitats over decadal time scales?
4.1.2 Is there an optimal strategy for BHBF implementation to manage tributary inputs on an annual to inter-annual time scale?
4.1.3 What are the short-term responses of sandbars to BHBFs?
4.1.4 What is the rate of change in eddy storage (erosion) during time intervals between BHBFs?
4.1.5 How does the grain-size distribution of the deposits affect sandbar stability? Main channel turbidity?
4.1.6 What are the effects of ramping rates on sediment transport and sandbar stability?
4.1.7 Can we develop a relationship between suspended sediment concentration and turbidity to support fisheries research?