FEDERAL INTERAGENCY SEDIMENTATION PROJECT
FY2015 PROPOSAL
REVISED 4/27/2015

Proposal Title:

Computational Fluid Dynamics Analysis of Suspended-Sediment Sampler Efficiency – Phase II

Project Chief: Justin A. Boldt, USGS, Kentucky Water Science Center

Project Chief Location: Louisville, KY

Proposed Start Date: June 1, 2015

Proposed End Date: October 31, 2015

1-Year Funding Request: $30,000

Relation to FISP Goals – Measurement and characterization of sediment transported by streams is of vital importance to the effective management of our Nation's water resources. Since its formation, the Federal Interagency Sedimentation Project (FISP) has worked to develop standard and scientifically valid equipment and methods for collecting sediment samples. The foundational design assumption for isokinetic suspended-sediment samplers is that the water velocity at the intake nozzle must match the ambient stream velocity; otherwise, a bias will be introduced into the concentration of the collected sample. The effect of the intake efficiency (intake velocity / stream velocity) on the sampled concentration is based on detailed laboratory flume tests conducted in the 1940s on four sediment sizes from 0.01 to 0.45 mm (FISP, 1941) as shown in figure 1. These laboratory results were validated with computational fluid dynamics (CFD) modeling in our 2014 FISP-funded project as shown in figures 2–3. This initial research now provides the foundation for additional use of CFD to evaluate and develop design specifications for existing and future nozzles and samplers.

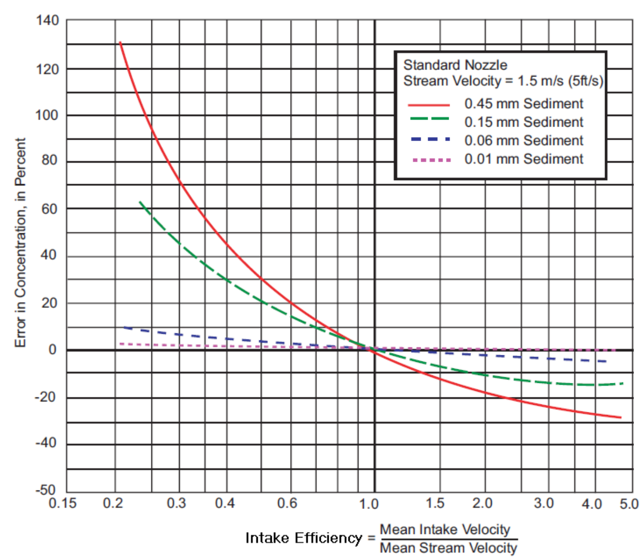

Figure 1. Errors in SSC for variable non-isokinetic sampling conditions for four sediment sizes, for flow velocity of 5 ft/s. Figure from Gray et al. (2008), based on data from FISP Report 5 (1941).

The FISP has identified the evaluation and verification of accuracy of FISP physical samplers as a research focus area for 2015. The use of computational fluid dynamics (CFD) modeling with particle tracking capability will allow a detailed evaluation of the effect of a number of variables of interest on the sampled sediment concentration in simulated turbulent flow.

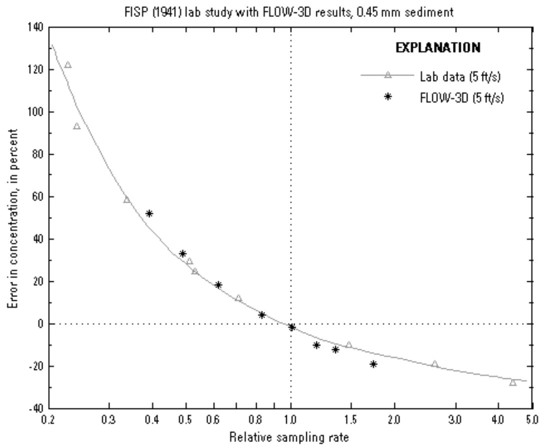

Figure 2. FLOW-3D results compared to FISP (1941) lab study, 0.45 mm sediment, 5 ft/s.

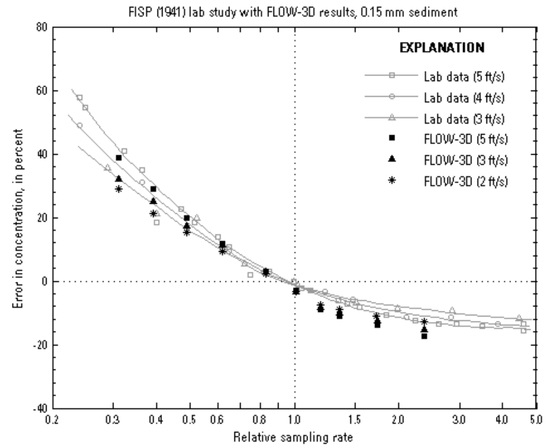

Figure 3. FLOW-3D results compared to FISP (1941) lab study, 0.15 mm sediment, 2–5 ft/s.

The most important limitation to the 1941 experiments (and previous CFD study) was that the experimental nozzle used is substantially different than current FISP sampler nozzles (sharp leading edge with abrupt taper vs. rounded leading edge with slight taper). Now that the CFD model has been established and proven accurate, it is trivial to run the simulations again with different nozzle designs. The nozzle(s) to be modeled will be selected in collaboration with the FISP. One option is the US D-77 1/4” suspended-sediment sampler intake nozzle.

Another important limitation to the 1941 experiments and previous CFD study was the lack of mixed sediment sizes. In both of those studies, it was important to isolate the effect of sediment size, but now it would be worthwhile to model mixed sediment sizes (sediment-size distribution) to more closely represent field conditions. Finally, Sabol et al. (2010) reported substantial differences in intake efficiencies observed in the field compared with the sampler design data collected in the laboratory. This is likely due to the turbulence found in field conditions. Additional simulations could further investigate this macro-turbulence and vertical velocity effects.

Although it is not feasible to model the entire suspended-sediment sampler, the nozzle can be modeled in a way to represent natural fill conditions. The 1941 experiments and previous CFD study both used a valve to control the intake efficiency (relative sampling rate). Natural fill conditions would test the isokinetic performance of the sampler over variables of interest (depth, velocity, temperature, SSC, etc), which would be of great value in the design and understanding of existing and new samplers.

Scientific Merit and Relevance – Water resources are becoming more and more important to the protection and wellbeing of the Nation’s population. Water supply, proper design of infrastructure, and protection of biological habit are all dependent on the accurate measurement and characterization of sediment transported in streams. However, decreasing budgets have had a significant impact on the number of continuous sediment monitoring stations and the number of physical samples that can be collected and analyzed. Therefore, it is imperative that sampler design and use be both accurate and cost-effective. Moreover, samples obtained with isokinetic samplers are the standard by which emerging sediment-surrogate techniques are calibrated and verified.

A significant amount of time and money are spent in the development of isokinetic suspended-sediment samplers. The intake efficiency criteria for the design of these samplers are based on flume tests conducted in the 1940s (FISP, 1941). In addition, the analysis of suspended-sediment sampling errors (Skinner, 2007) is also dependent on the results reported in FISP (1941). Recent research in the Grand Canyon (Sabol et al., 2010) indicate that intake efficiencies measured in the laboratory or from towing a sampler in a lake are not representative of the intake efficiencies observed in turbulent conditions typical of streams. Natural turbulence in a stream will have an effect on the transport of suspended sediment and on the boundary layer formed around an object (sampler or velocity meter) placed in the flow.

Through the use of CFD modeling, the effect of variables affecting the efficiency of suspended-sediment samplers on the sampled concentration can be evaluated in a manner that is not feasible in lab or field studies. The results of this research include:

- a better understanding of the hydrodynamics that are important to isokinetic sampling;
- an independent analysis of isokinetic sampling and sample concentration bias for variable sediment sizes, water velocities, and nozzle design(s);
- a basis to more accurately reference the isokinetic range and bias of FISP samplers; and
- a basis to adjust current design criteria for existing samplers to ensure that they are being manufactured to be both accurate and cost-effective.

Methodology – The U.S. Geological Survey has been using computation fluid dynamics (CFD) modeling to evaluate the flow disturbance caused by acoustic Doppler current profilers and other hydroacoustic instruments for measuring streamflow (Mueller et al, 2007; Mueller, 2009). The accuracy of the model simulations are within 1% when compared with both field and laboratory data. CFD is being used in such diverse industries as the design of inkjet printers, metal and plastic molding, tanker design, and many others (http://www.flow3d.com/apps/index.html). The advantages of CFD compared with flume and field testing include lower cost, control of flow conditions (velocity, pressure, turbulence), control of particle characteristics (concentration, size, density), known “true” values, and the ability to visualize the flow field. The FLOW-3D (Flow Science, Inc., 2014) CFD model will be used for all simulations.

This proposed research is an extension of our previous (FY2014) FISP-funded project. Simulations will be configured to evaluate the effect of nozzle design(s), mixed sediment sizes, and natural fill conditions (Table 1). The variables proposed in Table 1 were selected based on previous conversations with the FISP and by what we think are the most valuable scenarios to consider next. Should this proposal get funded, we are open to input from the FISP Technical Committee as to the exact variables of interest. There are 2–3 months between the proposal deadline and our anticipated start date in which this could happen. Simulations 1–100 can be run for the $30,000 funding limit imposed by the request for proposals. Given the apparent discrepancy between laboratory and field tests of fill times (personal communications with FISP Chief), the effect of macro turbulence and/or vertical velocities maybe be a key in identifying the cause of the disagreement. Therefore, we are offering an additional option to model macro turbulence and vertical velocities, plus simulations with another nozzle or different nozzle diameter. This additional work could be completed within the time allotted for an additional $5,100.

Table 1. Summary of proposed CFD simulations.

A. Testing D-77 nozzle[1]

Sim. #	Intake Eff.	Velocity (ft/s)	Sediment size (mm)
1–8	0.4–1.7 (8 pts)	2	0.45
9–16	0.4–1.7 (8 pts)	5	0.45
17–24	0.4–1.7 (8 pts)	2	0.15
25–32	0.4–1.7 (8 pts)	5	0.15

[1]valve control (as in FY2014 simulations)

B. Testing D-77 nozzle[1]

Sim. #	Intake Eff.	Velocity (ft/s)	Sed. dist.*
33–40	0.4–1.7 (8 pts)	3	A
41–48	0.4–1.7 (8 pts)	3	B
49–56	0.4–1.7 (8 pts)	3	C
57–64	0.4–1.7 (8 pts)	3	D

[1]valve control (as in FY2014 simulations)

C. Testing natural fill conditions[2]

Sim. #	Depth (ft)	Velocity (ft/s)	Temp. (°C)	Sediment size (mm)
65–68	3	2–5 (4 pts)	20	0.45
69–71	3	3	2, 20, 35 (3 pts)	0.45
72–75	3	2–5 (4 pts)	20	0.15
76–78	3	3	2, 20, 35 (3 pts)	0.15

[2]pressure boundary (replaces valve control)

*Sediment distributions A, B, C

	Particle size (mm)	A: 25% fines	B: 50% fines	C: 75% fines
fines	**0.01**	0.10	0.25	0.40
fines	**0.06**	0.15	0.25	0.35
sand	**0.15**	0.35	0.25	0.15
sand	**0.45**	0.40	0.25	0.10

79–90	D. Simulations to investigate macro-turbulence and/or vertical velocity effects.

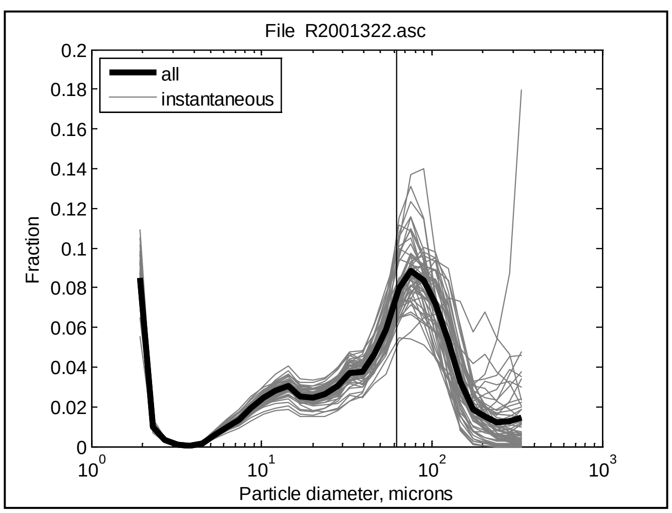

Fig. 4. LISST particle-size distribution for Puyallup River, 7/19/2011.

*Sediment distribution D

Particle size (mm)	Frac.
0.01	0.10
0.03	0.10
0.06	0.25
0.09	0.30
0.15	0.15
0.45	0.10

Simulations 1–64 will use valve control (as in FY2014 simulations) to control a range of intake efficiencies. The proposed simulations in Table A mimic the parameters used in the FY2014 simulations except now with a different nozzle (D-77 nozzle). Table B is an extension of the variables tested in FY2014 and ties-in directly with Table A. The new variable in the proposed simulations in Table B is a sediment distribution instead of a uniform particle size. We have results for two sediment sizes (0.15 mm and 0.45 mm), and this will test whether or not there is a linear relationship when multiple particles sizes are present and interacting in the flow. The proposed sediment distributions A, B, C are shown below Table B. The particle sizes used to build the distribution (0.01, 0.06, 0.15, 0.45 mm) are the same four sizes used in the 1941 study, and the benefit is that comparisons between groups of simulations may be more comprehensive with consistent particle sizes. Additionally, one real-world sediment-size distribution will be used (Fig. 4). The distribution would still have to be built out of discrete particle sizes in the model (likely not more than 8–10), see example next to Fig. 4, but could include the same four sediment sizes from the 1941 study plus additional sizes to create a smoother distribution curve.

The proposed simulations in Table C, called “natural fill conditions”, are very different from the other simulations. The simulations in Tables A and B use a value to control how fast or slow the water is drawn through the nozzle, and the purpose of that “valve control” is to cover a range of intake efficiencies. In Table C, the “valve control” will be replaced with a pressure boundary. This pressure will need to be specified based on archived bottle fill datasets (via Mark Landers) and held constant during a simulation. This setup represents the real-world operation of a FISP suspended-sediment sampler. There is no value (besides open/closed) to control the intake; rather, the sample bottle fills naturally. Thus, this group of simulations will test the extent of isokinetic sampling conditions, and if the sampler performs as designed, we would expect the intake efficiencies to be close to 1.0 for a range of flow conditions. The variables of interest are velocity, water temperature, and particle size.

Finally, the simulations in Table D will investigate macro-turbulence and/or vertical velocity effects. The idea here is to create highly chaotic flow to see how well the sampler measures in those conditions by comparing the variability between repeat samples and simulations. In order to create this flow condition in the model, we may specify a synthetic inflow velocity or place obstructions in the flow to cause large secondary flow vectors. The goal here is to evaluate methods to create turbulence, compare with measured physical turbulence (field work or lab), and vary some characteristic of turbulence such as magnitude with direction.

FLOW-3D will be configured using a multi-block mesh to allow complete control of the boundary conditions for the nozzle. A uniform, continuous water velocity (constant at 20°C) with specified turbulence parameters will be used as the upstream boundary condition. Mass particles with a specific gravity of 2.65 will be introduced in a continuous, uniform distribution at the upstream boundary. The upstream boundary will be located a sufficient distance upstream of the nozzle and the extent of the model domain sized to eliminate any boundary effects on either water or particles entering or passing around the nozzle. The downstream boundary condition will be adjusted to obtain the desired flow through the nozzle while maintaining equilibrium. In the case of natural fill conditions, the downstream boundary condition will be a pressure boundary to represent the actual operation of a suspended-sediment sampler. Flux surfaces will be used to track particles moving into and past the nozzle.

The results of this research will be reported to the FISP Technical Committee via an informal report or presentation and may also be published formally in a journal paper. The project chief is open to other publication outlets as directed by the FISP Chief or Technical Committee. The FY2014 work was reported in a presentation and a poster and will be published formally in a journal paper (in progress). There was the idea of publishing all of the work from FY2014 and FY2015 in a single journal paper, but we feel the studies are different enough and substantial enough to warrant separate journal papers.

Timeline, budget (Feasibility), and partners – The USGS is prepared to begin work on this project in June 2015 and anticipates about 8 months to complete the project. The project chief (GS-9 hydrologist) will oversee the project and perform the majority of the work. An experienced FLOW-3D modeler (GS-14) from the OSW staff located in the same office will provide technical direction and assistance at no cost to the project. The Office of Surface Water will cover the annual maintenance for the FLOW-3D model ($15,000).

Task 1 – Testing new variables with previous model setup (Jun – Aug). This task will make minor improvements to the previous model setup and investigate the effect of different nozzle design(s) and mixed sediment sizes (Table 1). Other variables could be tested here per the FISP's request.

Task 2 – New model configuration (Aug – Sept). This is a major task and will involve modifying the boundary conditions to represent natural fill conditions and macro-turbulence effects. Several simulations will be completed with variation in mesh configuration and boundary conditions to provide a sensitivity analysis for the model. The objective is to ensure the results are independent of the mesh size and location of boundaries. Flow Science will be consulted in this task to ensure the best possible model setup is used.

Task 3 – Configure and run specific simulations (Jun – Sept). The remaining simulations in Table 1 will be configured. Each simulation will be checked as it is completed.

Task 4 – Data analysis (ongoing throughout). As simulations are completed, graphical and numerical analysis of individual simulations and groups of simulations will be completed. Any preliminary results will be shared with the FISP chief. These analyses will include but are not limited to: visualization and animations of the flow in and around the nozzle, comparison of model results to other flume and field results, and addition or modification of future simulations to resolve any identified questions or issues.

Task 5 – Final report and journal paper (Sept – Oct). Final analyses will be completed and a draft paper prepared summarizing the findings. The draft paper will be provided to the FISP chief and technical committee prior to submission to a journal.

Proposed Budget – Proposed budget reflects cost reduction due to OSW absorbing some of the costs.

Project Chief	GS-9	440 hours	$16,000
Hydrologist	GS-14	80 hours	$0
Model maintenance		$15,000 / year	$0
Misc.			$500
Overhead			$13,500
Total Cost			$30,000

References

Federal Interagency Sedimentation Project, 1941, Laboratory investigation of suspended sediment samplers, Report 5, 99 p. (http://water.usgs.gov/fisp/docs/Report_5.pdf)

Flow Science, Inc. 2014. FLOW-3D v. 11 user's manual, Flow Science, Inc., Santa Fe, NM.

Gray, J., Glysson, J.D., and Edwards, D.T., 2008, Suspended-sediment samplers and sampling methods, in Garcia, M., ed., Sedimentation Engineering, Processes, Measurements, Modeling, and Practice: ASCE Manuals and Reports on Engineering Practice No. 110, p. 320-339.

Mueller, D.S., 2009, Evaluation of flow disturbance around FlowTrackers using Flow-3D: Presentation Abstract, 2009 Flow-3D World User's Conference, Seattle, WA, Flow Science, Inc., Sante Fe, NM.

Mueller, D.S., Abad, J.D., García, C.M., Gartner, J.W., García, M.H., and Oberg, K.A., 2007, Errors in acoustic Doppler profiler velocity measurements caused by flow disturbance: Journal of Hydraulic Engineering, v. 133, no. 12, p. 1411–1420. (http://hydroacoustics.usgs.gov/publications/13-Mueller-etal.pdf)

Sabol, T.A., Topping, D.J., and Griffiths, R.E., 2010, Field evaluation of sediment concentration errors arising from non-isokinetic intake efficiency in depth-integrating suspended-sediment bag samplers: 9th Federal Inter-agency Sedimentation Conf., Las Vegas, 12 p. (http://acwi.gov/sos/pubs/2ndJFIC/Contents/P23_SABOL_02_23_10.pdf).

Skinner, John, 2007, A spreadsheet analysis of suspended sediment sampling errors, Federal Interagency Sedimentation Project, Report TT, Vicksburg, MS, 70 p.