Proposal Title: Computational Fluid Dynamics Analysis of Suspended Sediment Sampler Efficiency

Project Chief: David S. Mueller, USGS, Office of Surface Water

Project Chief Location: Louisville, KY

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Proposed End Date: July 31, 2014

1-Year Funding Request: $28,000

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. Perhaps the most commonly used samplers are the isokinetic suspended sediment samplers. The foundational design assumption for isokinetic 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 majority of the effort in the design of existing and new samplers is spent in trying to achieve isokinetic performance of the sampler over a wide range of stream conditions (depth, velocity, temperature, and transit rate for depth-integrating samplers).

The effect of the intake efficiency (intake velocity / stream velocity) on the sampled concentration is based exclusively on meticulous and detailed laboratory flume tests conducted in the 1940s on four sediment sizes from 0.01 to 0.45mm (FISP, 1941), as shown in figure 1. However, there were important limitations to these experiments including: the experimental nozzle design is substantially different than current FISP sampler nozzles (bending nozzle with 4 degree versus typical 1.19 degree taper currently used) and; test water temperature varied from 65 to 85F. Sabol et al (2010) reported substantial differences in intake efficiencies observed in the field compared with the sampler design data collected in the laboratory. Sabol et al (2010) presented data showing the flume data collected during the development of the samplers were

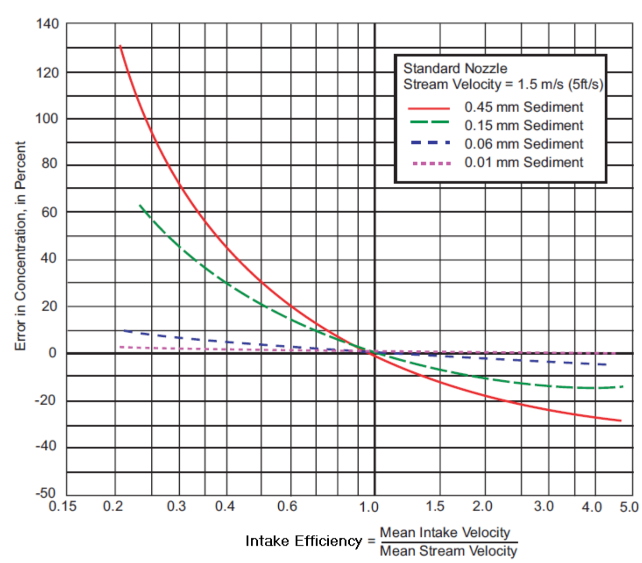

Figure 1. Errors in SSC for variable non-isokinetic sampling conditions for four sediment sizes, for flow velocity of 5 ft/s. Figure from Gray et al. (2008), based on data from FISP Report 5 (1941).

not adequate to characterize the intake efficiency of the samplers. Therefore, there is uncertainty in the adequacy of the flume experiments reported in FISP (1941) in characterizing the effect of intake efficiency on the sampled sediment concentration.

FISP has identified the evaluation and verification of accuracy of FISP physical samplers as a research focus area for 2014. The use of computational fluid dynamics (CFD) modeling with particle tracking capability will allow a detailed evaluation of the effect of intake efficiency on the sampled sediment concentration in simulated turbulent flow. The turbulence in a laboratory flume is typically limited to the characteristics of the flume (width, depth, roughness), however, the turbulence parameters can be set using a CFD model to more closely represent field conditions.

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. This finding is not completely surprising as tests to quantify the bias in measured velocity caused by flow disturbance around a FlowTracker acoustic Doppler velocimeter yielded slightly different results depending on whether the FlowTracker was towed through a still towing tank or deployed in turbulent conditions. The Flow-3D (Flow Science, Inc., 2013) CFD model proposed to be used for this research was able to duplicate laboratory data in both turbulent flow and movement of the FlowTracker through still water to within less than 0.2% (Mueller, 2009). 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 proposed herein, the effect of variables affecting the efficiency of suspended sediment samplers on the sampled concentration can be evaluated in a manner that was simply not possible in the 1940s. The results of this research include:

- a better understanding of the hydrodynamic characteristics that are important to isokinetic sampling;
- an independent analysis of isokinetic sampling and sample concentration bias for variable sediment size that will test and certainly extend previous results of FISP (1941);

- 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.

In addition, this initial research will provide the foundation for future use of CDF to evaluate and develop design specifications for existing and future nozzles and samplers.

Methodology – Flume tests are attractive because they allow significant control of the flow conditions and sediment concentration, but are hampered by their limited ability to reproduce field conditions. Field tests are difficult, time consuming, and expensive. Both flume tests and field tests are limited by the need to define the "true" velocity and sediment concentration, which ultimately is determined by some other measurement method which has its own uncertainty. An alternative to physical testing is to use computation fluid dynamics modeling (CFD). 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 U.S. Geological Survey has been using CFD to evaluate the flow disturbance caused by acoustic Doppler current profilers and other hydroacoustic instruments for measuring streamflow (Mueller et al, 2007). The accuracy of the model simulations are within 1% when compared with both field and laboratory data. 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., 2013) CFD model will be used for all simulations.

Simulations will be configured to evaluate the effect of turbulence, sediment size, and ambient velocity (Table 1). The nozzle to be modeled will

Table 1. Summary of CFD simulations.

Simulation	Turbulence	Velocity (ft/s)	Intake efficiency	Sediment Size (mm)
1	Low	5	0.4	0.45
2	Low	5	0.6	0.45
3	Low	5	0.8	0.45
4	Low	5	1	0.45
5	Low	5	1.2	0.45
6	Low	5	1.4	0.45
7	Medium	5	0.4	0.45
8	Medium	5	0.6	0.45
9	Medium	5	0.8	0.45
10	Medium	5	1	0.45
11	Medium	5	1.2	0.45
12	Medium	5	1.4	0.45
13	High	5	0.4	0.45
14	High	5	0.6	0.45
15	High	5	0.8	0.45
16	High	5	1	0.45
17	High	5	1.2	0.45
18	High	5	1.4	0.45
19	Medium	5	0.4	0.15
20	Medium	5	0.6	0.15
21	Medium	5	0.8	0.15
22	Medium	5	1	0.15
23	Medium	5	1.2	0.15
24	Medium	5	1.4	0.15
25	Medium	3	0.4	0.15
26	Medium	3	0.6	0.15
27	Medium	3	0.8	0.15
28	Medium	3	1	0.15
29	Medium	3	1.2	0.15
30	Medium	3	1.4	0.15
31	Medium	2	0.4	0.15
32	Medium	2	0.6	0.15
33	Medium	2	0.8	0.15
34	Medium	2	1	0.15
35	Medium	2	1.2	0.15
36	Medium	2	1.4	0.15
37	Medium	3	0.4	0.45
38	Medium	3	0.6	0.45
39	Medium	3	0.8	0.45
40	Medium	3	1	0.45
41	Medium	3	1.2	0.45
42	Medium	3	1.4	0.45
43	Medium	2	0.4	0.45
44	Medium	2	0.6	0.45
45	Medium	2	0.8	0.45
46	Medium	2	1	0.45
47	Medium	2	1.2	0.45
48	Medium	2	1.4	0.45

be selected in collaboration with the FISP. The simulation characteristics were selected to reproduce the characteristics of the flume experiments in figures 10 and 11 (FISP, 1941) and to span the variation in velocity reported in Sabol et al (2010). Since FISP (1941) found that bias for particles of 0.06 and 0.01mm was less than 5% even at intake efficiencies of 0.5 to 2.0 these small particles sizes are not included in the proposed simulations. All particles will be spherical and have a mass equal to a specific gravity of 2.65. The water temperature will be held constant at 20-degrees C.

Flow 3-D will be configured using a multi-block mesh to allow complete control of the boundary condition for the nozzle. A uniform continuous water velocity 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 conditions will be adjusted to obtain the desired flow through the nozzle while maintaining equilibrium flow. 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 and also published formally in a journal paper. The project chief is open to other publication outlets as directed by the FISP Chief or Technical Committee. Once this model is developed, it can be used in future evaluations of the effect of variable temperature, design tolerances, and other characteristics.

Timeline, budget (Feasibility), and partners –

The USGS is prepared to begin work on this project in January 2014 and anticipates about 8 months to complete the project. The project chief (GS-14) will oversee the project but the majority of the work will be completed by a GS-9 hydrologist located in the same office as the project chief. The Office of Surface Water will cover the salary for the project chief and the annual maintenance for the Flow 3-D model ($12,500).

Task 1 – Initial simulation configuration (Jan – Mar). This task will involve the building of the initial mesh and setting all initial and boundary conditions. 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 2 – Configure and run specific simulations (Mar – Jun). Each of the simulations identified in Table 1 will be configured. Each simulation will be checked as it is completed to ensure the simulations are working properly.

Task 3 – Data analysis (Apr – June). 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 4 – Final report and journal paper (Jul –Aug). 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-14	80 hours	$0
Hydrologist	GS-9	440 hours	$16,600
Model Maintenance		$12,500 / year	$0
Travel to Flow Science		2 people	$3,000
Misc.			$500
Overhead			$ 7,900
Total Cost			$28,000

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. 2013. Flow-3d v. 10.1 user's manual, Flow Science, Inc., Santa Fe, N.M.

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: Ninth Federal Interagency Sedimentation Conference, Las Vegas, NV, 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.