V. Fluvial: Monitoring Sediment Movement

V. FLUVIAL: MONITORING SEDIMENT MOVEMENT

MOTION CHARACTERISTICS OF COARSE SEDIMENT IN A GRAVEL BED RIVER

By E. F. Chacho, Jr., Engineer, USA Cold Regions Research and Engineering Laboratory, Fairbanks, Alaska; R. L. Burrows, Hydrologist, US Geological Survey, Fairbanks, Alaska; W. W. Emmett, Hydrologist, US Geological Survey, Lakewood, Colorado

Abstract Radio transmitters were implanted in natural river gravel to locate and track the movement of coarse sediment (39 mm or larger) through a natural river reach. An automatic data acquisition system was developed to continuously monitor the radio-implanted sediment particles to determine the travel time of the rocks through a 362-m study reach. A total of 24 radio-tagged rocks was monitored either continuously or by periodic location surveys. The travel time of the rocks through the study reach is better related to specific gravity than weight of the particles. In addition the automatic data acquisition system continuously monitors the periods of motion and rest of natural river gravel implanted with radio transmitters equipped with motion sensors. The capabilities of the system are demonstrated by describing the motion and rest periods of a single rock for a two-month period including a number of flood events.

INTRODUCTION

The use of radio transmitters, implanted in individual sediment particles, to track the movement of coarse sediment in natural river systems was developed independently and simultaneously by Chacho et al. (1989) and Ergenzinger et al. (1989). Both groups have reported results from the application of the technique: Ergenzinger and Schmidt (1990) on the travel characteristics of cobbles in a step-pool river and Chacho et al. (1994) on travel characteristics of coarse gravel in a steep mountain stream. In this paper, we describe the application of the technique and present examples of the type of data that can be acquired by continuously monitoring the motion and rest periods of various-size sediment particles and their travel time through a 362-m study reach.

The radio transmitter, enclosed in a hermetically sealed cylinder including battery and internal antenna, transmits a pulse at a specified frequency and period. Transmitter life is dependent on transmitting interval and battery size; for example, a 15- X 39-mm unit, transmitting at a pulse interval of about 0.5 msec, has a life of about 60 days, while an 18- X 72-mm unit, transmitting at the same pulse rate, lasts about 10 months. Natural sediment particles are collected from a study site and holes are drilled into the rocks to allow the implantation of the transmitters. The holes are sealed with epoxy and the rock is painted to aid in recovery at the end of the field season. Transmitters may be refurbished and used again. The tracking application of the technique requires the use of a directional antenna, radio receiver and signal strength meter.

In the continuous monitoring application of the technique, the transmitters are equipped with a motion-sensor which emits a signal at a single frequency but at a period which changes depending on whether the particle is at rest or in motion. A data acquisition system, utilizing a stationary antenna, radio receiver, automatic frequency scanner, digital processor and data logger is employed to continuously monitor the motion and rest periods of the motion-sensor equipped rocks.

The initial application of the data acquisition system took place in 1990, on Lignite Creek, in central Alaska. In this study, motion sensor-equipped radio transmitters, with unique frequencies, were installed in 17 sediment particles which were monitored by the data acquisition system and are referred to in this paper as the monitored rocks. An additional seven sediment particles were radio-tagged for periodic tracking only and are referred to as the unmonitored rocks. All 24 radio-tagged rocks were placed on a riffle at the head of the study reach. Periodically, following each flood event, all the rocks were tracked and travel distances measured.

STUDY SITE

Lignite Creek flows out of the foothills north of the Alaska Range into the Nenana River near Healy, Alaska. The drainage area of the basin is approximately 125 km^2. The lithologies of the basin are prone to mass wasting, producing high sediment loads on Lignite Creek. Average annual water discharge is 0.89 $m^3 s^{-1}$. Flow during the study period in 1990 ranged from 0.5 to 16.3 $m^3 s^{-1}$. Bedload transport, as computed from samples collected with a Helley-Smith bedload sampler, ranged from about 58 t day^{-1} to 365 t day^{-1}.

The study reach is 362 m in a straight line measure, from the point of introduction of the radio-tagged rocks to the bridge where the data acquisition system was located. The reach is relatively steep with slope changing from

0.0015 m m^{-1} upstream to 0.0008 m m^{-1} downstream. The reach is nearly straight, bending slightly from right to left downstream, and, depending upon discharge, may flow in more than one channel. Bed material varies from sand to boulders and is highly mobile; bedload transport occurs at all but the lowest flows.

INSTRUMENTATION

The data acquisition system sequentially scans a series of programmed radio frequencies. In this study 18 frequencies were scanned, 17 radio-tagged rocks and a stationary fixed pulse transmitter used to distinguish the beginning of a scan sequence. The system requires 15 sec to properly interrogate a given frequency. Therefore, in this study, each radio-tagged rock was interrogated once every 4.5 min. The motion sensor incorporates a delay time, that is, the time interval that the transmitter broadcasts the motion-indicator pulse rate following the occurrence of movement. In this specific application, the delay time was specified as 4.5 min so that each movement of a monitored rock during the total scan sequence would be recorded. This means that any movement of a monitored rock, even if it rolled only a partial revolution, would result in motion being recorded on the subsequent interrogation of that radio frequency in the scan sequence. If the rock started rolling and continued to move or moved in a series of short start and stop motions, multiple motion periods would be recorded on subsequent scans of that rock's frequency. Therefore, in this study, a motion or rest period is defined as movement or lack of movement in a 4.5 min time interval. Higher resolution of the motion periods is possible by reducing the number of radio frequencies to be scanned by an individual receiver.

The data record of motion and rest periods (4.5 min intervals) for a single radio-tagged rock is shown in Figure 1. For this specific transmitter, marks at approximately 1800 msec indicate periods of rest, and marks at approximately 800 msec indicate periods of motion. The upper plot is the original, raw data including radio interference and the record after the rock exited the study reach. Interference from extraneous communication signals is briefly discussed below. The break in record and the reduced quality of data as the rock was transported through the road bridge and out of the study reach is clearly seen beginning at day 253.714. The lower plot is the filtered data in which the extraneous interference and the record after the rock had exited the study reach have been removed. Four episodes of movement, which included multiple motion periods, were recorded near days 219, 238, 244 and 253. Two single motion periods were recorded on days 241 and 248.

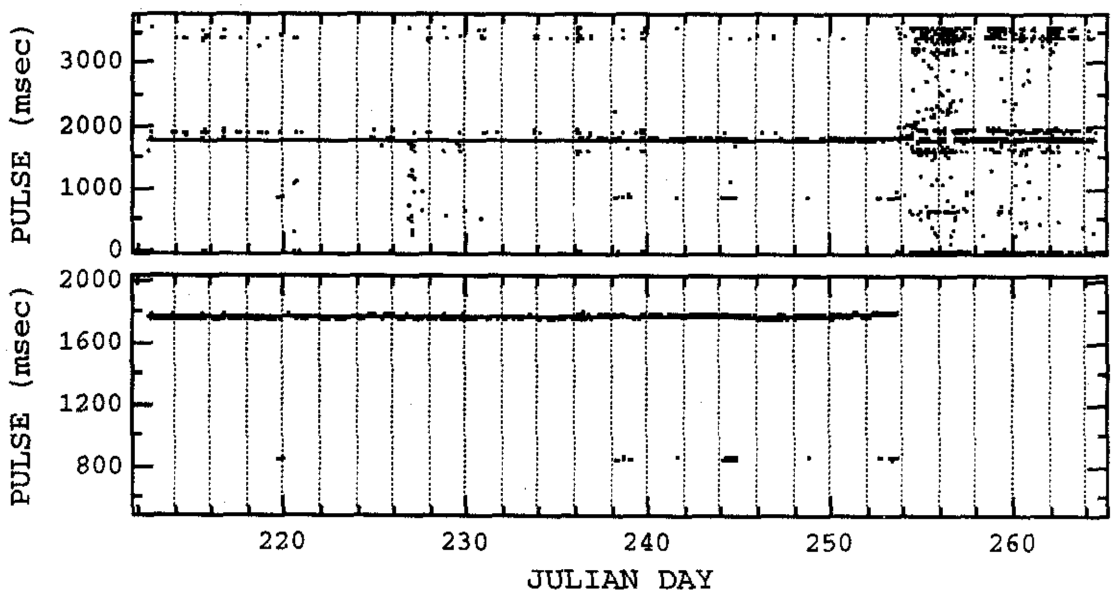

Figure 1. Data record of motion and rest periods for a motion sensor equipped radio-tagged rock (164.301). Upper plot is the original raw data, lower plot is the filtered data.

Due to a number of high strength transmitters (i.e., railroad communication, television and radio repeaters) in the vicinity of the study site which operated near the frequencies used in this study (163-164 MHz), interference was a problem. In some cases the interference was minor and could be filtered out of the record (e.g., Fig. 1); in other cases the interference was so great that the entire record of motion events for an individual rock had to be discarded.

The interference problem has been greatly reduced in a subsequent study by using transmitter frequencies (148 MHz) much lower than the usual communication frequencies.

RESULTS

Due to the somewhat unique setting of this study site, where the location of the bridge over the stream caused a perturbation in the record as the monitored rock was transported under the bridge, two types of data sets can be recovered. The first is the record of the occurrence of the motion and rest periods, a time record which does not include any information on travel distance. The second set is the record of the time the monitored rocks exited the study reach, that is, the time required for transport over a known distance. In this paper we include examples and initial results from both types of data sets. Complete analysis and interpretation is beyond the scope and length limitations of this paper and will be reported in the future.

The data from the 17 monitored rocks was filtered to remove interference and analyzed to determine the occurrence and timing of motion events. Due to the interference described above, only one rock had a complete record of motion events for its entire transit time through the study reach. The complete set of motion events for this rock is described below. A reach exit time was discernible for all 17 of the monitored rocks. In addition the reach exit time for the seven unmonitored rocks was estimated from the periodic location surveys. An initial analysis of these data sets is also presented.

Motion events The rock with a near-perfect record of motion events, radio frequency 164.301, was about mid-range in size and weight, and near the upper bound in specific gravity and reach exit date of the 24 radio-tagged rocks (Table 1). The discharge hydrograph and the motion events of this rock during its transport through the study reach is shown in Figure 2. As was shown in Figure 1, four flood events produced motion events with multiple motion periods, near day 219, 238, 244 and 253. The individual flood events and corresponding motion periods are replotted in Figure 3. In addition, two flood events produced a single motion period, near day 241 and 248. The

Table 1 Sediment size parameters and study reach exit dates of the monitored and unmonitored radio-tagged rocks from Lignite Creek 1990.

Radio Frequency	Median Axis (mm)	Final Weight (g)	Final Specific Gravity	Study Reach Exit Date (day)
163.501	60	404.10	2.55	241.460
163.521	71	500.10	2.74	238.817
163.491	75	670.60	2.42	241.458
163.531	73	974.50	3.01	250.548
163.421	64	751.10	2.95	253.751
163.471	74	949.20	2.88	244.467
163.460	75	605.30	2.57	238.754
164.301	74	902.90	2.90	253.729
163.541	73	904.10	2.58	238.510
163.552	85	785.00	2.53	238.489
163.241	80	802.10	2.35	236.089
164.597	98	1027.90	2.58	242.739
163.451	69	815.40	2.46	247.392
163.441	83	639.20	2.54	238.783
163.401	86	763.50	2.56	238.526
164.615	84	1155.00	2.58	238.298
163.412	94	1793.90	2.99	**
164.627	93	1159.30	2.43	235-239*
164.585	87	1337.10	2.84	239-250*
164.572	99	1557.50	2.96	250-264*
164.511	90	1790.80	2.45	235-239*
163.321	--	162.80	2.67	235-239*
163.341	--	144.40	2.21	220-235*
163.281	--	399.20	2.39	235-239*

**Did not exit study reach

*Unmonitored radio-tagged rocks

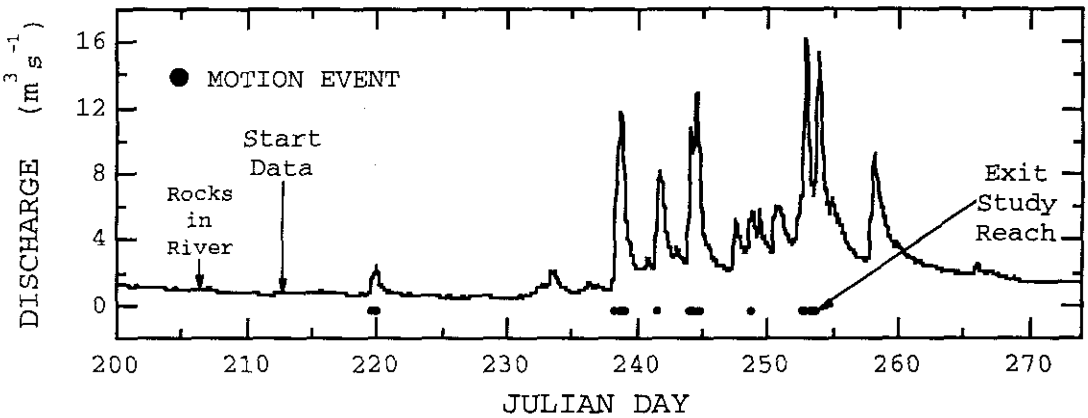

Figure 2. Discharge hydrograph and recorded periods of motion of a single radio-tagged rock (164.301) on Lignite Creek, 1990. Each mark represents the occurrence of motion during a 4.5-min scan interval.

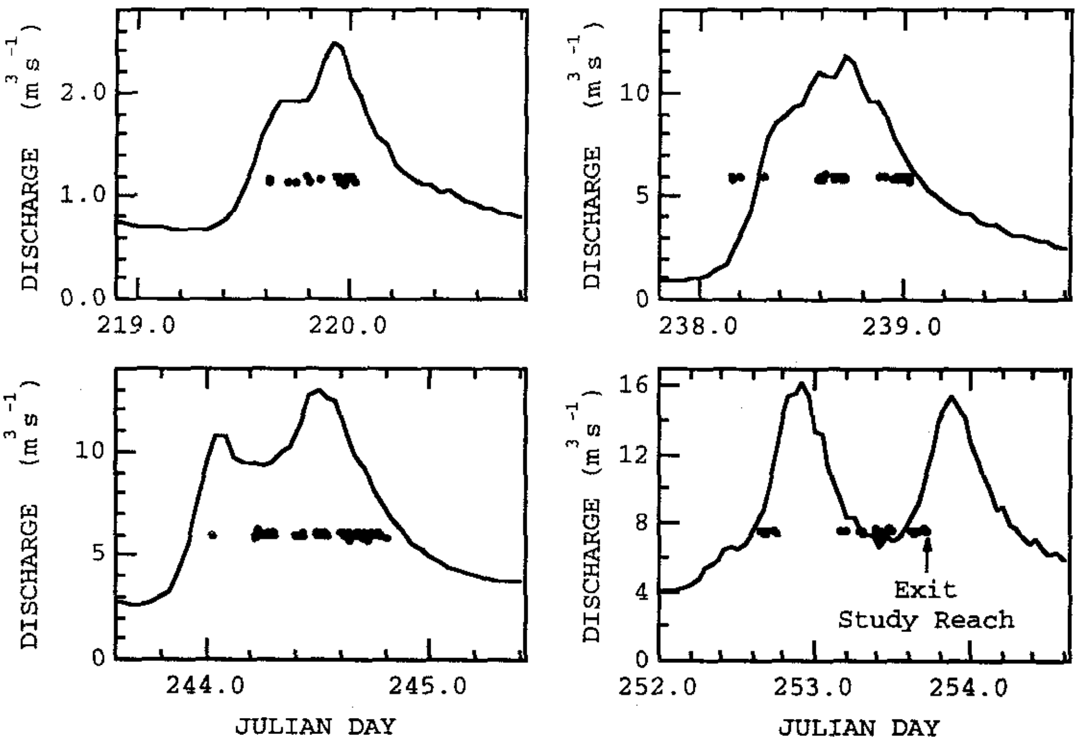

Figure 3. The relationship between motion periods and the four individual flood hydrographs which produced movement of rock 164.301. Circles represent recorded motion during a 4.5-min period. Note vertical and horizontal scales vary on the plots.

data on the flood events, including total number of monitored periods, and the motion events, including flow at the beginning and end of the event and the number of motion periods, are listed in Table 2. The flood event interval was arbitrarily chosen near the minimum flows between flood events, while the motion event interval is taken as the time between the first and last motion period for a given flood event.

The motion periods shown in Figures 2 and 3 are the recorded data near pulse rate 800 msec in Figure 1. The intermittent timing of the motion events (Fig. 3) result from either rest periods or missing data, therefore some discussion of the reliability of the data is required before progressing to further analysis or interpretation. For this rock, from the start of data acquisition on day 212 to its reach exit date on day 253, a total of 13,144 periods were

Table 2. Flood events and corresponding motion events on Lignite Creek 1990 for rock 164.301.

FLOOD EVENTS		MOTION EVENTS		
Interval (day)	Monitored Periods	Interval (day)	Flow ($m^3 s^{-1}$)	Motion Periods
219.401		219.614	1.73	
220.401	320	220.014	2.14	22
237.801		238.154	2.37	
239.701	609	239.035	6.41	44
241.251				
242.708	467	241.583	7.54	1
243.701		244.029	10.37	
245.401	545	244.808	7.23	84
247.001				
251.801	1535	248.748	5.77	1
252.010		252.660	8.80	
253.714*	546	253.714*	10.87*	49

*Exited study reach

monitored, each of length 4.5 min. Of this total, due to the extraneous radio interference, 238 periods (1.8%) were either missing or the recorded pulse rate was not near either 1800 msec (rest) or 800 msec (motion) (Fig. 1). The majority of the missing data, 177 periods, occurred during small stream discharges, such as day 212-219 and 220-232, when coarse sediment movement was unlikely. The remaining 61 missing periods occurred during flows which may have produced sediment movement. The recorded pulse rates from these periods were evaluated individually and all but two periods were categorized as either rest or motion periods. The most common problem that produced missing data in the original filter was a recorded pulse rate that was double either the rest or motion pulse rate. These periods could be reliably reassigned by halving the recorded pulse rate. Therefore the motion data for this rock appears to be complete and the patterns of the motion periods shown in Figure 3 are reliable and appear to be the actual sequence of rest and motion periods for this particular rock.

The sequence of motion events during a single flood event includes both single 4.5-min periods of motion and multiple consecutive periods of motion. A single motion period indicates that the rock rolled over and stopped and did not move again for two scan periods, or 9 min. Consecutive motion periods indicate that the rock moved once to initially trip the motion sensor, and then moved again sometime before the end on that period (4.5 min) to register a motion pulse rate on the subsequent scan in the scan sequence. The record of motion would be the same whether the rock moved only once at the beginning and once near the end of the period, or moved continuously throughout the period.

For the first flood event, on day 219 (Fig. 2 and 3), 22 motion periods were recorded, seven single period events and three multiple period events, one of which spanned seven motion periods. A location survey after this flood event measured a travel distance of 2 m for this rock. This results in an average travel distance of 0.091 m per motion period. Based on the median diameter of 74 mm and the total number of motion periods, the movement of this particular rock during this flood event can be characterized as rolling an average of 0.4 revolutions per motion period. Based on the ten motion events, the rock moved an average travel distance of 0.2 m per motion event or 0.86 revolutions per event. These are averages and do not account for sliding or bouncing, nor do they take into account the possibility that the majority of travel may have taken place during one event, perhaps the event of seven consecutive motion periods.

The frequency distribution of consecutive motion periods for all the motion events of this rock during its transport through the study reach is shown in Figure 4. A total of 201 periods of motion were recorded which were divided into 76 separate motion events, 34 single period events and 42 multiple period events. As was done for the first flood event, a similar analysis of the average travel distance can be performed for the remaining motion events.

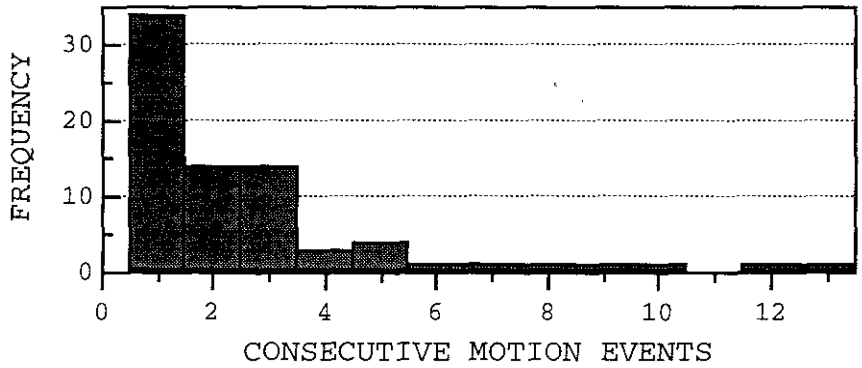

Figure 4. Frequency distribution of consecutive motion events (4.5-min period) for rock 164.301 transported through the study reach of 362 m.

Since the remaining motion events occurred after day 238, during much higher flood events, all these data are lumped together. A travel distance of 360 m was covered in 179 motion periods, or 66 motion events between day 238 and 253. This results in an average distance of 2.01 m per motion period or 5.45 m per motion event. In terms of revolutions, this is 8.6 and 23.4 revolutions per motion period and motion event respectively. It appears that the higher flows following day 238 resulted in longer travel distance (i.e., larger step lengths) per motion period of the rock. Further analysis along these lines await additional data from rocks of various sizes and flow conditions.

An additional observation of interest is the relation between flows at the initiation of motion and the end of motion for the flood events. With the exception of the single period motion event of day 248, motion did not begin during a flood event until flow equaled or exceeded the flow at which motion ended during the previous flood event (Table 2). This is offered only as an observation at this time and interpretation awaits the availability of additional data.

<u>Travel time over a known travel distance</u> The reach exit dates provide a second type of data from which analysis of travel times of all the radio-tagged rocks can be undertaken. The actual exit times from the study reach were recorded for the monitored rocks and are plotted on the hydrograph in Figure 5. The exit time for the unmonitored rocks was estimated based on the periodic location surveys. The rocks were placed in the river on day 205 and first surveyed on day 212 at which time no transport had taken place. The next survey on day 220, following a small flood event, measured some transport, but none of the radio-tagged rocks had exited the study reach. However, by

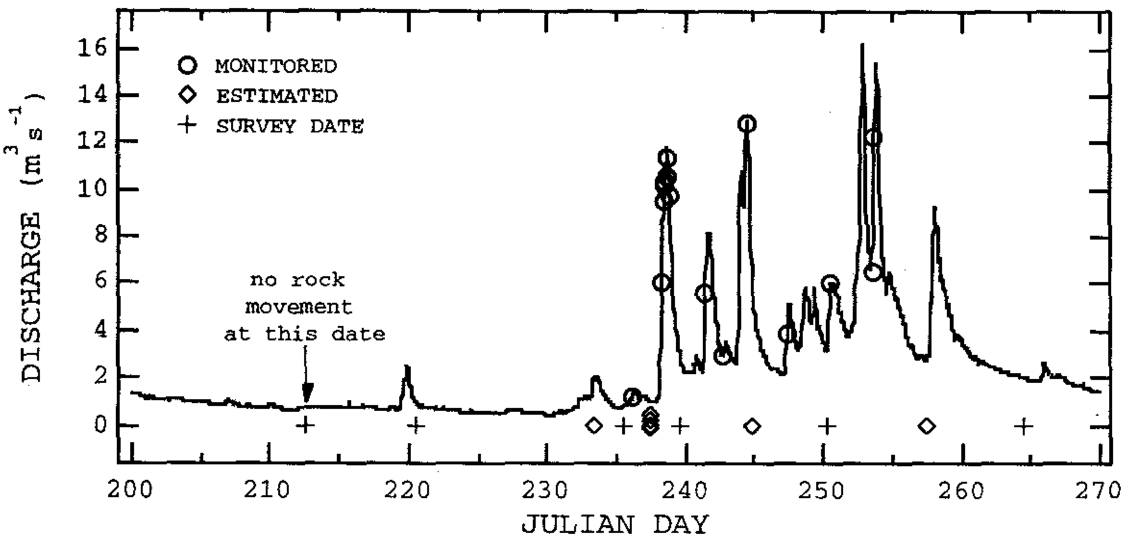

Figure 5. Discharge hydrograph showing the time the radio-tagged rocks exited the study reach (travel distance of 362 m). Monitored rocks are shown on the hydrograph, unmonitored rocks are shown as estimates between the dates of the location surveys.

the next survey on day 235, also following a small flood event, one unmonitored rock had left the study reach. It seems likely that the time of exit occurred during the small flood event on days 232-234. The exit time is estimated to be at the time of peak flow, day 233.5. The exit times for the remaining unmonitored rocks occurred during the large flood events after day 238 and were estimated as mid-way between the surveys dates (Table 1).

Two of the radio-tagged rocks had exited the study reach during relatively low flow events prior to day 238. The series of large floods beginning on day 238 was sufficient to transport all but one of the remaining radio-tagged rocks through the study reach. The one rock which was not transported out of the study reach was recovered at the end of the field season in the lee of a large, embedded boulder. In all but two cases, the monitored rocks exited the study reach on the rising limb or near the peak of the individual flood hydrographs.

The exit date is an indication of the time required for an individual sediment particle to travel the distance of the study reach, and, as such, can be used to address the effect of various sediment parameters on the transport time. In Figure 6, the exit date is plotted as a function of the weight of the sediment particles (Table 1). There is some scatter in the data and no clear relationship between weight and travel time is apparent; however, some trends are discernible. All rocks weighing less than 750 g exited the study reach by day 242, the second large flood event. The lightest rock (144 g) was the first to leave the study reach, and the other rock lighter than 200 g may also have exited the study reach before the first large flood event. However, the only other rock known to have exited the study reach before the first large flood event weighed 802.1 g, almost midway through the weight range. The heaviest rock (1793.9 g) did not exit the study reach (traveled about half the length), although a rock of nearly the same weight (1790.8 g) exited the study reach during the first large flood event. Rocks of weights between 750 and 1800 g traveled through the study reach with an apparent equal likelihood of exiting the study reach by a given date.

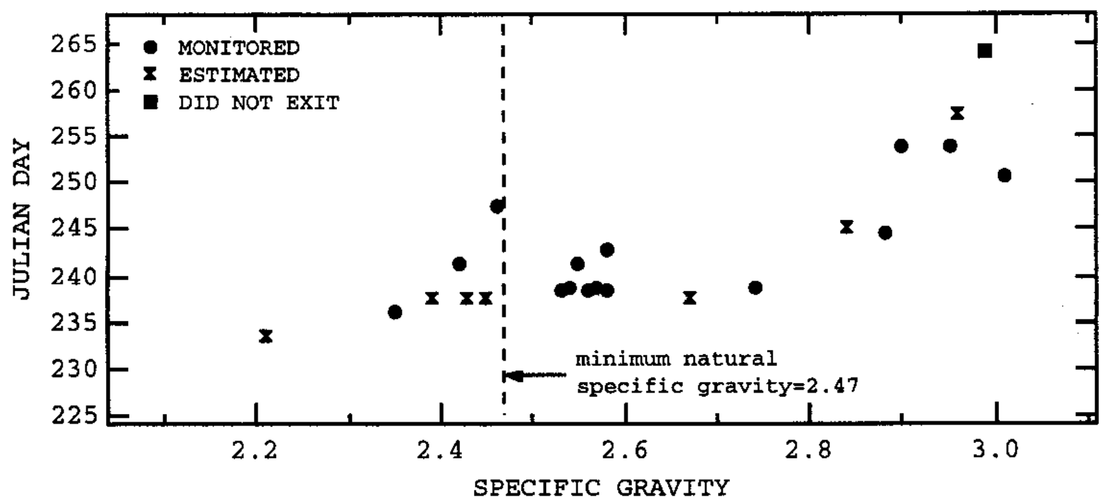

Figure 6. Date at which radio-tagged rocks exited the study reach (travel distance of 362 m) versus weight of individual particles.

In addition to particle weight, a number of other sediment parameters were investigated to find a relation between travel time and the material being transported. Various size and shape parameters (i.e., length, flatness ratio, volume ratio) were investigated. All showed considerable scatter except for specific gravity (Fig. 7, Table 1).

The two rocks known to have exited the study reach before day 238, the start of the very large floods, had the lowest specific gravities (Fig. 7). It is also possible that the remaining rock with a specific gravity below 2.4 may have exited the study reach before day 238. Rocks with a specific gravity above 2.9 required the longest time to exit the study reach. At specific gravities between 2.4 and 2.9 there was an apparent equal likelihood that a rock would travel the length of the study reach by a given date at the very large flows experienced in 1990.

The installation of the radio transmitter in the sediment particles reduced the specific gravity 0% to 18%, depending primarily on the size of the particle; smaller particles were affected more, larger particles were affected less. The minimum natural specific gravity of the radio-tagged rocks was 2.47. No attempt was made to correct to natural specific gravity during this study. Based on this limited data set, it appears that weights of the radio-tagged rocks should be corrected to maintain a minimum specific gravity of 2.4 for this particular stream. As a general rule of

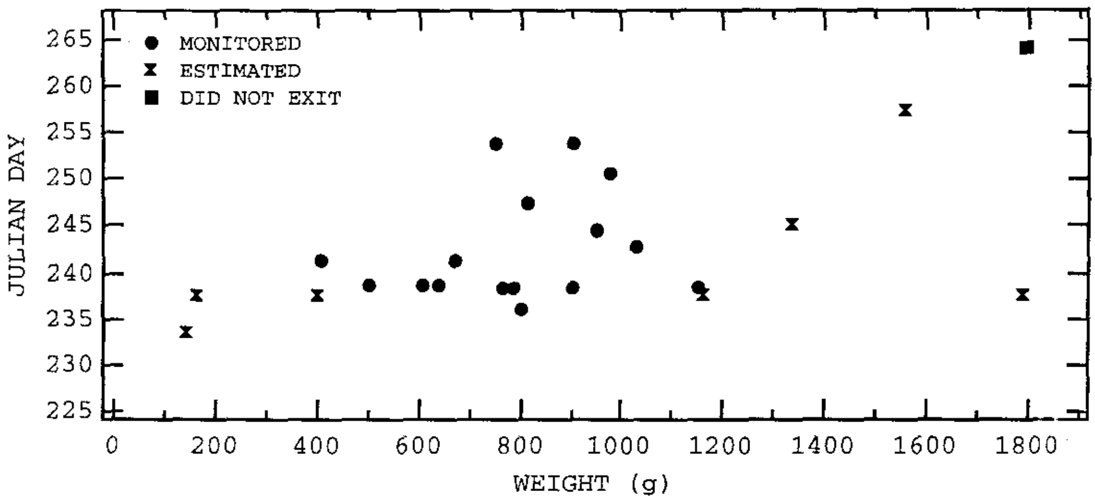

Figure 7. Date at which radio-tagged rocks exited the study reach (travel distance of 362 m) versus the specific gravity of individual particles.

thumb in future studies, weights should be corrected to maintain the minimum natural specific gravity of the material in the study stream.

SUMMARY

The use of implantable radio transmitters and an automatic data acquisition system can provide sediment transport data that was not previously available. An initial application of the system has demonstrated that a record of the rest and motion of coarse sediment can be acquired and related to sediment and hydraulic parameters. In a low magnitude flood event, a monitored sediment particle moved an average distance of 0.2 m per motion event over 10 motion events. During a series of five higher magnitude flood events, the same particle moved an average distance of 2.01 m per motion event over a total of 66 motion events.

Travel distances and the timing of transport can also be acquired. The relationship between periods of motion of a monitored sediment particle and flood hydrographs were shown. The time of travel of various size sediment particles over a known distance was monitored during a series of flood events. Results show the relationship between travel time and sediment weight is scattered while a much better relationship existed for travel time versus specific gravity. More data, under various hydraulic conditions is required to better define the relationships.

Application of the techniques described in this paper will result in unique data sets, that should be beneficial in understanding and modeling coarse sediment transport processes.

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PARTRIDGE CREEK: A CASE STUDY IN MONITORING A HIGH GRADIENT STREAM

By William G. Ypsilantis, Soil Scientist, U.S. Bureau of Land Management, Coeur d'Alene, Idaho, Craig A. Johnson, Fisheries Biologist, U.S. Bureau of Land Management, Cottonwood, Idaho

Abstract: Development, implementation, and monitoring of Best Management Practices (BMPs) for control of sediment in mountain streams is documented in this case history. The study area is situated on Partridge Creek, a high-gradient, fourth order tributary of the Salmon River in west-central Idaho that provides spawning and rearing habitat for rainbow/steelhead trout and rearing habitat for endangered populations of chinook salmon. High fishery values associated with this stream resulted in development and implementation of site-specific BMPs for salvage logging operations following wildfire in 1989. Monitoring documented implementation and local effectiveness of the BMPs and protection of beneficial uses, as well as sources of erosion, sedimentation, and cumulative impacts. Monitoring also clearly demonstrated problems associated with techniques for instream sediment monitoring in high gradient channels. A feedback loop developed to modify practices that were not working also is described. Monitoring results and conclusions and the lessons learned are summarized in the paper.

INTRODUCTION

A monitoring plan was developed by the Bureau of Land Management (BLM) for proposed fire salvage in the Partridge Creek watershed. This plan was also developed with the Partridge Creek Local Working Committee to monitor site specific BMPs and achievement of objectives established for the stream segment of concern. Partridge Creek was the first stream segment of concern to have a local working committee convened under Idaho's antidegradation program. The site specific BMPs and monitoring plan were pilot efforts in Idaho for designated stream segments of concern. The plan has subsequently been modified to include monitoring identified from Section 7 (Endangered Species Act) consultation on listed salmon with the National Marine Fisheries Service.

Wildfires can significantly increase surface erosion and mass wasting, with corresponding increases in sediment delivery to stream channels. During 1989, approximately 44 percent of the Partridge Creek watershed burned and during the summer of 1994 an estimated 4 percent of the watershed reburned. To assess salvage logging and fire related impacts, a monitoring station was established above logging related impacts (Station 3, stream km. 5.8). Two monitoring stations are located below logging activities (Station 1, stream km. 0.3 and Station 2, stream km. 3.9). The area updrainage from Station 3 is roadless.

Munther and Frank (1986) evaluated logging and roading activity by rating the degree of substrate sediment deposition within a stream by measuring the relative "embeddedness" of that substrate. Embeddedness has been demonstrated to be a key characteristic in describing fish habitat suitability (Burns 1984, Munther and Frank 1986, Burton and Harvey 1990). The interstitial space found in streambed cobble habitats is very important to juvenile salmonids as overwintering habitat, and for feeding and refuge cover during the summer months (Burton and

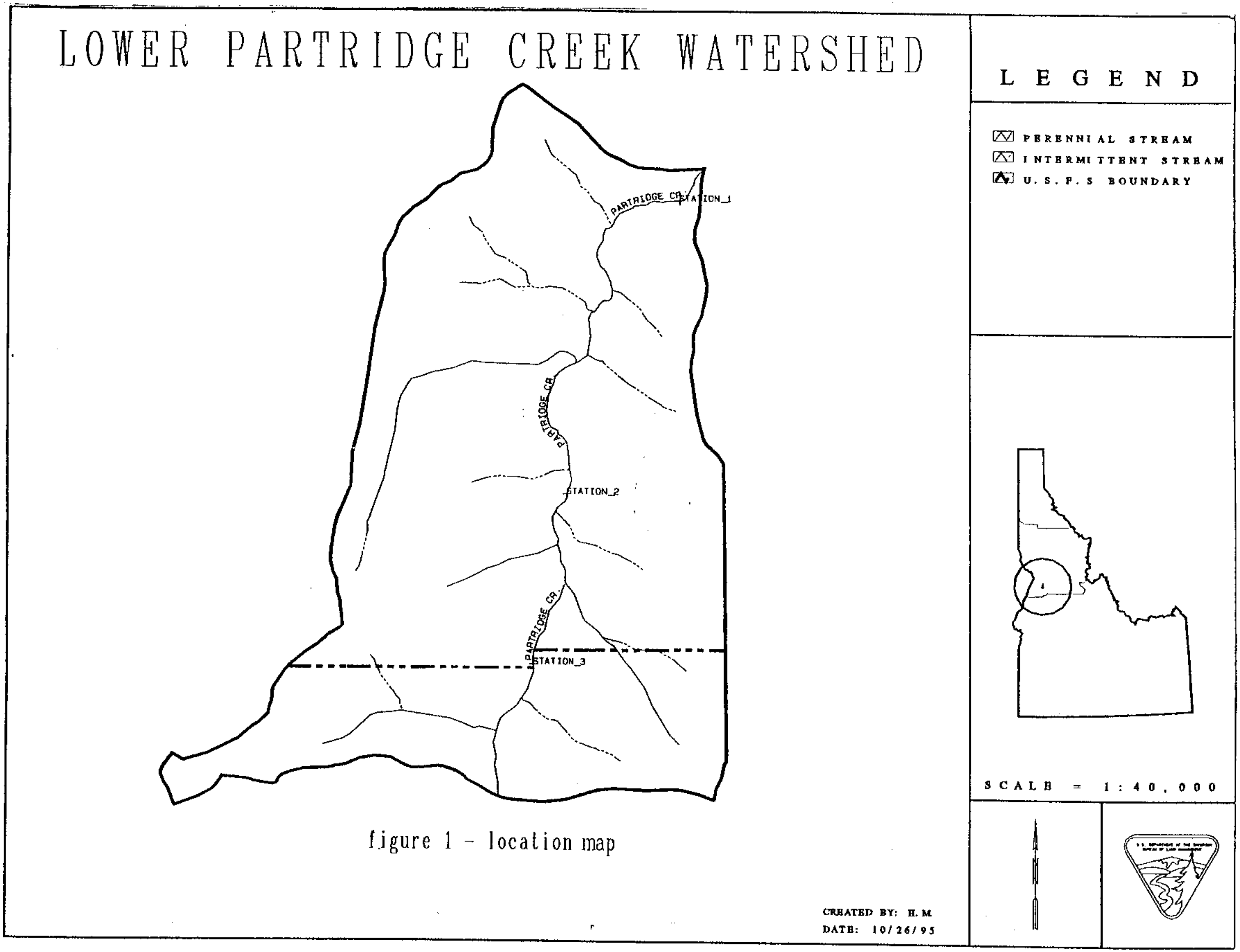

figure 1 - location map

Harvey 1990). If this habitat is not available, they must either find other suitable habitat by migrating or find replacement overwintering habitat (Bustard and Narver 1975, Hillman, Griffith and Platts 1986). As the amount of deposited sediment (embeddedness) increases, the quality of instream cover decreases. Embeddedness levels have been used to evaluate suitability for spawning, egg incubation and macroinvertebrate habitat (Munther and Frank 1986).

According to McDonald et. al. (1991), when developing a monitoring plan, the physical environment must be considered because specific parameters will vary in terms of (1) the values that can be expected under undisturbed conditions, (2) their sensitivity to different management practices, and (3) their usefulness in detecting a change in water quality. Rosgen (1994) developed a classification system in which a morphological arrangement of stream characteristics is organized into relatively homogeneous stream types.

STUDY AREA

Partridge Creek, located in west-central Idaho, is a steep gradient, fourth order tributary of the Salmon River. This 8,000 hectare watershed ranges from 1835 feet elevation at the mouth to 7,790 feet at the top. Annual precipitation ranges from 16 inches at the lower elevations to 26 inches at the higher elevations. Most occurs as snow fall. The stream flows through a V-shaped canyon with steep side slopes of 50 to 90 percent. Soils in the drainage are derived from granitic and other metamorphic rocks. They are highly erodible and susceptible to mass wasting. Vegetation ranges from grass communities at the lowest elevations to mixed conifer forests to subalpine forest at the highest elevations.

High energy characterizes Partridge Creek with stream gradients between five and nine percent and an A2 channel type (Rosgen 1994), dominated by rubble and small boulder sized substrate. Water quality is generally very high with sediment being the principal pollutant. Discharge ranges from 160 to 300 cfs during Spring runoff to 7 to 9 cfs during low flows.

Partridge Creek provides spawning and rearing habitat for rainbow/steelhead trout in the lower reaches. It also provides juvenile rearing habitat for the endangered Snake River spring/summer chinook salmon.

In 1990, the BLM harvested 3.5 million board feet of timber from lower Partridge Creek by helicopter logging 234 hectares and high lead and tractor logging 23 hectares. The Idaho Department of Lands (IDL) harvested a total of 8.15 million board feet, 197 hectares by helicopter and 62 hectares by high lead and tractor. The BLM and IDL constructed a total of 7 kilometers of new road. In addition, tractor and high lead logging occurred on approximately 200 hectares of private land and several miles of new private road were constructed.

The BMPs the BLM implemented on the existing steep gradient road included graveling approximately three miles of the road, constructing 20 rolling dips, installing 3 culverts, placing several flexible drainage structures in the road, seeding the cut and fill slopes, and hand placing slash filter windrows at sediment sources near the creek.

On June 4, 1990, a large slump occurred on private land on the east side of Partridge Creek due to failure of an old road. Approximately 450 to 700 metric tons of sediment reached the creek from that slide causing major concerns about impacts to the beneficial uses.

MONITORING PROCEDURES

The primary objectives for the Partridge Creek Monitoring Plan are as follows:

1. Document and monitor implementation and effectiveness of site specific BMPs for protecting and maintaining beneficial uses and water quality.

2. Document and monitor existing and new nonpoint source erosion and erosion/sediment reaching live waters.

3. Provide a feedback loop to modify management activities and BMPs that are not effective in reducing erosion and sediment delivery.

Sediment was the primary pollutant being monitored. As defined by Clark (1990), the objective of pollutant source and transport (PST) monitoring is to determine if BMPs were effective in preventing significant amounts of sediment from entering the water or channel systems that directly access the waters. Instream substrate monitoring protocols are summarized as follows:percent cobble embeddedness, percent free matrix particles, interstitial space index, percent surface fines, Wolman pebble count, and spawning gravel size distribution by depth (core sampling).

Other monitoring that was conducted includes the following: BMP implementation and effectiveness monitoring, photo points, road monitoring after precipitation events (spring and fall), sediment trap monitoring of intermittent and perennial streams, and greenline transects of streambanks.

Intensive surveys were also conducted for riparian areas and for fish habitat. Fish habitat surveys were conducted using Hankins and Reeves methodology (1988) which has been modified (Johnson 1994).

Cobble embeddedness sampling done prior to 1990 used a methodology developed by Burns (1984). Subsequent sampling used a consensus method developed by Skille and King (1989). A 60 centimeter sampling hoop was used for cobble embeddedness, free matrix particle sampling, and interstitial space index. Twenty one to thirty hoops were sampled at each station, except only two to three hoops were sampled for cobble embeddedness prior to 1989. Interstitial space index methodology developed by Skille and King (1989) and Burton and Harvey (1990) was used. Stream channel bed material size distribution was determined using a technique described by Wolman (1954). Core sampling of spawning gravels was measured according to a modification of the method described by McNeil (1964). Greenline methodology (Cagney 1993) was used to measure vegetation trends on streambanks.

BMP implementation was determined by documenting when and where specific mitigation took place. Effectiveness monitoring was conducted over the entire project area, with primary emphasis on roads and areas that were rated as high sediment delivery zones (within 90 meters of intermittent and perennial stream channels), Monitoring focused on periods after precipitation, primarily during the fall and spring. Active erosion and visual evidence of it reaching live water was recorded. Photos were taken of active erosion areas and mitigation measures that were implemented.

Monitoring channel sediment storage behind obstructions in a perennial and intermittent stream was conducted using a methodology described by Megahan (1982). This method was modified with the use of constructed "sediment traps", rather than monitoring "natural" obstructions. The sediment traps were constructed out of logs and filter cloth.

Monitoring was closely coordinated with IDL, US Forest Service and Idaho Division of Environmental Quality (DEQ). Monitoring methods and monitoring stations were established so that specific nonpoint activities could be evaluated.

RESULTS AND DISCUSSION

Overall monitoring objectives were met by instream aquatic monitoring and evaluating the effectiveness of site specific BMPs. Substrate monitoring provided no conclusive documentation that timber harvest related activities resulted in increased deposition of sediment. Increased deposited sediment levels can adversely affect spawning and rearing habitat. Salmonid production has been shown to be inversely proportional to cobble embeddedness and fines in spawning gravels (Stowell et al 1983, Chapman and McCleod 19887, Bjornn and Reiser 1991). Cobble embeddedness levels of 50 to 60 percent result in the departure of fry from the area (Chapman and McCleod 1987). Cobble embeddedness in excess of 70 percent has also been shown to cause alteration in macroinvertebrate abundance and diversity (Bjornn et al 1977).

This discussion of substrate monitoring will focus on cobble embeddedness and core sampling. Cobble embeddedness monitoring and sample size resulted in no significant differences between the stations for 90 to 95 percent confidence limits (see Figure 2). However, unexplainable sampling problems were evident during 1992 and 1993 at station 1 and 1991 at station 3. Because cobble embeddedness trend monitoring resulted in a decline the following year, with no significant increase in peak discharge, it may be assumed that sampling error was involved. The monitoring station located at stream kilometer 5.8, the US Forest Service boundary, provided a good control or reference, primarily because the area is roadless and hasn't been logged. Sediment delivery was documented as reaching Partridge Creek, however, steep gradients and flushing flows resulted in no detectable trend increases.

Core sampling of spawning gravels detected changes in percent fines. However, the data is difficult to evaluate because of fluctuations (see Table 1). It should be noted that spawning gravels are limited in this steeper gradient stream, and sampling consistency may be a problem. Spawning gravels are located primarily in deposition areas, such as stream margins or behind boulders and woody debris. Monitoring of "key" deposition areas can be a problem especially when deposition can vary as a result of annual peak discharge events.

Probably, the most beneficial monitoring for evaluation of past and present land uses which

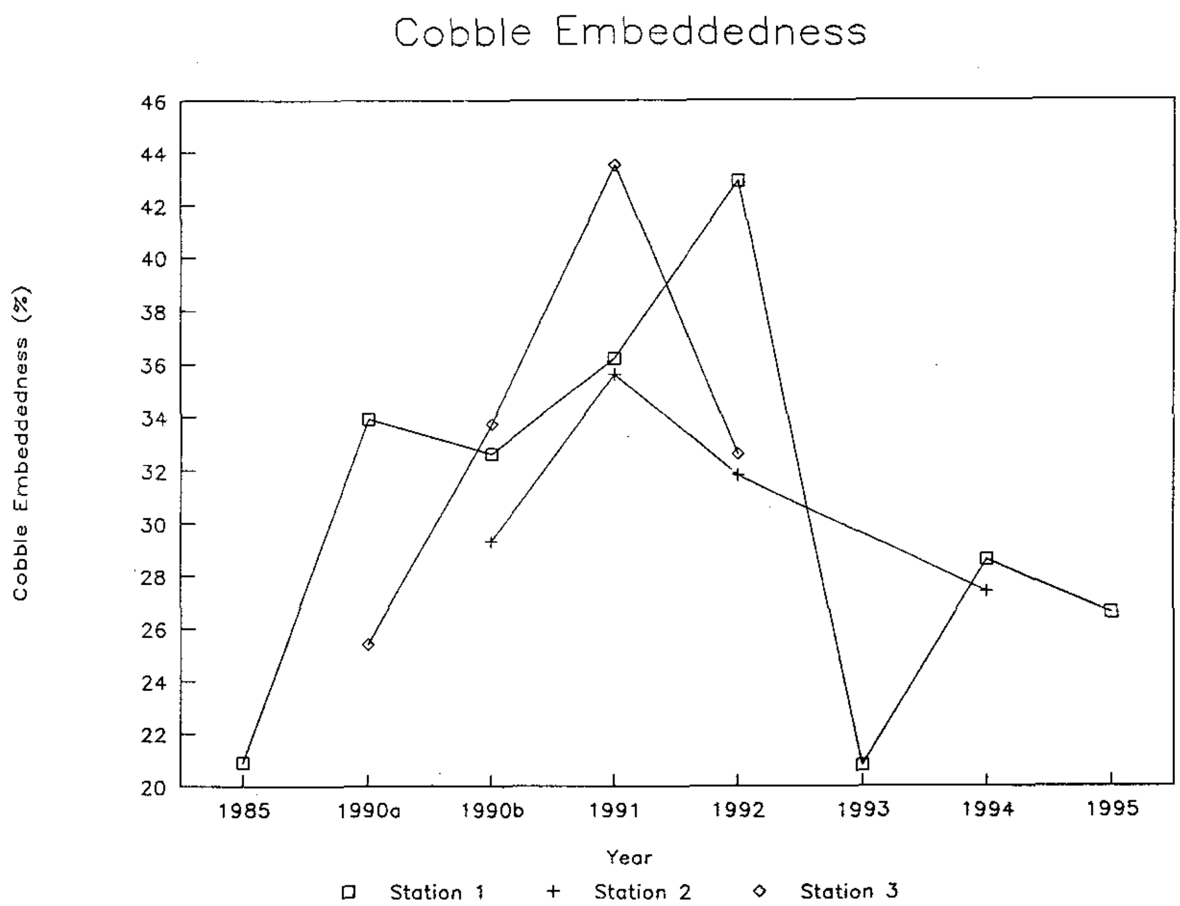

Figure 2. Cobble Embeddedness Monitoring - Partridge Creek, Idaho

Table 1. Core Sampling of Spawning Gravels - Partridge Creek, Idaho

Station	Year	% <9.5 mm	% <6.3 mm	% <.85 mm
1	1995	29.4%	23.6%	7.1%
	1994	35.4%	29.0%	7.6%
	1993	29.6%	24.9%	7.9%
	1990	34.0%	28.3%	6.4%
	1985	17.9%	14.1%	4.1%
2	1994	49.6%	42.0%	9.4%
	1990	24.3%	19.2%	5.0%
3	1990	24.9%	20.0%	5.7%

contribute to nonpoint source sediment was site specific implementation and effectiveness monitoring. The majority of erosion and sediment contribution to Partridge Creek was from the existing road system and/or drainage structures that failed. Other erosion and sediment sources were attributed to road improvement actions and new road construction. The existing road system, because of steep gradients and steep, erosive side slopes, presented major problems for installing proper drainage structures and reducing erosion.

Small order stream channels have the potential to store a large volume of sediment behind obstructions, such as logs and other debris. Megahan (1982) found an average of 15 times more sediment was stored behind obstructions than was delivered to the mouths of the drainages as annual average sediment yield. The majority of most sediment deposition measurements are made in fish-bearing streams. However, once sediment is delivered to streams providing fish habitat, the adverse impacts have already occurred. During the first year after construction of sediment trapping structures in a perennial tributary to Partridge Creek, the traps were 80 to 100 percent full. General observations and monitoring conducted in the perennial draw concluded that fire probably resulted in 95 percent of the accelerated erosion and road construction/timber harvest accounted for one to five percent. Even though the intermittent draw appeared to have minimal to no flows in the bottom, the traps were estimated to be 10 to 50 percent full the first year and 100 percent full after two years. General observations concluded that fire induced erosion accounted for 95 to 100 percent of the erosion and deposition in the intermittent draw.

SUMMARY AND CONCLUSIONS

Standard techniques for instream sediment monitoring in high gradient streams may not be sensitive enough to detect sediment delivery and movement through the system.
To properly complete the "feedback loop" and modify projects before sediment is deposited in fish-bearing streams, it is recommended that adequate site specific BMP monitoring and monitoring of small order tributaries be conducted. However, fish-bearing streams also need to be monitored for maintenance of beneficial uses. Cumulative impacts must be addressed; BMPs alone will not necessarily protect the beneficial use.

Other lessons learned from this case study are that close cooperation between agencies can save time and effort in monitoring. A comprehensive monitoring plan is needed by agencies to develop an efficient, cost effective monitoring program that will provide the information needed to implement management decisions. BMP implementation monitoring immediately after high precipitation events is vital to determine effectiveness. The timing of BMP implementation is very important. If they are not implemented as soon as possible their effectiveness will be greatly reduced.

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NOTES

SEDIMENT LABORATORY QUALITY: ARE YOU ASSURED?

***By* John R. George, Hydrologist, Emeritus, Evergreen, Colorado, USA, and LeRoy J. Schroder, Hydrologist, U.S. Geological Survey, Denver, Colorado, USA**

Abstract: Since the early 1950's, the U.S. Geological Survey has supported several Water Resources Division laboratories that routinely analyze river samples (suspended sediment and bed material) for suspended-sediment concentration and particle size. In 1992, the U.S. Geological Survey Office of Surface Water reviewed each of 19 laboratories to observe the quality of laboratory operations and determine the need for more rigorous quality assurance of laboratory processes and results. The reviews revealed: (1) Occasional departures from documented procedures, (2) a lack of state-of-the-art equipment, (3) few quantitative laboratory quality-assurance plans, (4) a need to document quality-control practices, (5) a lack of a National training policy, and (6) a tendency to over-emphasize production.

This report presents results of the laboratory reviews and the processes underway to establish a comprehensive quality-assurance program.

INTRODUCTION

In 1991, the Water Resources Division (WRD) of the U.S. Geological Survey (USGS) initiated a quality-assurance program for its laboratories that routinely analyzed fluvial-sediment samples. Table 1 summarizes the analytical output of WRD laboratories in 1991.

Table 1. Sediment Analyses Performed by WRD Laboratories in 1991

Analytical Processes	Total Number of Samples
Suspended-sediment concentration by filtration or evaporation method	62,000
Sieve separation of sands from finer sediments	12,000
Sieve separation of sands and coarser sediments	7,000
Particle-size distribution of sands using the visual accumulation tube	2,400
Particle-size distribution of sediment finer than sand (<0.0625 mm) using pipet or bottom withdrawal tube method	1,200

WRD Office of Surface Water (OSW) proposed to assure the quality of these laboratories by implementing the following steps: (1) Provide refresher training in laboratory procedures for all laboratory chiefs, (2) guide preparation of quality-assurance plans for each laboratory, (3) review each laboratory and its operations, and (4) initiate a standard reference-sample program for validating each laboratory's measurements of suspended-sediment concentration and particle-size distribution. This report discusses current progress in assuring the quality of the analytical products of these laboratories with special emphasis on the reviews and subsequent measures taken to improve quality assurance. This report also offers guidance to others operating similar laboratories.

QUALITY ASSURANCE

Quality assurance for a laboratory has been described as "... the application of prescribed practices necessary to minimize the systematic and random errors involved in personnel, instruments, reagents, supplies, analytical methods, data handling, and reporting." (Winter and others, 1993). Quality assurance has never been a simple issue for sediment laboratories. The analytical procedures and the quality-assurance philosophy for sediment laboratories were provided to the laboratory chiefs in reports by Matthes and others (1992), and Knott and others (1992). In a WRD sediment laboratory, however, several "givens" are missing. Duplicate samples? Hardly feasible. Replicates? Spikes? Splits? For a variety of technical reasons, these alternatives have either not been available or not practical for fluvial-sediment determinations. In a sediment laboratory, the analytical quality often may be only generally measured by the apparent procedural care afforded by the analyst. Quality of results is seldom challenged. Concerns for laboratory precision are often far outweighed by questions of representative river sampling. Little has changed for sediment laboratories for the past 50 years. Now, there are more reliable filters, more accurate balances, and auto-particle-size analyzers. However, there is very little new in terms of quality assurance.

BACKGROUND

In the mid-1940's, the USGS began providing a greater variety of hydrologic information for agencies of federal, state, and local governments. This was an era of planning for several major hydroelectric, flood-control, and irrigation-development projects. Sediment-transport data were important for reservoir and irrigation-channel design. As a result, WRD established several laboratories throughout the country, often collocated with its water-chemistry laboratories. It was relatively simple to use part of the chemistry laboratory for sediment analyses. This arrangement, often under the scrutiny of a senior chemist, helped provide ongoing respect for careful analytical procedures as well as for proper use and care of laboratory equipment. By the mid-1950's, there were at least 14 laboratories performing analyses of river samples collected by USGS field personnel for suspended-sediment concentration and particle size of river samples. These laboratories were making determinations using methods that did not include quality-assurance practices.

Laboratory methods conformed to: (1) Soils and sediment textbooks (Baver, 1956, Krumbein and Pettijohn, 1938, (2) industrial processes for analyzing coarser sediments using sieves (Tyler, 1991), and (3) several particle-size methods developed or refined by the Interagency Subcommittee on Sedimentation (U.S. Interagency Committee on Water Resources, Subcommittee on Sedimentation, 1943, 1953, 1958), and (4) Methods recommended by the American Society of Testing Materials (1986 and 1992). Differences in methods used by WRD laboratories were often related to the diverse nature of erosion and sediment transport throughout the country. Western rivers carry very high (tens to hundreds of thousands of mg/L) concentrations of sediment and usually more sand than western rivers. Western laboratories found the filtration process to be slow and sometimes unworkable. Those laboratories favored the evaporating dish method for determining sediment concentrations. Conversely, northwestern and northeastern rivers in the United States carried less sediment. These laboratories determined that filtration was quicker and more efficient. These kinds of regional characteristics also produced differences in particle-size methods that were used in the laboratories.

Guy (1969) provided WRD with the first written guidelines for performing laboratory sediment analyses. Many methods were presented in an historical, rather general manner. The manual offers the laboratories wide latitude both for procedure and technique. With few exceptions, the methods and techniques presented in Guy are the same that are used today.

In the 1970's, the USGS began periodic field reviews of the methods and techniques applied to data collection, analysis, interpretation, and reporting of results. These reviews of District offices were mostly intended to determine what was going on, discuss technical issues, share ideas and recommend alternative approaches. For sediment laboratory reviews, reviewers often returned with observations of unusual laboratory steps or procedures. Most WRD senior sedimentation scientists agreed that more detailed, formal reviews of WRD's sediment laboratories were needed.

SEDIMENT LABORATORY REVIEWS

As part of the newly agreed upon sediment-laboratory quality-assurance program, reviews of all laboratories were scheduled for 1992. Between April and September 1992, two-person review teams visited and reviewed 18 WRD laboratories and one contract laboratory. The teams consisted of laboratory chiefs and senior WRD sedimentation scientists. Reviews required 1-3 days to complete. Specific methods that were reviewed are shown on Table 2.

Table 2. Methods Reviewed in WRD Laboratories, 1992

SUSPENDED-SEDIMENT CONCENTRATION (Guy, 1969)

Decant and Filtration
Decant and Evaporation
Whole Sample Filtration

PARTICLE-SIZE DISTRIBUTION (Guy, 1969)

Particles with a mean diameter greater than 0.0625 mm
Wet sieve
Dry sieve with shaker
Visual accumulation tube
Particles with a mean diameter between 0.002 and 0.0625 mm
Pipet
Bottom Withdrawal Tube
Sedigraph 1/ (Micromeritics, 1982; American Society of Testing Materials, 1992)

Review direction was provided via guidelines supplied by the sedimentation specialist on the OSW staff (Glysson, 1989).

Points of common concern resulting from the reviews included:

Equipment: About one-half the laboratories received recommendations for equipment repair, augmentation, or replacement.

Training: Documentation of training activities for laboratory operations was not available.

Quality-Assurance Plans: Less than one-half of the laboratories had working QA plans.

Quality-Control Measures: Only a few measures were in place and even fewer with adequate documentation.

Procedures: Several laboratories introduced non-standard procedures or techniques that had potential for producing inconsistent results.

1/ The use of brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Review reports recommended steps to resolve most of the issues described above. The review teams proposed that quality-control procedures and appropriate documentation be established to assure the validity of the following laboratory procedures, which are considered to have greatest impact on analytical results:

- Use of blank samples for the filtration and evaporation methods.
- A method for estimating and correcting evaporation loss from sample containers during field and laboratory storage.
- A test for sampling the decant water for presence of sediment.
- A quality-control rinse for sample bottles.
- A test rinse for the wet-sieve procedure.
- Documentation of the dissolved-solids correction for concentration analyses performed with the evaporating-dish procedure.
- A quality-control process for ovens for both temperature monitoring and oven maintenance.
- A quality-control process for micro-balance maintenance, use, and calibration.
- A quality-control process for maintenance and use of desiccators.

REFERENCE SAMPLES

In 1992, the USGS prepared and distributed 9 test samples containing clay, silt, and sand-sized sediments for concentration analyses by 17 WRD laboratories. Sample masses ranged from 10 to 270 milligrams. A comparison of analytical results indicates that the filtration method routinely produced a result lower than the original reference mass. The median loss was 3.6 percent, of which 1 to 2 percent appears to be material lost through the Whatman No. 934-AH glass fiber filter (Schroder, 1992).

In 1994, a set of 6 test samples, containing pre-measured amounts of sand, silt, and clay-sized sediment, was distributed to 3 WRD laboratories with experienced capability in the Pipet analysis of fluvial sediments finer than 0.0625 mm. The results produced a median error of +4.4 percent for the 0.002 mm sediment and -0.5 percent for the 0.032 mm size. The results (Schroder, 1996) suggest that reference materials in the particle-size class finer than sand (0.0625 mm) can be prepared with significant precision for both concentration and particle-size analyses. The results appear to satisfy reasonable accuracy criteria for routine analytical testing.

DEVELOPMENT OF QUALITY-ASSURANCE MEASURES

The sediment-laboratory chiefs met in Vancouver, Washington, in May 1994. Discussions were directed to the development of quality-assurance measures to address some of the critical laboratory review comments of 1992. Work groups of laboratory chiefs agreed to develop quality-control protocols for the following processes: (1) Sample evaporation, (2) desiccator maintenance and use, (3) maintenance, use, and calibration of balances, (4) maintenance, use, calibration, and temperature monitoring of ovens, (5) decant process, (6) filtering, (7) use, cleaning, and storage of glassware, (8) sample blanks. Soon after this meeting, the work groups submitted draft reports describing proposed quality-control protocols. In response to these reports, each laboratory was asked to incorporate their work group's recommendations into their operation and report later on progress, problems, and recommendations. At this writing, this process is underway in most participating laboratories. The data derived from the proposed quality-control procedures, along with further reference-sample testing, should permit development of reasonable measures of precision for the bench methods presently used.

APPLICATION OF THIS QUALITY-ASSURANCE PROGRAM

How does WRD's review and qualification process apply to others? Consider the early goals: (1) Enhance awareness of the need for quality-control measures, and (2) Involve laboratory managers in sharpening methods and procedures, and establishing quality controls where needed. Here are our recommendations:

- Designate a senior scientist within your organization as ad hoc quality-assurance manager for the laboratory. This person will report only to top management and should not have any production responsibility in the laboratory.
- Take no existing process for granted. Call in a team of outside specialists to review and discuss all laboratory procedures. Have them follow up with a detailed, critical report that includes recommendations for high-priority quality-control measures, both short term and long term.
- Develop a laboratory quality-assurance plan that presents detailed methods and procedures. This plan must describe quality-control steps and documentation.
- Obtain refresher training for all processes from outside laboratory personnel who have strong backgrounds in methods, procedures, and quality control.
- Get management involved. This may be the only opportunity to demonstrate that quality improvement will save time and money.
- Acquire and regularly use reference samples.
- Encourage communication and visitation with other laboratories. This heightens awareness and encourages greater focus on quality.
- Document! Document! Document! Neither routine nor unique quality-control measures will help unless there are clean "tracks."

- Keep the laboratory chief fully involved. Some methods for increasing production introduce new error. The chief will appreciate quality control more when it is possible to measure comparative errors and their long-term costs.

SUMMARY

A concluding thought goes back to the original concern for laboratory products. Reasonable measures are needed for showing how well, or how poorly, the laboratories are performing. Without a well designed quality-assurance program with appropriate quality controls, we can only rely on trust. That's not enough!

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A METHOD FOR EVALUATING SEDIMENT LABORATORIES

By **LeRoy J. Schroder, Daniel W. Shupp, H. Keith Long, and Edward J. Gilroy**
U.S. Geological Survey, Denver, CO, USA

Abstract: The U.S. Geological Survey operates laboratories to determine suspended-sediment concentration and the silt-clay fraction of the fluvial sample. A need was identified for a reference material for verification of the laboratory analysis of suspended sediment. A natural clay, available to monitor air-testing instruments, was chosen by the U.S. Geological Survey to test as a possible reference material. The first test samples of the reference material were prepared in 1991 and were distributed in 1992 for the determination of suspended-sediment concentration. The results from the 1992 test samples for sediment concentration indicated that the filtration method for concentration analysis routinely produced a low result. The median percent error was 3.6 for a mass range from 10 to 270 milligrams. In 1993, test samples were distributed for the determination of the silt-clay fraction of a sample, and the results indicate that the analyses of 2.2- and 2.7-gram samples were reproducible. The median relative standard deviation from pipet analyses was 1.5%, and the magnitude of the standard deviation was related to the reported particle-size fraction.

In 1994, an interlaboratory comparison was initiated using this reference material for both concentration and particle-size analyses. Eighteen laboratories received a 9-sample set for concentration analysis, and 3 laboratories received a 6-sample set for particle-size analysis. The preparation of a test sample, the analysis of the test sample, the approval of the test-sample material as a reference material, and the evaluation of laboratories using the reference material are recommended quality-assurance practices.

INTRODUCTION

The Water Resources Division of the U.S. Geological Survey (Survey) has conducted hydrologic studies and investigations of fluvial sedimentation for more than 45 years. As part of these studies, the Survey has operated laboratories for the analysis of the physical characteristics of sediment since initiating the study of fluvial materials. The Survey operated 17 sediment laboratories and contracted with one college in 1994 to provide concentration and particle-size analyses of suspended sediment. Twelve of these laboratories and the contract laboratory provided only suspended-sediment concentration analyses and particle-size determinations by dry sieving. Three laboratories provided concentration analyses, dry and wet sieving analyses, and particle-size determinations by pipetting and visual-accumulation analyses. Two laboratories provided a limited number of particle-size determinations using X-ray equipment. These 18 laboratories provided more than 63,000 suspended-sediment concentration analyses, 16,000 separations of sands from fines, and about 800 particle-size determinations in 1994.

The individual laboratory has been responsible for the quality assurance and quality control practices performed at that laboratory. Although the Survey has provided a methods manual (Guy, 1969), guidelines for quality assurance of laboratories (Matthes and others, 1991 and Knott and others, 1992), and a quality assurance plan for collecting and processing sediment data (Knott and others, 1993), the enhanced quality assurance program among the laboratories identified the requirement for interlaboratory comparison program. A reference material was needed to assess the results of the intercomparison program.

REFERENCE MATERIAL PREPARATION

The initial test samples were prepared in 1991 from 20 grams (g) of AC Spark Plug dust, batch number 1639 (AC dust) and 5 g of sand that had been dried at 105°C for at least 8 hours and cooled in a desiccator for at least 4 hours. The dust and sand were added to polyethylene vials. The total mass of dust and sand in each polyethylene vial was measured to the nearest 0.1 milligram (mg). After the dry material was added to each vial, 1 milliliter (mL) of deionized (DI) water was added to each test sample, and the samples were stored for about 3 months. After the test samples were analyzed by the Iowa City, Iowa, laboratory (see section titled "Reference Material Evaluation"), a second set of reference samples was prepared. This set of samples was composed of the AC dust without any additional sand added to the samples.

A third set of reference samples was prepared in June 1993 using only the AC dust for particle-size intercomparisons. The bulk dust was dry sieved through 125- and 63–μm openings. Material that was retained on the 125 μm sieve was discarded. The two aliquots (retained on the 63 μm sieve and in the pan) were recombined and dried at 103 ±2°C overnight and stored in an air-tight polyethylene bottle. Small amounts of the material were placed in a Heiruth Model 3100 computer-controlled powder-dispensing system, and the dust was dispensed into 20 mL polyethylene vials. About 10 reference samples were prepared before the dust exposed to the air was replaced with a fresh supply of dry dust and the process repeated.

The five masses selected for the individual reference samples were 0.010 ±0.001 g, 0.050 ±0.002 g, 0.200 ±0.003 g, 2.20 ±0.020 g, and 2.7 ±0.025 g. The equipment used to prepare these individual samples utilizes an analytical balance. The allowance variance at each mass range is programmed into the memory of the computer, and the dispensing speed is set by the equipment operator. This process resulted in a small number of individual reference samples that exceeded the target mass. These reference samples were discarded.

REFERENCE MATERIAL EVALUATION

Nine samples were evaluated by the sediment laboratory in Iowa City in December 1991. The percent error was calculated using the following equation:

$$PE = \frac{KM - RM}{KM} \times 100 \qquad (1)$$

where

PE is percent error,

KM is the mass of the sample determined gravimetrically in milligrams, and

RM is the reported mass from the Iowa laboratory in milligrams.

These samples contained 20% sand by mass, and the data for the evaluation of the samples are summarized in Table 1. The mass of each sample was reported to be less than the known mass determined gravimetrically when the samples were prepared.

Table 1. Data from nine test samples analyzed by the U.S. Geological Survey, Iowa City, Iowa, sediment laboratory in December 1991
[mg, milligrams]

Test sample mass (mg)	Percent error calculated with equation 1		
10-15	7.1	3.9	4.9
150-170	3.8	4.9	5.4
250-270	3.8	4.2	3.3

This systematic difference between the reported mass of the Iowa City laboratory and the known mass was examined by analyzing four additional samples. Four samples were analyzed twice using the standard procedure (Matthes and others, 1991) except that the filtrate was analyzed using an evaporation dish. Data from the evaporation dish analyses are summarized in Table 2.

Table 2. Data from the U.S. Geological Survey Iowa City, Iowa, sediment laboratory test of the four additional test samples in April 1992
[mg, milligrams; --, not reported]

	Percent error calculated by using the equation 1	
Approximate sample mass (mg)	First determination	Second determination
10-15	-1.6	--
150-170	2.9	3.1
250-270	2.3	2.9
250-270	2.0	2.1

A second set of 4 test samples was analyzed at the Iowa City laboratory. The results of the second evaluation indicate that about 1.3% of the known mass in the sample vial is lost in the sample-transfer procedures that started with the removal of the sample from the vial and ended with the material collected in the filter. About 1% of the mass of the test sample material passes through the filter (Whatman No. 934-AH) and is lost unless the filtrate is analyzed with an evaporating dish. The median loss of mass for all 8 test samples evaluated was 3.6%.

The possible loss of part of the reference sample through the filter was studied by analyzing 6 of the reference samples using a filter with a reported pore size of 0.1 μm. The 0.1 μm pore-size filter was chosen to meet the criterion proposed by Jackson (1979) that particles <0.1 μm are colloids. Each sample was removed from the vial, and the vial and cap were washed with 100 mL of DI water into a 1-L polyethylene bottle containing 500 mL of DI water, and additional DI water was added to the bottle for a total of 1,000 mL. This mixture was stored in the laboratory for one week. The mixture of reference material and DI water was filtered, and the inside of the bottle was scrupulously washed with DI water. The wash water was also filtered. The results of this experiment indicates that greater than 99% of the reference material can be recovered from the vial and storage bottle, indicating that there was reference material passing through the No. 934-AH filter (particle retention reported to be 1.5 μm).

PARTICLE-SIZE REFERENCE MATERIAL

Visual inspection of the amount of the AC dust retained on the 63-μm sieve (see section titled "Reference Material Preparation") indicated sand-size material and that the dust could be used as a particle-size reference material. Samples of about 2.2 and 2.7 g were evaluated using the Cascades Volcano Observatory laboratory, Vancouver, Washington. Ten samples at each of the 2.2- and 2.7-g mass range were sent to the laboratory for a sand split and pipet analysis (Guy, 1969). The laboratory was requested to transfer the contents of each vial into a bottle containing a known mass of about 300 g of DI water and analyze each sample. The results from the laboratory indicated that these samples were suitable as a reference material for the sieve/pipet method (Table 3).

Table 3. Results from the sieve/pipet analyses of 20 test samples prepared from AC Spark-Plug dust at the Cascades Volcano Observatory sediment laboratory

Particle-size reported finer than in micrometers	Median in percentage	Interquartile range in percentage
63	97.4	0.2
31	77.5	1.5
16	55.6	1.7
8	37.1	2.9
4	26.0	3.6
2	20.2	4.4

The value of the interquartile range increases as the size of the dust particle decreases indicating that the uncertainty in the reported result is larger for fine-silt and clay-sized particles than for the coarse and medium silt. However, the graphic display of these results (Figure 1) suggest that AC dust is a suitable reference material and that the method of sample preparation (see section titled "Reference Material Preparation") did not cause systematic errors in the particle-size distribution.

SEDIMENT LABORATORY INTERCOMPARISON STUDY

A sediment laboratory intercomparison study was used to assess both the sediment-concentration analysis and the sieve/pipet analysis made by all Survey and contract laboratories. Each laboratory was requested to use routine sediment-concentration analysis or sieve/pipet procedures and to use its own equipment, laboratory ware, and DI water. The processing of the reference samples was designed to replicate the processing of environmental samples. Sixteen laboratories reported results for the sediment-concentration intercomparison, and three laboratories participated in the sieve/pipet intercomparison.

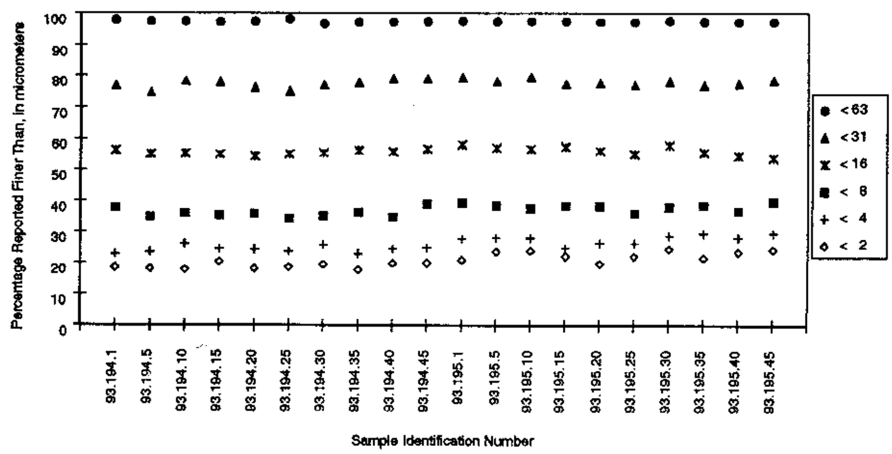

Figure 1. Analysis by the sieve/pipet method of 20 test samples containing either 2.2 or 2.7 grams of AC Spark-Plug dust

Sediment Concentration: Each laboratory received 3 sets of reference samples. Each set of samples was composed of 3 reference samples, so each laboratory received 9 samples for suspended-sediment concentration analysis. The results obtained from the intercomparison using the reference samples were similar to the results obtained from the evaluation of the test samples in that nearly all the participant laboratories reported concentrations that were less than the known mass of the reference samples. The median percent error was 4.5% with an interquartile range of 3.2%. As stated before, the analysis of the test samples by a single laboratory resulted in a median percent error of 3.6%. The comparison of the median percent error from the analysis of the reference samples (4.5%) to the median percent error from the analysis of the test sample by a single laboratory (3.6%) was judged to be adequate.

The calculated percent error from the analysis of the sediment-concentration data from the 1994 interlaboratory comparison is presented in Figure 2. Although the interquartile range is 3.2%, the majority of the reported results are positive, indicating a loss of reference material during the analysis. The relationship between percent error and the reference-sample mass was not examined during the evaluation of the reference samples. However, this relationship was examined after the return of the intercomparison data, and the percent error is essentially independent of the reference-sample mass. The p-value obtained from a one-way analysis of variance is 0.11.

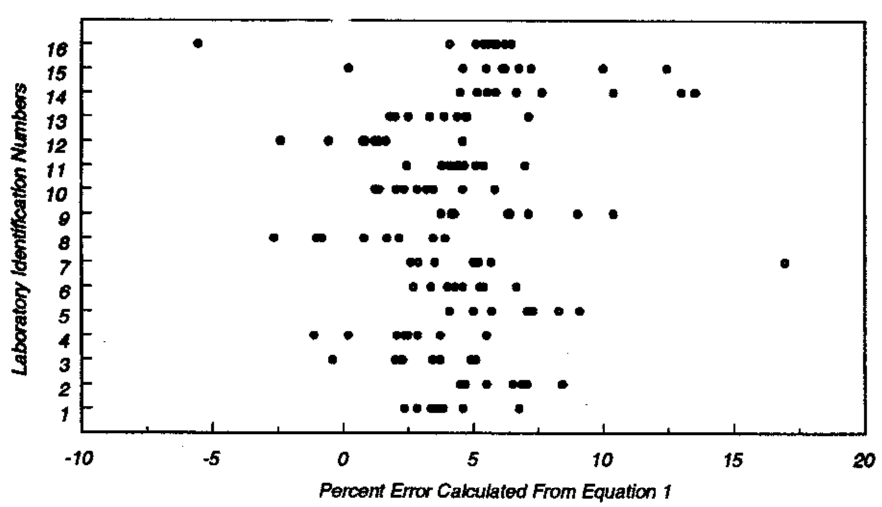

Figure 2. The calculated percent error from the analysis of the sediment reference sample in the 1994 intercomparison for suspended-sediment concentration

The interquartile range of the percent error was used to estimate the variability for the analysis of suspended-sediment concentration by the laboratories. This estimate is shown graphically in Figure 3. For example, a suspended-sediment concentration determination of 0.3 g or about 850 parts per million sample is predicted to have an interquartile range of about 0.009 g or about 25 parts per million.

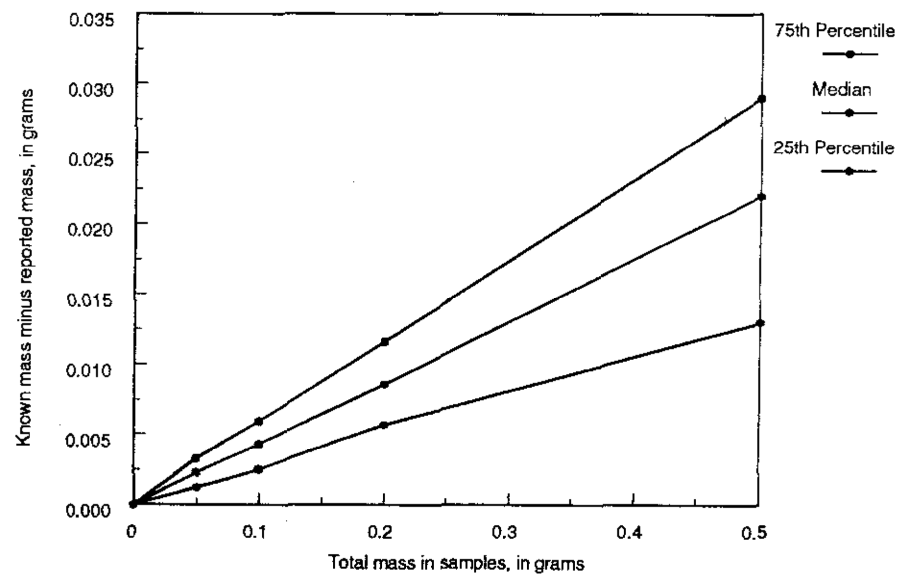

Figure 3. Estimated interquartile range for suspended-sediment concentration analyses by all laboratories

Sediment Particle Size: Three laboratories received two sets of reference samples for the determination of particle size. Each set of samples consisted of three reference samples, so each laboratory received six samples for sieve/pipet analysis. The results obtained from the intercomparison using the reference samples were comparable to those obtained from the evaluation of the test samples for particle size. The data from the intercomparison and the evaluation of the test samples are shown in Table 4.

Table 4. Results from the sieve/pipet analyses of the test samples and the particle-size data from the 1994 interlaboratory comparison
[IQR, interquartile range; number of samples is 6; %, percent]

Particle-size reported finer than in micrometers	Test samples		Reference samples	
	Median in percent	IQR in percent	Median in percent	IQR in percent
% sand	2.2	0.4	3.0	2.7
63	97.4	0.2	97.0	2.7
31	77.5	1.5	77.0	2.5
16	55.6	1.7	56.2	1.9
8	37.1	2.9	40.2	2.8
4	26.0	3.6	25.9	2.3
2	20.2	4.4	15.8	5.2

The reference-sample interquartile range for particles finer than 63 µm is more than 10 times the test sample interquartile range. This fact is caused by one laboratory reporting nearly twice the percent of sand-size particles that was reported by the other two laboratories. The median percentage for particles finer than 2 µm for the reference sample is nearly 5% less than the test-sample median. This difference is caused by one laboratory reporting results greater than the other two laboratories.

The sediment-laboratory committee decided to use variance from the single-laboratory analysis data to appraise the results from the particle-size intercomparison. A mean and standard deviation were calculated for each size class by using the data from the analysis of the 20 samples by the single laboratory. The single laboratory variance statistics, and the data from the three laboratories are shown in Figure 4. The particle-size analyses reported by the three laboratories are within the variance from the 20 reference samples. Therefore, the approach to appraise laboratories based on single-laboratory data appears to be an acceptable philosophy unless the reported results from the single-laboratory are in error.

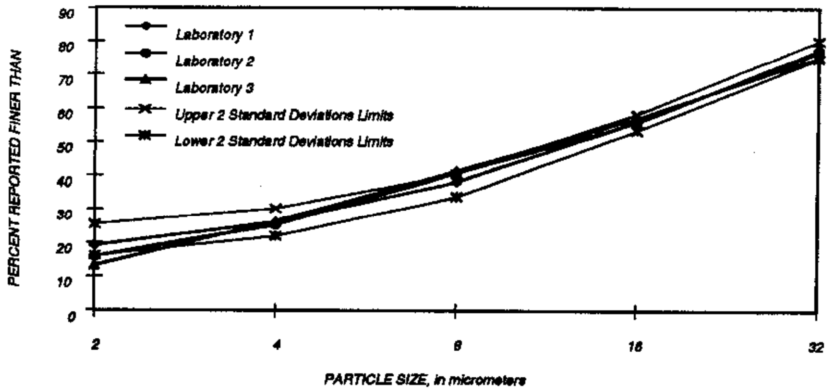

Figure 4. Results of the 1994 interlaboratory comparison for sieve/pipet analysis and the evaluation variance used to appraise the data

SUMMARY

The authors recommend the following steps in preparing a reference material for the quality-assurance testing of sediment laboratories:

1. Select a material that is available in bulk quantities;
2. subsample the material to prepare a test sample;
3. analyze the test samples with proven methods;
4. approve the test-sample material as a reference material; and
5. evaluate laboratories using the reference material.

This approach was used successfully to produce reference samples for suspended-sediment concentration and sieve/pipet analysis. These samples will be submitted to the U.S. Geological Survey sediment laboratories as part of the quality-assurance program.

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THE CASE FOR A NATIONAL BEDLOAD TRANSPORT OBSERVATORY AT SQUAW CREEK'S GRAVEL-TRANSPORT DETECTOR IN MONTANA.

Stephan G. Custer, Associate Professor of Geology, Department of Earth Sciences, Montana State University, Bozeman, Montana

Abstract: The U.S. Forest Service Stream Technology Center has suggested an international bedload-transport observatory be established to provide data on coarse sediment transport processes relevant to analysis of consequences of changed flow regimes and stream channel maintenance in steep mountain streams. An observatory would provide a permanent measurement platform, reduce costs, place new data in a long-term context, and encourage data sharing. Squaw Creek is a good candidate site. Many of the measuring platforms (power, phone, instrument shelter, foot bridges, detectors, lighting) have already been installed. The site is on federal land. Since 1981, bedload-particle-transport experiments have been conducted at Squaw Creek, Montana. The detector counts the large naturally magnetic clasts which pass on the bed. Bank-full discharge is 5 m^3s^{-1}. Transport takes place in the stream when discharges of about 3.5 m^3s^{-1} occur for several days. Stream slopes are variable but approximately 0.02. Median particle size in the channel is 140 mm. Data from the detector has shown that the coarse-bedload transport at the site is temporally and spatially variable. Peak discharge is generally snow-melt controlled. Gravel transport occurs most years. There is a relatively long record of measurement at the site. The stream has braided, anastomosed and meandering reaches so a variety of measurement sites are possible in the future. Geomorphic as well as hydraulic process are known to operate at the site. The long data base, frequent transport events, and the existing infrastructure at the Squaw Creek bedload detection site make this an excellent place for researchers to study gravel transport in a natural setting and to share data. The observatory should be available for experiments and data collection by anyone with the proviso that the primary data be placed in a centralized public data base when the experiment is completed.

INTRODUCTION

<u>Need for a Gravel-Bedload-Transport Observatory:</u> There is a growing need to understand gravel transport in high gradient streams as people move into the mountainous regions of the U.S. Bridge scour estimates require data on the threshold of cobble and boulder bedload motion and quantities of transport. Timing and character of coarse bedload transport can influence fish spawning habitat (eg: Chapman, 1988; Lisle and Lewis, 1992). Reservoirs are filled by coarse bedload. Bedload-transport rates can increase or decrease following changes in reservoir management, flow diversion, land-use, or climate. In response, the stream may cut or aggrade with concomitant changes in habitat, form, and stream behavior (Hey, 1994). Knowledge regarding threshold of coarse-particle motion can help managers decide the what flows and flow characteristics are required to maintain dynamic equilibrium in a stream.

As development pressure and landuse activities intensify in the forested mountain watersheds of the U.S., the demand for and importance of natural gravel-bedload-transport in steep streams will continue to increase. This need is reflected in the gravel-bed-river symposia held every 5 years (Hey, and others 1982; Thorne and others 1987; Billi and others, 1992), by a U.S. Army Corps of Engineers workshop on steep streams (U.S. Army, 1992), by the recent symposia on Mountain Rivers at the ASCE Hydraulic Engineering Conference (Cotroneo and Rumer, 1994) and by U.S. Forest Service Rocky Mountain Forest and Range Experiment Station Stream Systems Technology Center (STREAM) which identified as its first priority the response of different channel types to changes in sediment and discharge in steep gradient, gravel and cobble bed streams commonly found on U.S. Forest Service lands (Meiman and Schmidt, 1994).

An important gap in the gravel-bed research exists. There are very few long-term field studies in streams with cobble beds. This problem was identified as important at the 1994 Task Committee meeting on Applied Hydraulic Analyses of Flow in Mountain Rivers convened by Bob Jarrett at the ASCE Hydraulic Engineering Conference. Field studies of gravel-bed transport exist to be sure (eg: Leopold and Emmett, 1976, Andrews, 1983; Carling, 1983, Reid and Frostick, 1986; Gomez and Church, 1989; Gomez and others, 1989; Adenlof and Wohl, 1994) but the studies tend to measure transport at one place, at one moment in time. Such measurements tend to ignore the fact that there are both hydraulic and sediment supply variables at work (Bunte, 1991, 1994; Ergenzinger and others, 1994; Hey, 1994). Adenlof and Wohl (1994) found a lack of correlation between shear stress and sediment movement that may suggest important reach scale factors which influence transport. Hey (1994, p. 22) in his discussion of dominant bedload transporting discharges observes,

> "In gravel-bed rivers, bedload transport rates are, in part hydraulically controlled, (by) transport of locally derived bed material which is dependent on excess shear stress but can (also) be dominated by finer material supplied from upstream which is derived from failed banks, tributaries and catchment sources (Hey and Meigh, 1992). Much of this supply controlled material is dependent on antecedent conditions and can be independent of discharge. Consequently sediment rating curves derived from bed load transport equations can seriously underpredict actual loads by ignoring the supply controlled component of the load."

This statement and the observations of others (Bunte, 1991, 1994; Custer, 1992; Ergenzinger and others, 1994; de Jong, 1995) regarding the importance of sediment supply, even in streams apparently in equilibrium, suggests the need for long term measurements of total sediment transport to adequately characterize, assess, or even predict gravel transport in natural systems.

To gain a better understanding of bedload transport and channel-change processes in gravel bed streams, long-term measurements at a site are needed. The current U.S. research infrastructure is not well designed to conduct such experiments. This problem arises because funding is typically targeted for short term (one or two year) experiments. As a result, the sediment supply and system dynamic issues tend to be neglected. One solution to this problem would be to establish one or more National Bedload Transport Observatories. The establishment of an observatory would ensure that infrastructure for measurement remains in place, and would attract researchers to the observatory over a relatively long period of time. The long-term database generated from many workers would provide important context for current work and better insight into both hydraulic processes and sediment supply aspects of gravel-bed transport in mountain streams at many time scales.

General Observatory Structure and Characteristics: The primary objective of a National Gravel-Bedload-Transport Observatory would be to provide a natural setting in which to develop and test physical, conceptual, and numeric models of gravel-bed transport. Experiments would be brought to the Observatory by many agencies and investigators. The Observatory site should be maintained by an interagency task force. The Observatory would provide a physical measuring site which has infrastructure for measurements in mountain gravel-bed stream. The observatory would provide 1) instrument shelter, 2) measurement platforms, 3) power connection, 4) phone connection, 5) facilities for instrument repair and fabrication, 6) data depository for all data generated at the site, 7) an annual report summarizing data collected at the site. Data generated by experimenters would be released for public use within 0.5-1 year of generation to allow lead time for analysis and publication while at the same time providing access to data for other research purposes.

SQUAW CREEK -- AN OBSERVATORY CANDIDATE.

Site Context: A good potential observatory site is at the mouth of Squaw Creek on the Gallatin National Forest in southwest Montana approximately 50 km (30 mi) south of Bozeman (Figure 1). The drainage basin is 106 km^2 (48 mi^2) and is dominated by andesitic volcanic rocks (lava flows, debris flows, and fluvial deposits with some intrusives) which erupted through a faulted landscape of Archean quartzo-felspathic gneiss and Paleozoic and Mesozoic sedimentary rocks in the Eocene (McMannis and Chadwick, 1964; Table 1). The stream includes reaches with gravel, cobble and boulder beds. At the site, the stream bed is composed of coarse particles (median channel size 140 mm). Different particle-size distributions occur at different locations on the stream bottom. The stream displays gravel transport in most years, but one must be ready to measure throughout May and June. Bank-full discharge is approximately 5 $m^3 s^{-1}$. Peak flow typically occurs between 2200 and 2400 hours in response to snow-melt processes in the watershed. Particles may begin moving at about 3.5 $m^3 s^{-1}$ but threshold depends on bed conditions and flow patterns. Channel slope is approximately 0.02. Mark Story, Gallatin Forest Hydrologist, reports Rosgen stream types vary from A2 and A3 to B3 and C3 and C4.

Research Context: An important attribute of a National Bedload Transport Observatory is a history of research which can be built upon to provide a context and long-term data base. Data collection at Squaw Creek has intermittently occurred since 1980. The work to date has focused on gravel transport. A coarse-bedload-particle detector capable of counting the passage of naturally magnetic particles has been developed at the site to measure the temporal and spatial variability of bedload particle motion in 1981, 1982, 1986, 1988, and 1991 (Ergenzinger and Custer, 1983; Custer

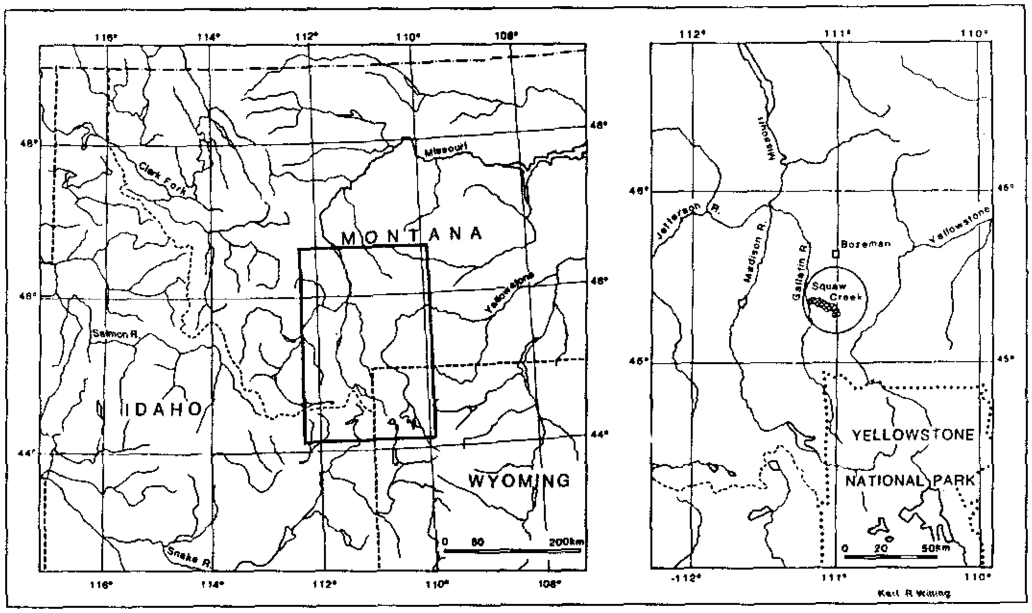

Figure 1. Location map (from Bunte and others, 1987, p. 60).

Table 1. Characteristics of Squaw Creek and the Research Site (after Ergenzinger and Custer, 1982; Bunte, 1994).

1. Watershed Characteristics
   a. Drainage area 105.7 km^2 (40.8 sq mi)
   b. Drainage length 20.3 km (12.6 mi)
   c. Maximum elevation 3150 m (10,333 ft)
   d. Relief 1520 m (4,890 ft)
   e. Mean basin slope 25 degrees
   f. Stream order 4 Strahler 1:62,500
   g. Forest cover -- Fir and Lodgepole 50 %
   h. Step pool, riffle pool, bedrock notch, braided, meandering, anastomosed
2. Site Characteristics
   a. Naturally magnetic basalt and andesite pebbles and cobbles
   b. Channel width 8-20 m (25-65 ft)
   c. Discharge:
      1) Bankfull 5.0 m^3/s (180 cfs)
      2) Low flow 0.5 m^3/s (20 cfs)
      3) Modal peak 6 m^3/s (200 cfs)
      4) Threshold for Motion $Q>3.5$ m^3/s for more than 2-3 days
      5) Month of peak flow late April through June
   d. Time of peak flow 22:00 to 24:00 hours
   e. Spatially averaged shear stress 30-160 N/m^2
   f. Bankfull stream power 1000 $kg/m\ s^{-3}$
   g. Channel gradient 0.02 m/m
   h. Gravel transport rate 10 g/m·s; Range: 0.1 - 100 g/m·s
   i. Particle sizes

	d_5	d_{16}	d_{25}	d_{50}	d_{75}	d_{84}	d_{95}
1) Bar 1	0.5	2.3	7	19	32	40	67
2) Bar 2	0.4	1.8	5	24	60	90	200
3) Channel	0.5	2.8	18	140	190	200	220

and others, 1987; Bunte 1991, 1994; Carling and others, 1993; Ergenzinger and others, 1994). An example of detector output reflecting the passage of naturally magnetic particles over two detector logs in the stream bottom is shown in Figure 2. During this event 16,319 particles passed over the upstream detector and 17,479 particles passed over the downstream detector (Carling and others, 1993, p. 21). The channel during the measured event was in dynamic equilibrium. A detector like this is capable of particle-motion detection anywhere there are pebbles and cobbles in the stream bed sufficiently magnetic to attract a carpenter's stud-finder. Such settings are common in volcanic terrains which form an important part of many mountains in the world (Custer, 1992).

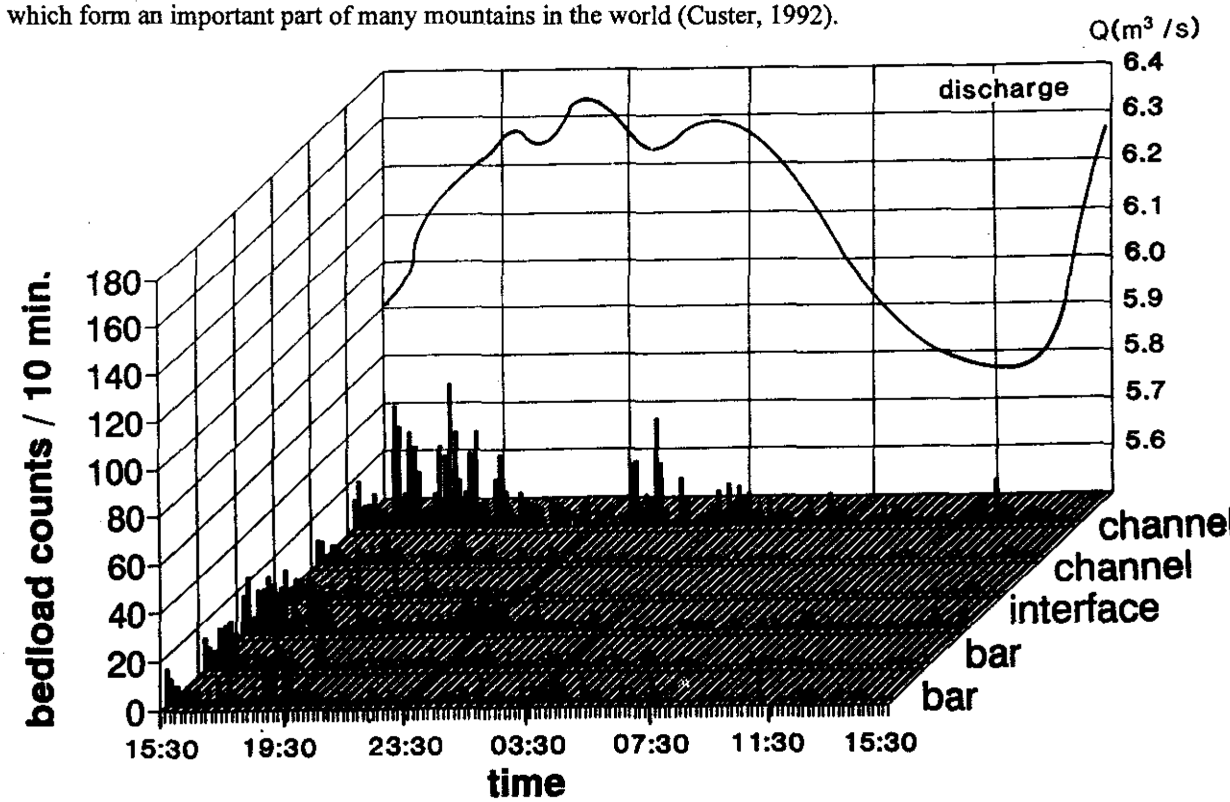

Figure 2. Bedload particle counts and discharge on May 23-24, 1991 (de Jong, 1995, p. 135).

Gravel transport measurements at the site suggest that although there is a broad general relationship between discharge peaks and transport, the transport is unsteady and influenced by hysteresis effects and bed conditioning, and geomorphic variables (Bunte, 1991,1994; Carling and others, 1993, and Ergenzinger, 1992; de Jong, 1995). There may also be transport events related to geomorphic or human-induced processes which have yet to be recognized and require long observation times. Sediment supply at or upstream of the site may influence transport. Questions remain regarding the importance of variation in particle size at different locations in the channel(s), particle clusters, bank collapse, channel switching related to sediment supply and flood conditions, avulsion linked to log-jam burst (Bugosh and Custer, 1989), beaver-dam burst, sediment related to mass movement, climatic events, or land use changes (clear cut; log debris removal and habitat modification projects in the early 1960's) (Custer, 1992). A permanently monumented five km stream survey directly up stream of the site is underway to help provide context for sediment supply issues and will be reported elsewhere. Establishment of a bedload-transport observatory at Squaw Creek would help focus research attention on the relative roles of such processes.

Site Infrastructure: Because of the long history of research at the site, much of the infrastructure for research is already in place (Figure 3). The site has power and a phone line installed. There are two detector logs installed in the main stream 28 m apart. The upstream detector log has six detectors across the stream, the down-stream detector log has five. The detectors are capable of measuring the passage of naturally magnetic particles on the stream bed when a filter/amplifier is attached (Ergenzinger and others, 1994). There is an up-stream foot bridge which serves as a measuring platform and a downstream measuring platform near the down-stream detector which needs improvement. The measurement platforms are lighted with flood lights. The upstream measuring bridge is fitted with a Tausendfussler device which facilitates measurement of relative roughness (de Jong and Ergenzinger, 1992).

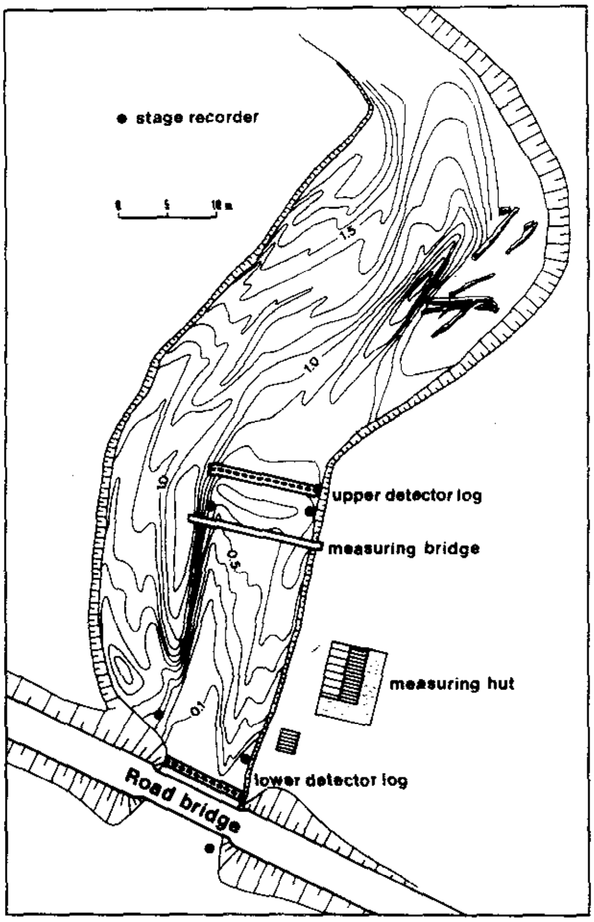

Figure 3. Squaw Creek research-site map (from Ergenzinger and others, 1994, p. 143)

By lowering rods to the water and bed surface, the relative roughness can be measured at 10 cm spacing or larger. (de Jong and Ergenzinger, 1992). There is an 8 x 12 ft instrument shelter and a 4 x 8 foot storage shelter from which to work. There is a U.S. Forest Service Road Bridge directly downstream of the downstream detector log. A 1.2 m-wide vortex sampler has been constructed and is available for sampling as is a large net sampler for bedload transport sampling (Bunte, 1992). The vortex sampler currently requires annual installation if use is required. Four stilling wells and two staff gages are present at the site. One of the stilling wells has 20 years of peak discharge data collected by the U.S. Forest service through 1981 with intermittent peak discharge data since 1981. The data are intermittent because the studies are intermittent. An observatory would help create a more continuous database and expand the measurements if more researchers worked collaboratively at the site.

Montana State University is 50 km (30 mi) from the site. The University has a Technical Services group with a machine shop, motor pool, computer facilities, a Geographic Information and Analysis Center, and departments of Electrical Engineering, Civil and Agricultural Engineering, and Earth Sciences which have students and technical expertise relevant to bedload transport research . The site is owned by the U.S. Forest Service and is currently operated under a special-use permit. Both infrastructure and logistical support are available at or near the site.

CONCLUSION

One or more National Gravel-Bedload Transport Observatories are needed to better understand sediment transport processes in steep gravel-bed rivers in a natural context. Such an observatory would provide a platform for multidisciplinary research, calibration experiments, and model verification in the difficult gravel transport measurement environment. Such a site would produce long-term data on gravel transport that would place the research performed in hydraulic, geomorphic and sediment supply context. The data produced should be shared and available to all after appropriate limited time for data generators to reduce and analyze the data. Squaw Creek is a good candidate site. Measuring platforms and shelters exist. There is a hydrologic and geomorphic context in which future research can be placed. The site is near a research university.

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Contact Point: Phone 406 994 6906, FAX 406 994 6923, Internet uessc@msu.oscs.montana.edu

OHIO RIVER SEDIMENT MONITORING STUDY, OLMSTED LOCKS AND DAM

by David R. Busse, Senior Water Control Manager, Potamology Section, US Army Corps of Engineers, St. Louis, Missouri; Robert D. Davinroy, District Potamologist, Potamology Section , US Army Corps of Engineers, St. Louis, Missouri; and John Naeger, Engineering Technician, Potamology Section, US Army Corps of Engineers, St. Louis, Missouri

__Abstract:__ A sediment monitoring study on the Ohio River in the vicinity of the Olmsted Locks and Dam construction site (river mile 964.4) was conducted by the St. Louis District for the Louisville District. Velocity, suspended sediment, and bed sediment data were collected for a variety of flow conditions. Intensified hydrographic surveys were also obtained concurrently using multi swath technology. The main goal of this study was to monitor, analyze, and gain a better understanding of the sediment transport behavior of the Lower Ohio River and ensure the preservation of existing mussel beds during and after construction. The results of the study will be addressed, including a brief description of the collection process and interpretation of the data.

INTRODUCTION

In 1992, as the start of construction of the largest civil works project on the inland waterways (Olmsted Locks and Dam, Ohio River, Mile 964.4, estimated cost $1.1 billion) drew near, engineers within the Louisville District saw the need for detailed monitoring of the river bed of the Ohio River. Biologists from both the Corps of Engineers and the Fish and Wildlife Service were concerned about the preservation of critical mussel beds near the construction site (located approximately 3 miles downstream), of which several endangered species existed, including the orange-footed pimple back mussel (Turner 1994). It was feared that increases in sedimentation from construction of the project would result in deposition over these mussel beds, thereby directly threatening their future existence.

It was vital to Louisville District engineers to obtain as much information as possible about the sediment transport characteristics of the Lower Ohio River before construction commenced. Very little in the way of historical prototype information existed. It became apparent that a baseline trend condition needed to be established if a proper environmental prognosis and impact was to be made before, during, and after construction.

DATA COLLECTION SCHEME

__Field Setups.__ In the Fall of 1992, ten data collection ranges were established along the Lower Ohio River (Figure 1). Velocity was measured and both suspended sediment and bed sediment samples were collected at each range for a variety of flow conditions. Data was always collected perpendicular to the flow.

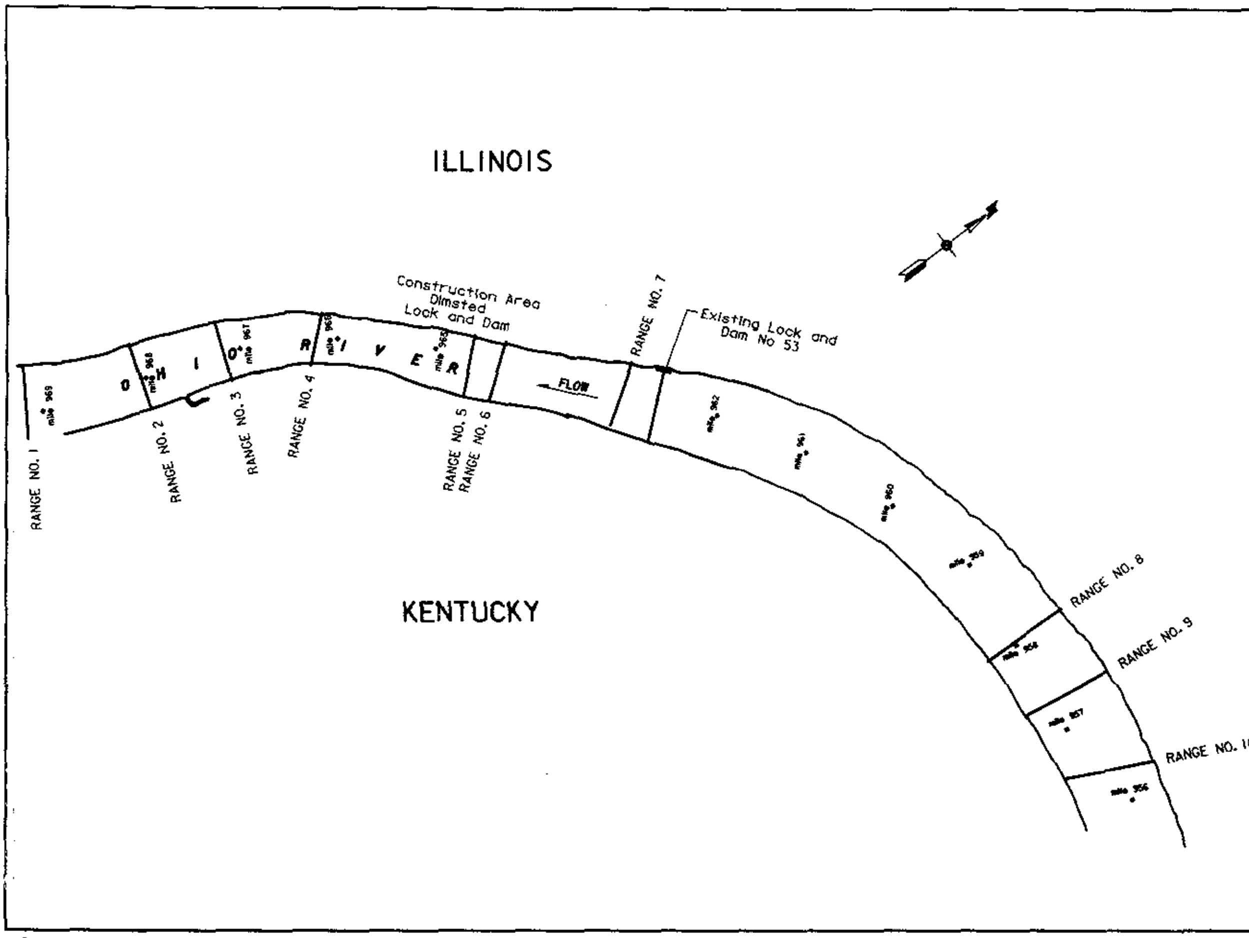

Figure 1. Data Collection Ranges On the Lower Ohio River

Velocity data and suspended sediments were collected simultaneously, always starting on the right descending bank. Two heavy duty cranes, each equipped with a power sounding reel, were used for deployment of the data. This is the type of equipment normally used in large rivers where heavy weights are required. Velocity data was collected on one crane using a Price AA current meter in conjunction with an onboard computer system. Two samplers were used on the other crane, a P61 depth integrated suspended sediment sampler and a BM54 bed material sampler. At each range, samples were consistently taken laterally at 70 meter intervals. Velocity readings were taken in 5 foot depth increments starting at the water surface and extending down the water column. Immediately after each range was completed, the P61 was replaced with the BM54. The path of the boat was retraced across the river, and each sample site was revisited.

During the first three sampling events, positioning was determined from trisponders set on the bank. Survey stakes were established as control coordinates. It soon became apparent that the stakes would be of limited value. The stakes went underwater shortly after the initial survey and weren't seen again. In addition, there were accessibility problems caused by flooded trees along the bank. To overcome this, the trisponders were secured to portable tree stands.

Figure 2. Double Rig System For Simultaneous Data Collection

In the summer of 1993, positioning was established by differential GPS. This greatly increased the efficiency and accuracy by which data was collected.

Of primary importance to engineers was detailed analysis of the bed configuration, especially in the mussel bed area. This was accomplished by use of the multi swath technology and digital terrain modeling (Davinroy and Naeger, 1995). In theory, comparisons of periodic multi swath surveys could indicate to engineers and biologists detailed changes in the river bed, if any, due to both natural and man induced effects.

Format of Data Output. The enormous amount of data collected in the field had to be managed and graphically output in a user friendly manner. All field data was electronically collected and transferred to the office for post processing. Supercalc and CADD were used as the primary tools for graphical output. Figures 3 through 5 typify the graphical output format for the velocity, suspended sediment, and bed sediment data used for the analysis of trends in this study.

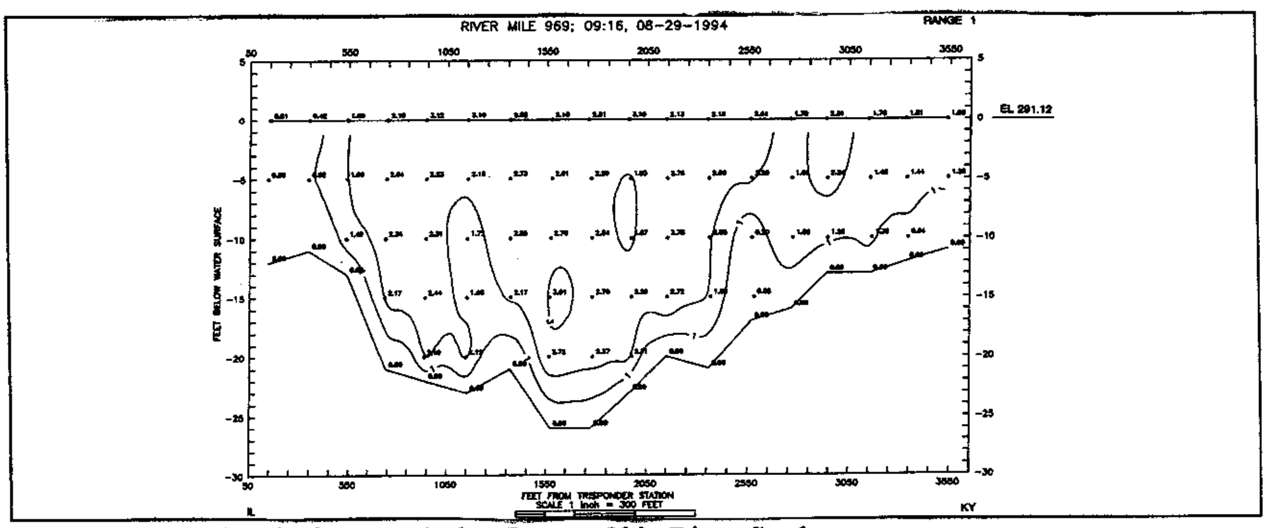

Figure 3. Typical Velocity Isovel Plot, Lower Ohio River Study

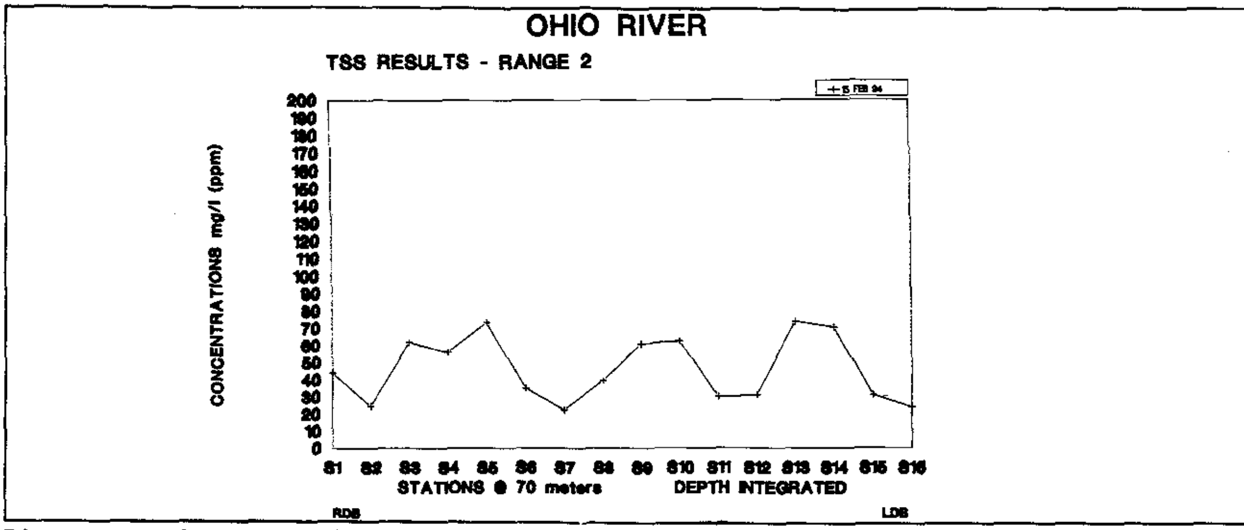

Figure 4. Typical Suspended Sediment Plot, Lower Ohio River

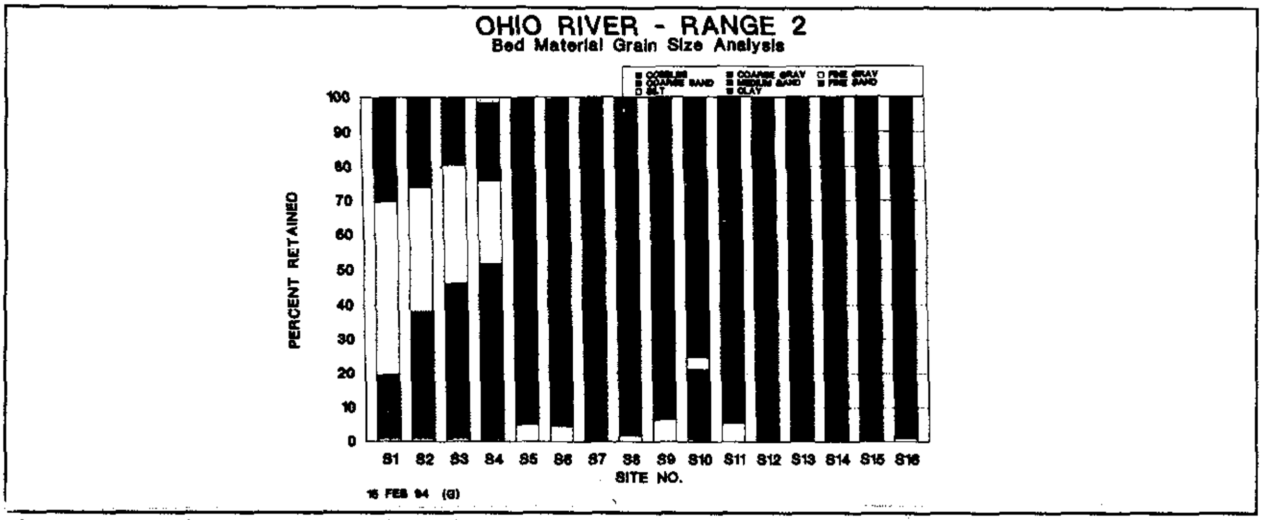

Figure 5. Typical Bed Gradation Plot, Lower Ohio River Study

DATA TREND ANALYSIS

Bed Composition. Based on the bed samples collected over an 18 month period, the data revealed that the Lower Ohio River contains a surprisingly large amount of heavy material in the form of course gravel, fine gravel, and dense sand. The high density of this materially profoundly influences the development of the bed configuration of the river, as verified by channel sweep surveys. The river channel is exceptionally wide (4000 ft) and relatively shallow (10 to 20 feet at low water). Conversely, the bed material found on the Middle Mississippi River consists mainly of finer sands and silts. This lighter material is more easily transported causing typical channel cross-sectional development to be narrower and deeper. The result is a pronounced alternating channel system containing deep pools and shallow crossings. This bed pattern is not as pronounced on the Lower Ohio River and cannot be easily detected.

Velocity and Suspended Sediment Trends. Velocities in the Lower Ohio River, except for rare occurrences, are extremely low for a typical big river. Field data revealed that under normal to bankful conditions, velocities ranged between 1.5 fps and 3.0 fps. The Mississippi River backwater effect contributes to this phenomena, which is discussed later in this paper.

Typically, a direct correlation between velocity and suspended sediment concentration can be deduced on large rivers. Generally, higher SSP concentrations would be reflected where higher velocities exist. However, on the Lower Ohio River, this relationship is extremely low. Utilizing the data for six collection periods between November 1992 and July 1993, statistical analysis employing several regressions were performed. A linear, quadratic, and cubic regression was performed using SSP as the dependent variable and velocity as the independent variable. All three regressions produced R^2 values of 0.23 to 0.27. R^2 is a statistical indicator of predictability ranging in value between 0 and 1. These results indicate a weak relationship between velocity and SSP. This is no doubt due to both the relatively low velocity and SSP values. Relatively speaking, the overall suspended sediment concentrations were found to be exceptionally low and fairly uniform over the entire section. This remained consistent regardless of the velocity trends. Concentrations on the Middle Mississippi River are in the order of 200 ppm to 300 ppm during normal stage conditions which is approximately double the amount observed on the Lower Ohio River.

Bed Configuration Trends. Over a time span of 22 months, a total of seven detailed hydrographic surveys, using multibeam swath echo sounding systems, were performed. The total survey area was approximately seven miles long varying in channel width between 4,000 and 6,000 feet.

Several three dimensional bathymetric models were generated by computer for qualitative and quantitative analysis. Figure 6 illustrates the typical output form these models (the actual plots in the study report were displayed in color for additional visual enhancement). These plots served as important graphical communication tools between the engineers and the biologists. Quantitative plot comparisons indicated very little in the way of natural bed transport, especially in the area of the mussel beds. Combined with the bed material data (indicative of a hard river bottom), these findings exemplified the fact that natural conditions were ideal for mussels.

Sediment Transport Trend. The Lower Ohio River is dominated and greatly influenced by geomorphic effects of the Mississippi River . Figure 7 is a photo illustrating the alignment and confluence configuration of the Ohio and Mississippi Rivers. The Ohio meets the Mississippi at an approximate 50 degree angle. A pronounced sediment line separates the two rivers (this line is visually apparent on color photography). The separation line indicates that the Ohio River's original surface area is reduced to approximately 50 percent, while the Mississippi retains 100 percent of it's original area. The entry angle and the sediment line verify the physical dominance of the Mississippi River. This dominance directly influences the extremely flat slopes and low sediment transport energy of the Lower Ohio River.

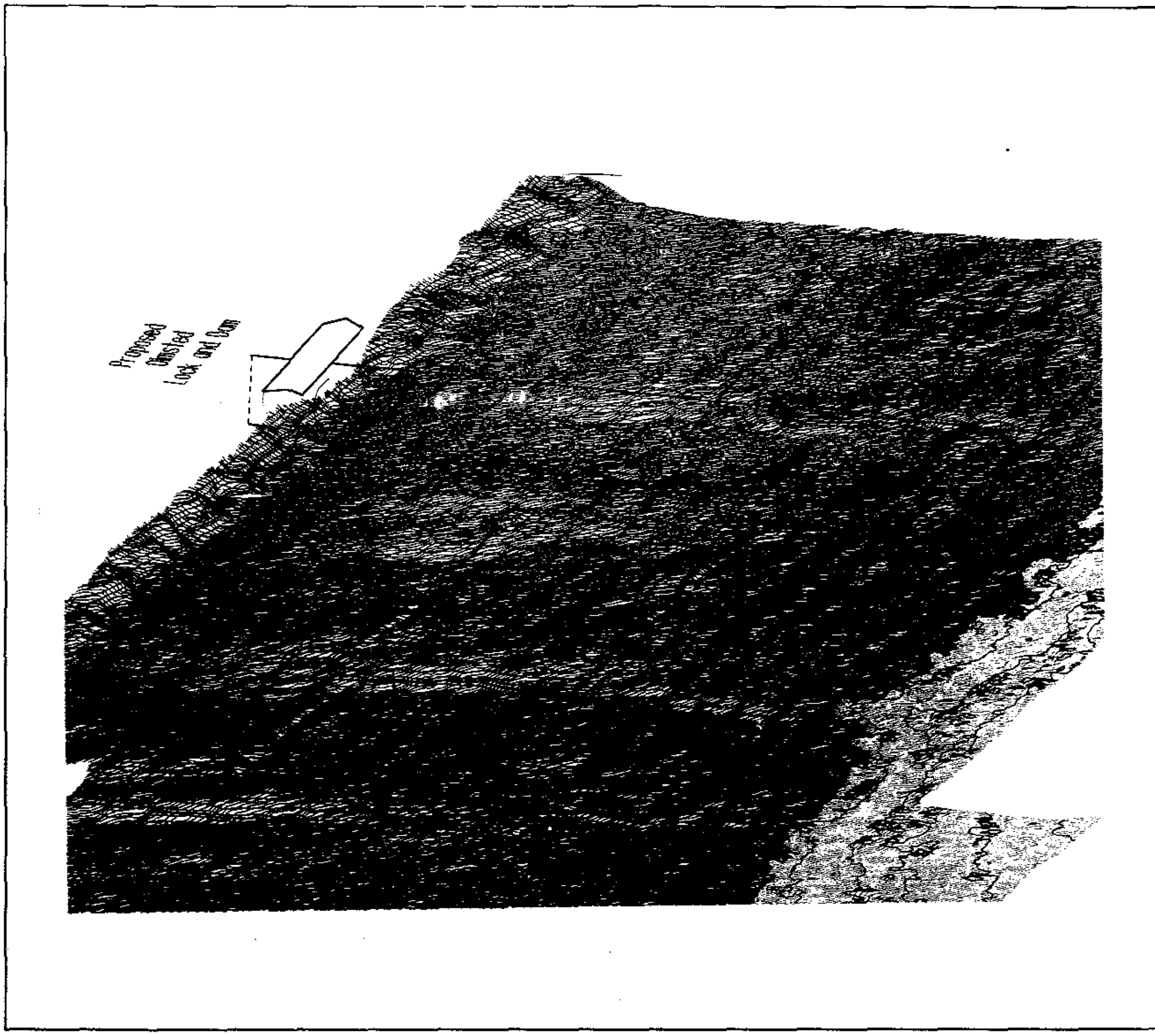

Figure 6. Three Dimensional Bathymetric Model of the Lower Ohio River

<u>Slope Profile.</u> While the Mississippi River physically dominates the Ohio River, the historical discharge records show that greater and more frequent floods have occurred on the Ohio River. When a flood occurs on the Ohio but not on the Mississippi, it would normally be assumed that large energy slopes would occur on the Ohio. This is not the case. Whenever moderate slopes develop on the Lower Ohio River, the duration is only for a few days, and the slopes immediately return to much lower and flatter values. Just the opposite is true on the Mississippi River. High slopes are the norm and low slopes are the unusual. This is directly due to the physical characteristics of the confluence configuration, as discussed previously. Figure 8 illustrates the historical comparisons in slope between the two rivers.

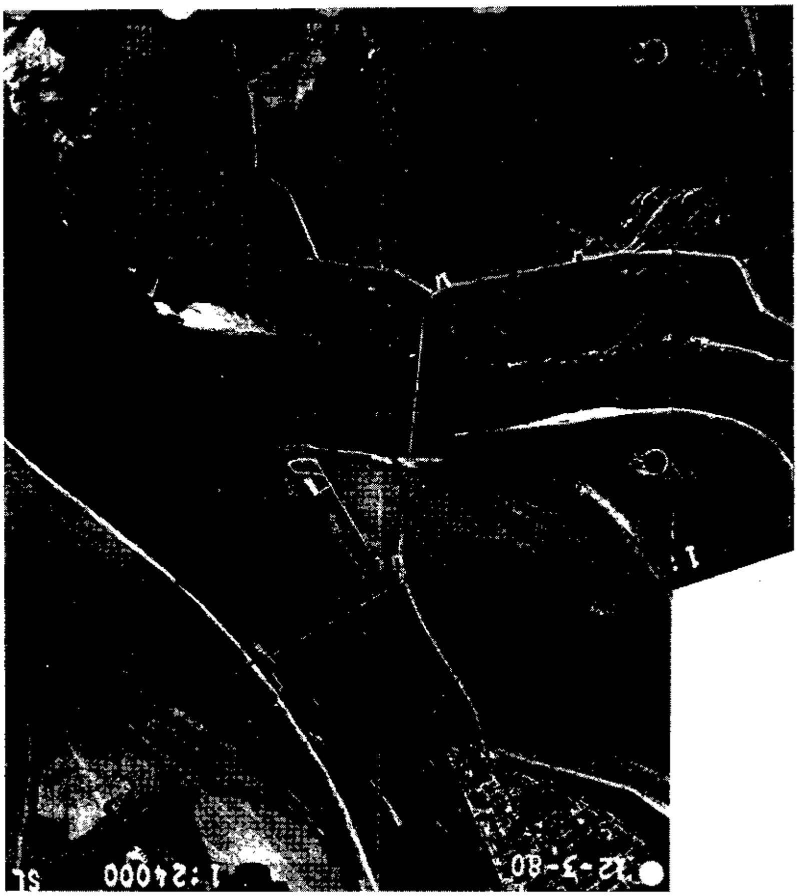

Figure 7. Confluence of the Ohio and Mississippi Rivers

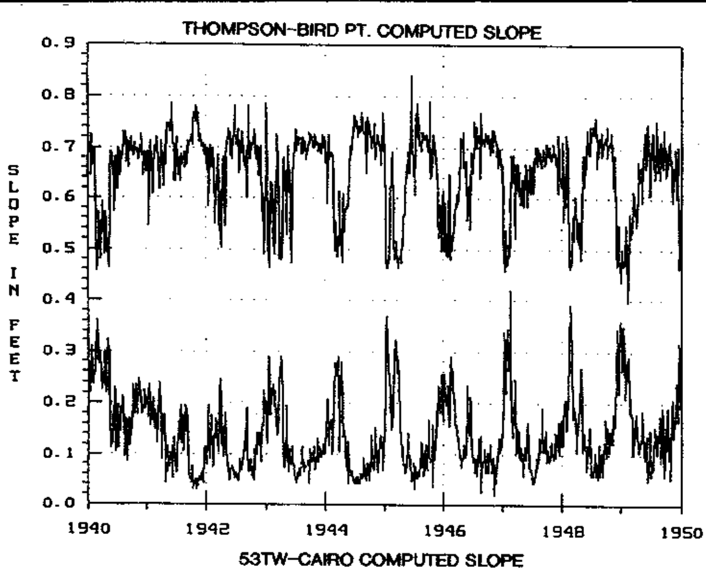

Figure 8. Historic Water Surface Slopes of the Ohio and Mississippi Rivers

The Invasion of the Zebra Mussel. Native mussels within the downstream mussel bed were collected and studied by a team of biologist between 1983 and 1994 (Turner 1995). Until 1991, a thriving, healthy mussel bed existed. However, in 1994, an explosion of zebra mussels (Bachant 1993) had completely covered the mussel beds as well as rocks, lock walls, gates, barges, and just about anything else submerged in water. This explosion may have been attributed to the prolonged backwater effects of the Mississippi River during the flood of 1993 (Turner 1995). Monitoring will continue indefinitely in the future.

CONCLUSIONS

The sediment, velocity, and bed configuration data collected in this study combined with the morphological and hydraulic data conclude that the Lower Ohio River contains an unusually small amount of sediment transport potential. The data clearly shows that conditions are excellent for mussels. The prognosis for additional sedimentation from construction of Olmsted Locks and Dam indicates little if any negative impact. Monitoring will continue to further analyze prototype trends. Of greatest concern now is the explosion of the Zebra Mussel population, which, if current trends continue, could adversely harm or completely destroy the existing mussel beds and other animal species in the Lower Ohio River.

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INDIVIDUAL GRAVEL TRACKING USING A PASSIVE RADIO TRANSPONDER SYSTEM

By Charles L. Rosenfeld, Associate Professor, Oregon State University, Corvallis, OR; Janine M. Castro, Graduate Student, Oregon State University, Corvallis, OR; and Elayne S. Childers, Graduate Student, Oregon State University, Corvallis, OR

__Abstract__: Monitoring numerous individual particles during transport in natural stream channels has not been feasible as single particles are difficult to track, identify and locate after a transport event. Tracers for monitoring gravel transport in streambeds have included painted clasts, radioactive tracers, magnetic tracers, and "active" radio rocks. The "active" radio rocks are the most technically advanced of the methods currently available, but are relatively expensive and rely on an internal power supply.

This paper gives describes a feasibility study of an inexpensive "passive" tracer that stores and relays information without an internal power supply. The small transponder ampule (1 mm x 9 mm) can be implanted in individual clasts and remain viable for years and possibly several decades. The low cost of this technology enables them to be employed in sufficient quantity to assure statistically reliable results.

The feasibility study was conducted at Oak Creek, Corvallis, Oregon. An existing vortex bedload sampler was used to divert all particles over a receiver installed in the discharge trough. All particles implanted with a transponder ampule were recorded by the scanner as they passed over the receiver. This technology has the potential to provide detailed information on sediment transport in gravel bed streams. Efforts are continuing with this technology, including development of a portable transponder reader linked to a Global Positioning System (GPS) receiver for field-tracking in gravel-bedded streams, and a fixed-site installation for gravel transponder recording across wider natural streams.

INTRODUCTION

Measuring the movement of bedload in gravel bed streams is difficult and has limited accuracy. Many techniques have been developed during the past fifty years but none provide complete information on the location, trajectory, or timing of movement of particles. Physically capturing bedload material is possible by using a Helley-Smith Bedload Sampler, vortex bedload sampler, or instream pits with pressure pillows (Spieker and Ergenzinger, 1990). The Helley-Smith is relatively inexpensive and simple to use but the data is spatially and temporally limited. The latter two options are expensive, require instream alterations, and completely stop bedload transport. This makes it difficult to monitor the movement of channel bedforms. For meaningful quantitative data it is necessary to measure bedload movement including individual particle source, size, trajectory, and relative velocity.

Tracers for monitoring gravel transport in streambeds have taken many forms including dyed or painted clasts, radioactive tracers, magnetic tracers and "active" radio rocks. Limitations to these methods have included duration of markings and signals, and the cost of the tracers. This paper describes a small (1 mm x 9 mm) glass ampule that can be placed in drill holes of individual particles that are 10 mm in diameter or larger. This ampule, or transponder, will deliver a radio signal with a unique hexidecimal number when exposed to a magnetic field. The transponder ampule has no internal power supply allowing a functional transponder a residence time in the range of several decades.

THE EQUIPMENT

The BioMedic Data Systems' DAS4003 is a microprocessor and radio scanner designed to identify and record the unique tag number associated with an individual transponder. This technology is marketed for positive laboratory animal identification. BioMedic Data Systems envisions other potential uses which include inventory tracking, industrial process control, robotics, security systems, and industrial applications (BioMedic Data Systems, 1991).

The tracking equipment utilizes a magnetic field, radio scanner, and transponder. The transponder contains a cold storage microchip and a copper coil. The copper coil is energized as it passes through a magnetic field and gives off a radio signal. The receiver picks up this signal and records the data in its internal memory. The time is also recorded as the transponder passes through the magnetic field. Particle size, shape (a, b, and c axes, angularity), density, volume, weight, composition, UTM location, and beginning bedform location of each particle can be recorded and stored in a spreadsheet.

The transponder microchip and copper wrapped diode are contained within a 1 mm x 9 mm sealed glass capsule. The minimum particle size for transponder implantation is one with a c-axis of 10 mm. At present, a fixed plate scanning antennae and a mobile scanning wand are available. The scanning plate is approximately 18 cm x 15 cm and is contained in a hard plastic cover. The wand is narrow and comes in variable lengths. The microprocessor/radio scanner and scanning equipment are not sealed and are sensitive to high moisture conditions. The microprocessor/radio scanner is also sensitive to vibration and stray radio waves.

FEASIBILITY STUDY

Location: The feasibility study was conducted at Oak Creek, Corvallis, Oregon. Oak Creek is a fourth order stream that drains the eastern Coast Range in north-western Oregon. The contributing watershed is approximately 6.7 square kilometers above the vortex bedload sampler located in the upper watershed of Oak Creek. The contributing watershed is almost entirely forested providing a fairly uniform hydrologic environment. Roads with culverts which drain directly into the stream are present along the stream channel. The bed material is predominately basalt. Bed material recruitment is primarily by debris flows and landslides directly into the channel.

Sample Preparation: BioMedic Data Systems ran a laboratory test using the basalt particles from Oak Creek to determine the level of interference caused by the iron contained in the basalt. No significant interference was experienced during the laboratory procedure.

Bedload samples were collected above and below the vortex. The samples were sieved, measured, weighed, and sorted. Particle samples used in the feasibility study represented particle sizes in the range of 1.2 to 5.1 cm. Larger particles were not sampled because of the limits of the study and particles smaller than 1.2 cm were difficult to drill.

Several methods for placing the transponders within the selected particles were attempted. A drill press at a slow RPM (500) with a carbide drill bit was found to be the most efficient and successful method for drilling holes into the basalt particles; different mineral compositions will require variations in drilling techniques. After the holes were drilled, the transponders were inserted and sealed with marine grade silicone gel. The particles were painted for easy identification during the testing procedure. Painting is not necessary for a large scale experiment.

Field Preparation: The in-situ vortex bedload sampler was modified to accommodate the receiver portion of the transponder unit. The receiver was placed at the point where the vortex enters the catch basket. This allowed the receiver to be directly mounted on the basket. The receiver is not water resistant so the unit was sealed with silicone gel to prevent system malfunction during the field trial. Because the receiver has a small surface area, it was necessary to create a constriction so that all particles carried through the vortex would pass over the scanning surface.

Field Trial: The field trial took place in April of 1994 during a period of low stream flow. The particles were placed directly in the instream portion of the vortex so that they would immediately pass over the receiver. Due to the low flows, only the particles small enough to be mobilized by the water were used. Holes in the vortex caused some of the smaller particles to become temporarily lodged inside of the vortex culvert. Once the particles were transported through the culvert, they passed over the receiver. All samples that passed over the receiver were read by the scanner and recorded. As a test of relative sensitivity of the receiver, several particles were manually moved over the receiver at 8 to 10 cm above the scanning surface. These transponders were detected and recorded.

RESULTS

All transponder implanted particles tested at the Oak Creek vortex bedload sampler were adequately read by the scanning receiver, including particles passed 8 to 10 centimeters above the scanning surface. A larger scale study utilizing modified field equipment will provide further insight into the feasibility of this technique.

Potential Problems: Protecting the electronic equipment from moisture is of primary importance. Sealing the scanning unit with silicon gel was adequate for a short duration field trial. It is not known if the receiver could withstand a long period of inundation.

Natural abrasion of particles will be a serious consideration for long duration projects. Sufficient abrasion could dislodge or destroy the transponder ampule. Deep emplacement of transponders into larger particles could overcome this problem. Alteration of the particle density due to drilling could also be an important factor. In small particles, a significant amount of material is replaced with an air encapsulated ampule. The remainder of the drill hole is filled with low density silicone gel. This will likely have an effect on the required velocity for incipient motion. Large particles with deeply buried transponders may be difficult to detect because of weak or non-existent signals.

Equipment Alterations: Using this technology, it seems feasible to drastically improve the hardware available to meet the needs of bedload research. Since this technology was developed for the monitoring of laboratory animals, there are several limitations in the fluvial environment. Replacing current equipment encasements with waterproof shells is of primary importance.

The hardware would need to be adapted for use in streams which do not have a vortex bedload sampler. Equipment modification could include developing a mobile scanning head to detect the particles in the channel. The receiver and magnetic field mechanism could be separated into two individual pieces of equipment; they are currently both contained within the scanning head. This type of monitoring system has already been developed by Spieker and Ergenzinger (1990) and could be modified to read the BioMedic transponder signal. With the magnetic field separated from the receiver, stronger and larger magnetic fields could be generated. This magnetic field could be focused on a stream cross-section or it could encompass an area of the channel. The scanner could be modified to receive data from the cross section or specified area of the magnetic field.

POTENTIAL APPLICATIONS

Once the equipment is modified for regular field use, the applications for this technology are widespread. The most obvious application of this transponder system is the tracking of individual particles to determine trajectory, velocity, and deposition location. If the equipment were modified to record X and Y coordinates, bedform movement could also be studied. This type of research would require a multi-channel receiver and a pulsating magnetic field. The pulsating field would reduce redundant information and maximize available memory. Monitoring the X and Y coordinates of individual particles would be especially valuable in multiple channel or braided stream systems that have traditionally been too complex to model.

Directly linking the scanning unit to a computer would make the entire system operable from a remote location. This would enable a researcher to collect data on several sites simultaneously. This would also allow an upstream/downstream analysis by placing two or more scanning areas on a single stream increasing the spatial range of the study area.

Abrasion is a limitation of particle transport research but, it could also be studied. Placing transponders in particles of known size and recovering them from a stream system after a specific period of time, would provide abrasion rates data for specific stream systems.

Armor layer and imbrication studies could be enhanced with the transponder system. With X and Y coordinates and a constant magnetic field, incipient motion of particles could be directly recorded. This would be an improvement over flume studies of incipient motion and the empirical data could be used to evaluate mathematical models. Scour depth could also be determined using a similar procedure. Constant data or pulse data could be collected to determine scour depth during higher flow events. Magnetic field penetration into the stream substrate would need to be evaluated to undertake this type of study.

Particle recruitment areas or surface stability could be evaluated using this technology. These studies would require a much broader placement of particles and could provide valuable data. Bedforms could be evaluated to determine overall stability as well as stability or recruitment and transportation of individual particles.

CONCLUSION

The preliminary field test of the inexpensive "passive" radio transponder system indicates that the potential of this technology to monitor bedload transport and provide information on location, trajectory and timing of individual particle movement is excellent. This technological approach may overcome some of the obstacles of previous bedload monitoring techniques including streambed alteration, cost and temporally limiting aspects. Through further technological alterations including separating the scanning system into its component parts, many modifications of the current system could be investigated. Ongoing tests will provide more information concerning the accuracy, reliability, and limitations of the technology. Coordination of research ideas and developments in this area will increase the availability of these systems and will expedite the technology development process.

ACKNOWLEDGMENTS

We would like to thank the United States Army Corps of Engineers at the Vicksburg Waterways Experiment Station and project sponsor Monte L. Pearson, Senior Scientist, Geotechnical Laboratory, for supporting the equipment needs of this feasibility study. We also would like to thank Mark Kuechel for lending his practical hand in the preparation of the sample particles.

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A STUDY OF UNCERTAINTY IN MEASUREMENT OF SUSPENDED SEDIMENT

By **Niu Zhan, Senior Engineer, Bureau of Hydrology, YRCC, MWR, 2 Chengbei Road, Zhengzhou, Henan, China; Wang Xiongshi, Engineer, Bureau of Hydrology, YRCC, MWR, Zhengzhou, Henan, China; Zhao Boliang, Professor, Bureau of Hydrology, YRCC, MWR, 2 Chengbei Road Zhengzhou, Henan, China**

Abstract: In this paper, based on the classical theory of error and in combination with the basic measurement procedures of the suspended sediment, a complete formula system computing the uncertainties in the measurement is derived in detail, which will make a contribution to the assessment of the engineering error in the measurement of suspended sediment.

THEORETICAL BASIS

Error Propagation: Let Y varies with K independent readings' $x_1, x_2, \ldots, x_k$, i. e.,

$$Y = f(x_1, x_2, \ldots, x_k) \tag{1}$$

then the variance m_Y^2 of relative error of Y is

$$m_Y^2 = \frac{1}{Y^2}\sum_{i=1}^{k}(\frac{\partial f}{\partial x_i} m_i x_i)^2 \tag{2}$$

where m_i is a mean Square deviation corresponding to x_i.

If sum Y_s, product Y_p, and quotient Y_q are expressed as follows:

$$Y_s = \sum_{i=1}^{k} x_i \tag{3}$$

$$Y_p = \prod_{i=1}^{k} x_i \tag{4}$$

$$Y_q = x_1/x_2 \tag{5}$$

then the formulas of propagation of relative error are

$$m_s^2 = \frac{1}{Y_H^2}\sum_{i=1}^{k}(m_1 x_i)^2 \tag{6}$$

$$m_p^2 = \sum_{i=1}^{k} m_i^2 \tag{7}$$

$$m_q^2 = m_1^2 + m_2^2 \tag{8}$$

In addition, when some resultant quantities are influenced by measurement factors, and if the influence cannot be written as an analytical formula, the variance of the resultant quantities can be obtained by adopting the structure of the square sum of formula (7).

Uncertainty of Normal Distribution: Thinking observed quantities of suspended sediment are independent and their error distributionagrees with the Gaussian distribution, when confidence coefficient corresponding to a confidence level:

$$\Phi(Z_a) = \frac{1}{\sqrt{2\pi}}\int_{-Z_a}^{+Z_a} e^{-z^2/2} dz \tag{9}$$

is Z_a and a standard deviation (mean square deviation) of the relative error of the observed quantities is m, then the general formula of uncertainties is

$$X_B = Z_a m \tag{10}$$

where the uncertainty is an error limit, which corresponds to a certain confidence level in the normal error distribution.

When the variance relationship of the function Y is

$$m_Y^2 = am_i^2 + bm_j^2 + cm_k^2 + \cdots\cdots \tag{11}$$

the combinatory relationship of the corresponding uncertainties is

$$X_{BY}^2 = aX_{Bi}^2 + BX_{Bj}^2 + cX_{Bk}^2 + \cdots\cdots \tag{12}$$

where a, b, c, ⋯, are combinatory factors (coefficients). Find that formula (11) and formula (12) have an isostructuralism.

Fluid Model and Its measurement — Computation Mode: A fluid spatoal model, enclosed by a measured cross—section, water surface, and velocity vector is an irregular shape. For turbid watet, the distribution of sediment conc entration in the shape is heterogenous generally. So the basic procedure for measurement of suspended sediment is: according to the spatial distribution laws of velocity and sediment concentration at Spatial, several verticals are placed over a cross—section to divide the cross—section into several segments. Water depth, velocity, sediment concentration at each vertical are measured and computed. To use a method of average to compute the representative mean values of each segment; To multiply the discharge area of the segment and the corresponding velocity to obtain the sediment discharge through a segmint; the sediment discharge through the cross—section is obtained by accumulating the sediment discharge through each segment. Generally, this procedure is called formula Q, Q_s→C. But another procedure can be called formula Q, C→Q_s. In this procedure, at first, according to a fixed law, mean sediment concentration at across—section is obtained from the sediment concentration at each segment or vertical, then the sediment discharge through a cross—section is obtained by multiplying the sediment concentration at the cross—section and the discharge through the cross—section.

UNCERTAINTY OF FORMULA Q_S, Q→C

Systemic Diagram of Error Propagation:

In Diegram C=true value of mean sediment concentration at a cross—section,

Q=true value of discharge through a cross—section,

Q_s=true value of sediment discharge through a cross—section,

Q_m=measured discharge through a cross—section,

F_m=factor for number of verticals and computation rule the measurement of discharge

Q_{sm}=measured sediment discharge through a cross—section,

$f_n(C_s)$=factor for number of verticals and computation rule for measurement of sediment discharge,

q_i=measured discharge through a partial section

q_{si}=measured sediment discharge through a partial section

V_i=mean velocity at a partial section

C_j=mean sediment concentration at a partial section

W_i=area of a partial section

b_i=width of a partial section

d_i=water depth of a partial section

c=influence of flow pulse on velocity

e=precision of a velocity—measuring equipment

p=vertical velocity—measuring method and computation rule

C_{s1} =influence of a sediment pulse on measurement of sediment concentration

C_{s2} =vertical sediment—measuring method and computation rule

C_{rq}=precision of sediment—measuring equipment

C_{cl}=influence of the pretreatment in a sediment laboratory

- $C=\dfrac{Q_s}{Q}$
  - $Q=F_mQ_m$
    - $Q_m=\Sigma q_i$
      - q_1
      - q_2
      - ⋮
      - $q_i=v_iw_i$
        - $w_i=b_id_i$
          - b
          - d
        - v_i
          - c
          - e
          - p
      - ⋮
      - q_m
    - F_m
  - $Q_s=f_nQ_{sn}$
    - $f_n(C_s\ \text{II})$
    - $Q_{sn}=\Sigma q_{sj}$
      - q_{s1}
      - q_{s2}
      - ⋮
      - $q_{sj}=q_j\,\overline{c_j}$
        - $\overline{c_j}$
          - C_s I
          - C_s II
          - C_{Yq}
          - C_d
        - $Q_j=v_jw_j$
          - $w_j=b_jd_j$
            - b_j
            - d_j
          - v_j
            - c
            - e
            - p
      - ⋮
      - q_{sn}

Relationships of quantities for measurement—computation

$$Q=F_mQ_m=F_m\Sigma q_i=F_m\Sigma(b_id_iv_i) \tag{13}$$

$$Q_s=f_nQ_{sn}=f_n\Sigma q_{si}=f_n\Sigma(b_id_iv_i\,\overline{c_j}) \tag{14}$$

$$C = Q_s/Q \qquad (15)$$

Uncertainty Formulas Derived: By using formulas (6), (7), (8), variance propagation relationships can be obtained from formulas (13), (14), (15), then following formulas can be derived accordingto the isostructuralism of formulas (11) and (12).

$$X_Q^2 = X_{F_m}^2 + \frac{\sum_{i=1}^{m} q_i^2}{(\sum_{i=1}^{m} q_i)^2}(X_b^2 + X_d^2 + X_c^2 + X_e^2 \cdot X_p^2) \qquad (16)$$

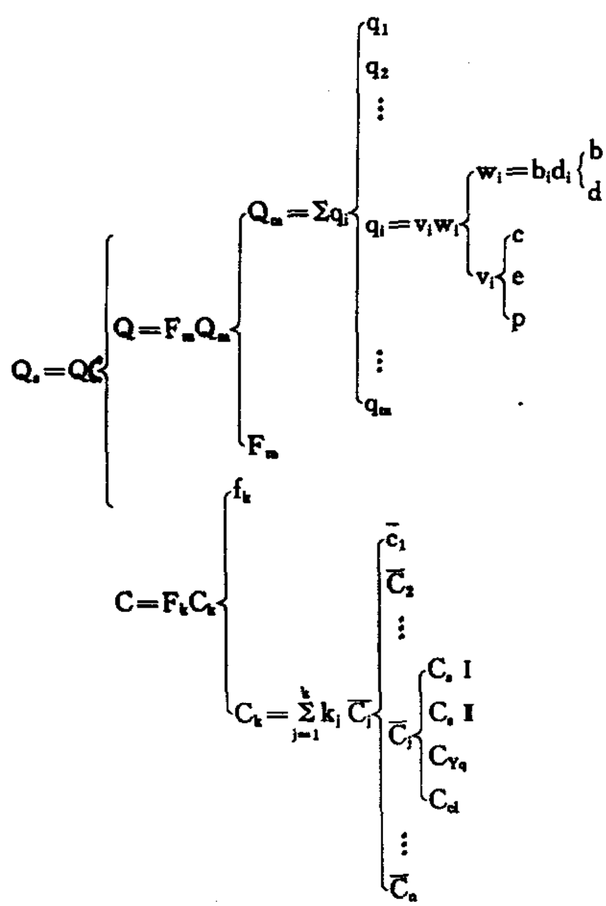
$$X_{Q_s}^2 = X_{f_n}^2 + \frac{\sum_{i=1}^{n} q_{s_i}^2}{(\sum_{i=1}^{n} q_{s_i})^2}(X_b^2 + X_d^2 + X_c^2 + X_e^2 + X_p^2 + X_{C_{s1}}^2 + X_{C_{sI}}^2 + X_{Y_q}^2 + X_{cl}^2) \qquad (17)$$

$$X_c^2 = X_{Q_s}^2 + X_Q^2 \qquad (18)$$

where uncertainties are named by subscript, which meaning may befound in the description of the systemic diagram of error propagation.

UNCERTAINTY OF FORMULA Q,C→Q_s

Systemic Diagram of Error Propagation:



In which f_k=number of verticals spaced over a cross—section and computation rule for measurement of sediment concentration, C_k=mean measured sediment concentration at a cross—section, meaning of other symbols may be found in the description of the errorpropagation formula of the formula Q_s,Q→C. Comparing the two diagrams, the discharge—computing parts are thesame. The different parts are: In the former, sediment discharge through each segment, and sediment discharhe through the cross — section must be computed first, then the sediment concentration at the cross—section is computed; In the later, sediment concentration at a cross—section must be obtained first, then the sediment discharge through a cross—section is computed. Generally, it is thought that the sediment concentration at a cross—section in the formula Q, C→Q_s is a linear combination of partial sediment concentrations;Seeing from the balance that the sediment discharhe through a cross—section is equal to the sum of sediment discharhe through each segment, the linear combinatory coefficient k_j is the ratio of the discharge through each segment to the discharge through a cross—section.

Computation Relationships:

Discharge Q is the same as formula(13).

$$C = f_k C_k = f_k \sum_{j=1}^{k} k_j \overline{c_j} \tag{19}$$

$$Q_s = QC \tag{20}$$

Uncertainty Formula Derived: As the same, formulas (6), (7), (8) and (11), (12) are used to derive uncertainty formulas.

X_Q^2 is the same as formula (16).

$$X_{Q_s}^2 = X_{f_k}^2 + \frac{\sum_{j=1}^{k}(k_j \overline{c_j})^2}{(\sum_{j=1}^{k} k_j \overline{c_j})^2}(X_{C_{s1}}^2 + X_{C_{s2}}^2 + X_{Y_q}^2 + X_{cl}^2) \tag{21}$$

$$X_{Q_s}^2 = X_Q^2 + X_c^2 \tag{22}$$

Notation: Formula (22) is different from formula (18), which is the result of the difference between the computation procedures. Error propagation only can conduct according to the computation procedures. The uncertainties are named by subscript, which meaning may be found in the description of the systemic diagram of error propagation.

COMPUTATION RULE OF INDIVIDUAL UNCERTAINTIES

Let B_i=standard value, G_i=corresponding measured value, E_i=relative error, u=statistical average for Sample of error series, m^2=statistical variance, X=uncertainty, Z=confidence coefficient, I=sample capacity, then an individual uncertainty may be obtained with a set of formulas following.

$$\left.\begin{aligned} E_i &= \frac{G_i}{B_i} - 1 \\ u &= \frac{1}{I}\sum_{i=1}^{I} E_i \\ m^2 &= \frac{1}{I-1}\sum_{i=1}^{I}(E_i - u)^2 \\ X &= Zm \end{aligned}\right\} \tag{23}$$

Because river water flow is difficult to be measured repeatedly,here a merging statistical method of relative error series is used to compute an individual uncertainty, which can be used to reflect general character of error of a certain station or under a certain condition. This is the reason the individual uncertainty can be extracted from the accumulateing symbols in the former formulas (16),(17), (21).

The individual errors influencing the measurement of the suspendedsediment can be divided into 3 types: precision of equipment, water flow character, and computation method. When deriving an individual uncertainty, we take the representative values at each vertical as a computation basis, may compute vertical averages first, then use the set of formulas (23).

REDUCED FORMULAS OF UNCERTAINTIES WHEN USING EQUAL—DISCHARGESEGMENT

For formula (16), when all the q_i are equal, have the formula $\sum_{i=1}^{m} q_i^2 = mq_i^2$, $(\sum_{i=1}^{m} q_i)^2 = m^2 q_i^2$, then the formula can be reduced to

$$X_Q^2 = X_{F_m}^2 + \frac{1}{m}(X_b^2 + X_d^2 + X_c^2 + X_e^2 + X_p^2) \qquad (24)$$

For formula (21), when q is are equal, all the corresponding k_j are equal, then the formula can be reduced to

$$X_C^2 = X_{f_k}^2 + \frac{\sum_{j=1}^{k} \overline{C}_j^2}{(\sum_{j=1}^{k} \overline{C}_j)^2}(X_{C_{s1}}^2 + X_{C_{s2}}^2 + X_{Y_q}^2 + X_{cl}^2) \qquad (25)$$

EXPRESSION OF PHYSICAL QUANTITIES FOR COMPUTATION OF SUSPENDED SEDIMENT AFTER KNOWING UNCERTAINTY

$$Q_{JX} = Q(1 \pm X_Q) \qquad (26)$$

$$C_{JX} = C(1 \pm X_c) \qquad (27)$$

$$Q_{SJX} = Q_S(1 \pm X_{Q_s}) \qquad (28)$$

In which Q_{JX}, C_{JX}, Q_{SJX} indicate the limit values of discharge, sediment concentration, sediment discharhe under a certain confidence level. In other words, the probability, of which each quantity falling into an interval, is called a confidence level. In the engineering practice, generally true Q, C, Q_s are replaced by observed values.

PRELIMINARY ANALYSIS OF THE NCPA-NSL SUSPENDED SEDIMENT CALIBRATION SYSTEM

By R.W. Derrow II, Research Physicist, National Center for Physical Acoustics, University of MS, University, MS 38677; R.A. Kuhnle, Research Hydraulic Engineer, National Sedimentation Laboratory, USDA - Agricultural Research Service, P.O. Box 1157, McElroy Drive, Oxford, MS 38655

Abstract: A water/sediment recirculation system, driven by an impeller based pump, has been designed and built to maintain various sizes and densities of sediment in suspension. Acoustic backscatter models and algorithms will be developed to measure suspended sediment concentration and size distributions using these suspensions. An impeller driven pump was chosen because this type of pump is relatively inexpensive and readily available. Since the impeller has an increased tendency to create cavitation over other pump types, a simple equation was used as a part of the design process to estimate and minimize the potential for cavitation. The first generation system has been built and simple acoustic backscatter tests have been performed on the water filled system and will be discussed. Test results indicated no impeller created cavitation but bubble production was caused by turbulence generated at the pump intake structure. Steps have been initiated to solve the problem. The design, construction and preliminary testing of the system will be discussed.

INTRODUCTION

Accurate determinations of the amount of sediment delivered by flows in an alluvial channel are important for a number of reasons. First, the sediment delivered to a channel reach represents net erosion from upstream areas - from either the watershed surface or the boundary of the channel itself. Second, the sediment conveyed downstream may fill reservoirs, interfere with navigation, or degrade water supplies. Also any long term program of channel stabilization must take into account the transport of sediment through the watershed. If sediment supplied to the channel is either more or less than the capacity of the channel to transport it, deposition or erosion of the channel boundary will occur and instability of the channel may result.

Sediment transport rates of channels may either be calculated using one of the many transport relations or by sampling the sediment in transport. The prediction of the rate of sediment transport is problematic because no transport relation is generally applicable to alluvial streams and the relations yield widely different results for the same flow and sediment conditions.

Sampling of the sediment in transport is also difficult. Variable conditions in transport rates require that many samples be collected at each flow rate to accurately calculate mean rates. With few exceptions practical automatic samplers do not exist. Fine sediment (< 0.062 mm) can be reliably sampled at a point using automatic pumping samplers (Kuhnle et al, in press). Also, automatic pit samplers can be used in small streams to sample the bed load (Reid et al., 1980). In most cases, however, reliable samples of the transport of the sand and gravel fractions must be collected manually, which was the finding from the Goodwin Creek Experimental Watershed, (GCEW) (Bowie and Sansom, 1986; Willis et al., 1986). Runoff events on the GCEW often occur at night, on weekends or holidays, when workers may not be on call. Also a crew of 2 or 3 people are needed to cover only one site on a watershed.

Use of acoustic techniques to measure suspended sediment concentration have been ongoing for several years (Urick, 1948). In most of these systems a short burst of high frequency (>1 MHz) sound is emitted from a transducer and is scattered off the sediment in suspension. The magnitude of the backscattered energy is related to the concentration and size of the sediment. Current technology can measure suspended sediment concentration within limited size distributions with high accuracy (Thorne et al., 1993), but success been limited at determining sediment size distribution to a reasonable accuracy. Very high concentrations where multiple scattering effects are more dominant are especially problematic (Crawford and Hay, 1993; Thorne et al., 1994).

The Suspended Sediment Calibration System (SSCS) has been built as part of a research program started in 1994 as part of a collaborative effort between the National Center for Physical Acoustics and the USDA-ARS National Sedimentation Laboratory to develop a general-purpose suspended sediment measurement system for watersheds such as the GCEW. The SSCS will be utilized as a laboratory tool in the development of the necessary models and algorithms to measure suspended sediment processes in the field.

Numerous sediment calibration systems have been built (Hanes et al., 1988; Lohrmann et al., 1994; Wylie et al., 1994) and all have had problems with air entrainment and/or uniform mixing of the sediment. Most systems used pumps such as diaphragm pumps or peristaltic pumps that do not create as much turbulent flow as a impeller driven pump, , but these pumps are relatively expensive compared to an impeller driven pump of the same flow capacity. Impeller driven pumps produce a more homogenous mix of sediment in suspension than do the other pumps. The SSCS must be bubble free because bubbles in the system may be indistinguishable, acoustically, from sediment. When an impeller driven pump was chosen a theoretical analysis of cavitation was conducted was done to determine at what pump speed the onset of cavitation would occur. According to the analysis, the pump speed required to suspend particles up to 1 mm in diameter should not produce cavitation. The same analysis was used to optimize the entire recirculation system. Following the theoretical analysis, a complete system was constructed, and a simple real-time acoustic backscatter test was performed. Modifications to the system are proposed based on results of this test.

DESIGN AND CONSTRUCTION

Theoretical Analysis: The equation used in the analysis to predict the presence of cavitation on the impeller was (John, 1980):

$$p = p_\infty - C_p\left(\frac{\rho V^2}{2}\right), \tag{1}$$

where p is the pressure at the tip of the impeller, ρ is the density of water, and V is the linear velocity at the tip of the impeller in m/s. The impeller tip was used as the calculation point because cavitation starts at the edges, where the linear velocity is greatest and pressure is the lowest. The term , p_∞, is equal to, *atmospheric pressure + head pressure*, or $p_\infty = p_{atm} + p_{head}$, and C_p is the pump cavitation index that is derived from the ratio of the dynamic depression head to the total head of the pump. It is a quantity that is specific to the design of each pump and it's specific speed (Warring, 1984a). An approximate value for C_p, for this pump, is 0.88 (Warring, 1984a).

Cavitation would be generated by the impeller if p falls below the saturation vapor pressure (p_{sv}) for water, which is a function of the water temperature. For the work in the lab p_{sv} will fall in the range of 2.5-4.5 kPa.

Careful analysis using Eq.(1) shows a few efficient methods to minimize the onset of cavitation. First, by increasing p_{head} or p_{atm}, p_∞ will increase, thereby increasing p. However, most of the techniques used to increase p_{atm} would entrain bubbles in the system, but increasing p_{head} is easily attained by raising the height of the recirculation pipe balanced against maintaining the pumps' head capability. Hence, by using a 4 meter head the cavitation resistance is improved. Eq.(1) also indicates that the probability for cavitation grows with the square of the velocity of the impeller. Therefore a pump speed has been chosen that produces a flow that is no greater than twice the fall velocity for particles up to 1 mm in diameter. Determining an optimum p was an iterative process and the final values used in Eq.(1) were, $p_\infty = 140.4$ kPa, $C_p = 0.88$, $V^2 = 147.8$ m^2/s^2 (1160 RPM), and $\rho = 997.1$ kg/m. This resulted in $p = 75.5$ kPa. Therefore, since $p >> p_{sv}$, the impeller should not generate any cavitation.

Construction Phase: Once it was determined that the pump would not generate any cavitation, construction of the system began. Figure 1 shows the details of the major components of the system. Figure 1 is divided into six sections, for descriptive purposes. Section I is the measurement area that is 3 m in length and 0.3 m in width. The 3 X 0.3 m measurement volume was chosen because field applications would require a 3 m measurement range and the 0.3 m width prevents transducer side-lobe interference. Seven equally spaced sample ports were affixed to the pipe wall to measure flow velocity and to sample the flow. Each port has a plastic threaded plug that fits flush with the inside pipe wall. The acoustic transducer carriage (top of section I) is designed to minimize the amount of surface area in the flow and will hold up to 4 transducers. The carriage is attached to the pipe wall by eye screws that protrude from the pipe. The transducers are connected to the electronics via waterproof cables that feed out through the top of the system (see section II) via a waterproof feed-through assembly. Section III contains the sediment and water fill port that uses a simple garden hose connection to fill the system with tap water and various sediments. Section IV is the 8 inch return pipe for the system. Section V has a 1 inch diameter threaded drain plug to periodically flush the system. The SSCS is built entirely out of PVC and CPVC except for the pump, transition 'A' and 'B', and the transducer holder. PVC and CPVC were chosen because they are relatively light weight, don't rust, and have smooth inside surfaces that minimize the turbulence. Any metal components that could possibly rust were coated with either multiple coats of paint or special rust-proof coatings to prevent any potential backscatter from rust that may enter into suspension.

A linear, gradual taper was chosen for flow transition "A" to reduce flow separation that could occur when moving from a 0.2 to 0.3 pipe diameter. Flow transition 'B', however, is a simple rapid expansion, nonlinear taper since separation of flow is not important outside of the measurement area.

The pump drive is a 3 phase motor mated to a variable-speed belt transmission that varies from 583 to 1750 rpm. However, since the pump cannot overcome 4 meters of head pressure at the lower rpm's and the potential for cavitation increases at higher rpm, the pump realistically has a limited rpm span. That is why we have used 1160 rpm as a practical value.

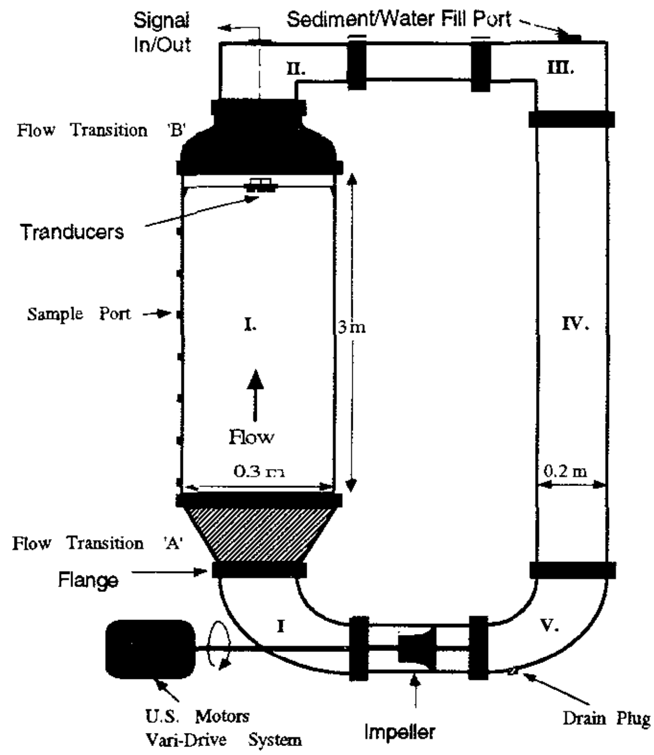


Figure 1. First generation suspended sediment recirculation system as was built and tested.

CAVITATION TEST

Experimental Setup: A simple acoustic backscatter measurement at an acoustic frequency of 1 MHz was used to determine the onset of cavitation in a qualitative way. Figure 2 details the components used in the experiment with the 1 MHz transducer. All of the components are controlled by the PC computer including the oscilloscope that interfaces to the computer via an IEEE-488 bus. The acoustic functions of the system are controlled by a transmitter/receiver plug-in card (MATEC Instruments, TB-1000*) that allows complete programmability through software. The board was operated in pulse/echo mode. This mode uses the same transducer for both transmit and receive functions. Once the transmit pulse is sent to the transducer, any backscatterd echoes, received by the same transducer, are routed to the fixed-gain receiver amplifier. The amplified signal is then output to the oscilloscope for display and analysis.

Test Results: The objective of the test was to measure the backscattered noise level in the measurement area with and without the pump running and compare the two levels. Both measurements were made with the system filled with clean tap water with no sediment added. The system was allowed to degas for 48 hrs. before the measurements were conducted. Figures 3 and 4 detail the results of the measurements. Figure 3 shows the oscilloscope trace when the pump was off. It is a very 'clean' environment with no visible trace deflection, except for the 2 echoes from

* Mention of commercial products and organizations in this publication is solely to provide specific information. It does not constitute endorsement by the U.S. Department of Agriculture over other products and organizations not mentioned.

the flange (b), and elbow (section V), which are shown in figure 1. Figure 4 shows the same measurement area with the pump on. Backscatter from bubbles is evident throughout the water column as shown by the significant increase in oscilloscope trace deflections. The bubble density generated from the cavitation is such that backscatter from the flange and pump elbow, as seen in Figure 3, is totally blocked in Figure 4. It is obvious that cavitation is occurring within the system. Not so obvious, though, is the source of the cavitation. Before the cavitation

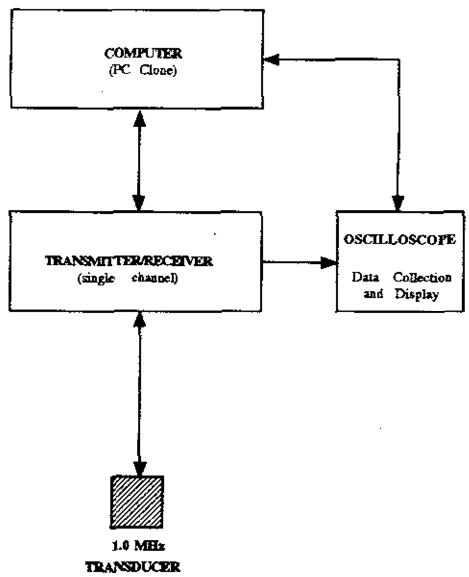


Figure 2. Block diagram of the components used to measure the acoustic backscatter from particulate matter in the water column.

can be eliminated, the source must be determined. After we analyzed the data and verifying the accuracy of the calculation's involving Eq. (1), we focused attention on the piping geometry of the recirculation system. The pump manufacturer suggested that the pump intake piping could be causing an undesirable flow into the pump. Referring to Figure 1, the elbow in section V, at the pump intake, may be causing a flow restriction to occur, which would create a lower pressure zone around the impeller than predicted by Eq.(1). Eq. (1) assumes unrestricted flow in and around the impeller body. One solution to minimize this condition is to insert a relatively long, straight piece of pipe on the pump intake to allow the flow to straighten before entering the pump. Therefore, as part of the modification to the system, a 1.8 m clear acrylic extension pipe will be fitted to the pump intake as shown in Figure 5. A transparent pipe was chosen to allow visual verification of proper flow into the pump. Another modification shown in Figure 5 is the addition of a flow straightener at the pump output that will breakup any large eddies in the output flow. This modification will provide a more homogeneous flow field in the measurement area (section I).

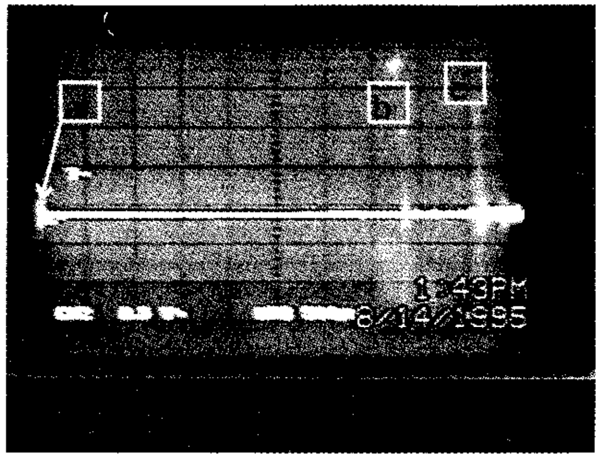


Figure 3. Oscilloscope trace from the water-filled tower. The trace shows: (a) time t=0:near transducer (b) backscatter from flange of flow transition 'A' and (c) backscatter from pump elbow. Note pump has not been turned on.

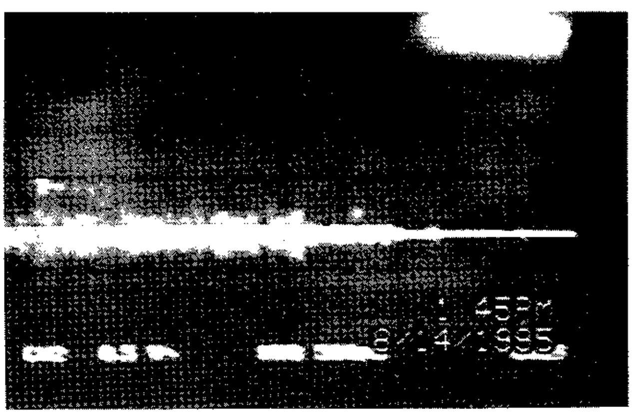


Figure 4. Same trace as Figure 3 shortly after pump was turned on. Note the significant increase in backscatter due to cavitation generated by the pump intake restriction. The bubble cloud is dense enough to mask the echo's (a) and (b) in Figure 3.

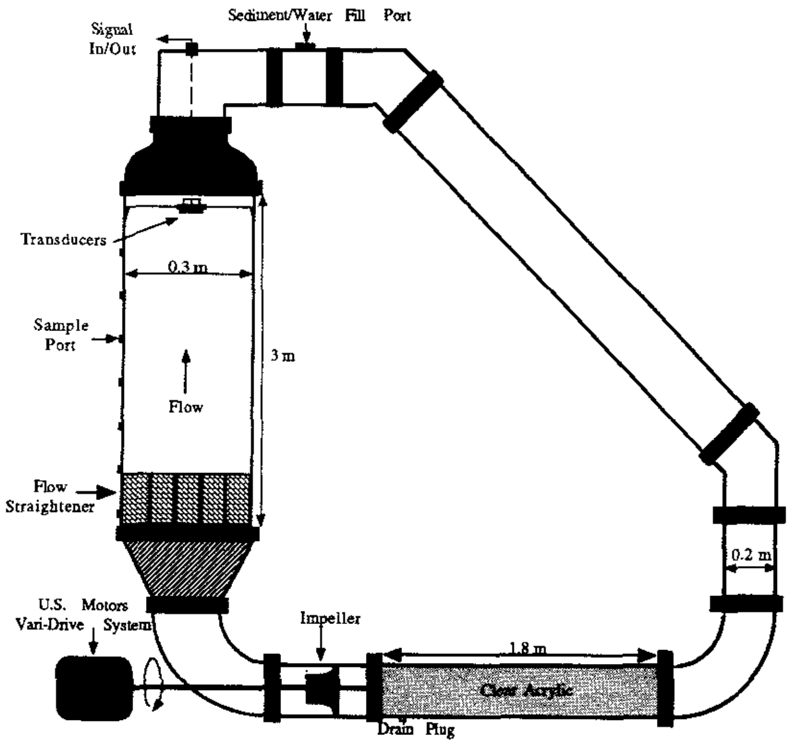


Figure 5. Modified recirculation system with the length of straight acrylic tubing added to the pump intake which is designed to reduce pump cavitation.

SUMMARY

A suspended sediment calibration system has been designed and built using an impeller driven pump to recirculate water/sediment mixtures. Preliminary acoustic measurements revealed that modifications are needed. Once the system is cavitation free, it will be used to develop algorithms to predict suspended sediment concentration and size distribution using acoustic backscatter techniques.

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Author's Contact Points:

	Robert W. Derrow II	Roger A. Kuhnle
Ph#	(601)-232-5613	(601)-232-2971
fax#	(601)-232-7494	(601)-232-2915
E-mail:	derrow@sparc.ncpa.olemiss.edu	kuhnle@gis.sedlab.olemiss.edu

USE OF AN ACOUSTIC RANGING SYSTEM TO MONITOR SEDIMENT DEPOSITION FOR PROTECTION OF AN ENDANGERED MUSSEL

By Michael S. Griffin, Hydrologist, U.S. Geological Survey, Water Resources Division, Louisville, Kentucky

Abstract: The U.S. Army Corps of Engineers (COE), Louisville District is replacing Ohio River Locks and Dams 52 and 53 with a single facility located near Olmsted, Ill. The endangered orange-footed pearly mussel (Plethobasus cooperianus) is found in two mussel beds in the lower Ohio River, near the site of the new locks and dam. The construction and operation of the Olmsted Locks and Dam could change the current sediment deposition and erosion patterns. Sediments deposited on the mussel beds could threaten the viability of the beds and the survival of the orange-footed pearly mussel. The guidelines in the biological opinion (U.S. Fish and Wildlife Service, 1993), set forth by the U.S. Fish and Wildlife Service (USFWS) to ensure protection of the mussels, state that if one sensor indicates an hourly accumulation of 0.787 inches (in.) (2 centimeters) above baseline levels on the mussel bed and if the accumulated sediment remains at the elevated level or increases over another 3-hour period, construction activities will cease and corrective actions will be taken.

The U.S. Geological Survey (USGS), Kentucky District, in cooperation with the Louisville District COE, has designed and installed a multi-transducer acoustic ranging system interfaced with satellite telemetry to continuously monitor changes in elevation of the river bed over the mussel bed, located downstream of the construction project. The acoustic equipment is rugged, capable of providing the required measurement accuracy over a broad range of environmental conditions with minimal manual adjustment, and operates with low power consumption. Accurate detection of 0.787 in. of sediment accumulation requires the acoustic ranging system to have an accuracy of plus or minus 0.394 in. in environmental conditions typical of the Ohio River. This system will be operational during construction and normal lock and dam operation until such time that it is determined that the new locks and dam are not adversely affecting the mussel bed by sediment deposition or erosion.

INTRODUCTION

Background: The Ohio River flows 981 miles (mi) from the confluence of the Allegheny and Monogahela Rivers at Pittsburgh, Penn. to the Mississippi River near Cairo, Ill. The entire river, except for the last 19 mi (from Lock and Dam 53 to the Mississippi River), has been altered by construction and operation of locks and dams to provide a stable navigational channel. During the past 50 years, all but 2 of the original 53 wicket dams and locks have been replaced with high-lift dams. Figure 1 shows how the new high-lift dams have increased pool levels on the Ohio River that border the State of Kentucky.

The Ohio River and its tributaries have historically supported a multitude of aquatic species, including fish and mussels. Construction of navigation facilities on the river significantly altered the river into a series of lake-like pools. Extensive artificial impoundments of the river slowed current velocities, and subsequent accumulation of silt resulted in reductions in mussel fauna (Thorp and Covich, 1991). The lower Ohio River, from Lock and Dam 53 to its confluence with the Mississippi River, contains the only remaining free-flowing riverine habitat in the entire main stem of the river and supports the largest populations of pre-impoundment fish and mussel species (U.S. Fish and Wildlife Service, 1993).

On the basis of investigations to improve navigational conditions on the lower Ohio River, the U.S. Army Corps of Engineers (COE), Louisville District, was authorized to replace Locks and Dams 52 and 53 with a single structure. This new facility will be located at Ohio River Mile 964.4, near Olmsted, Ill., and will be known as Olmsted Locks and Dam. The facility is located approximately 1.8 mi downstream of the existing Lock and Dam 53. It will consist of the following: two parallel lock chambers approximately 110 feet (ft) wide by 1,200 ft long constructed on the Illinois side of the river, a 2,200 ft navigable pass section, and a 425 ft section of fixed weir on the Kentucky side of the river. The navigational pool created by the new dam

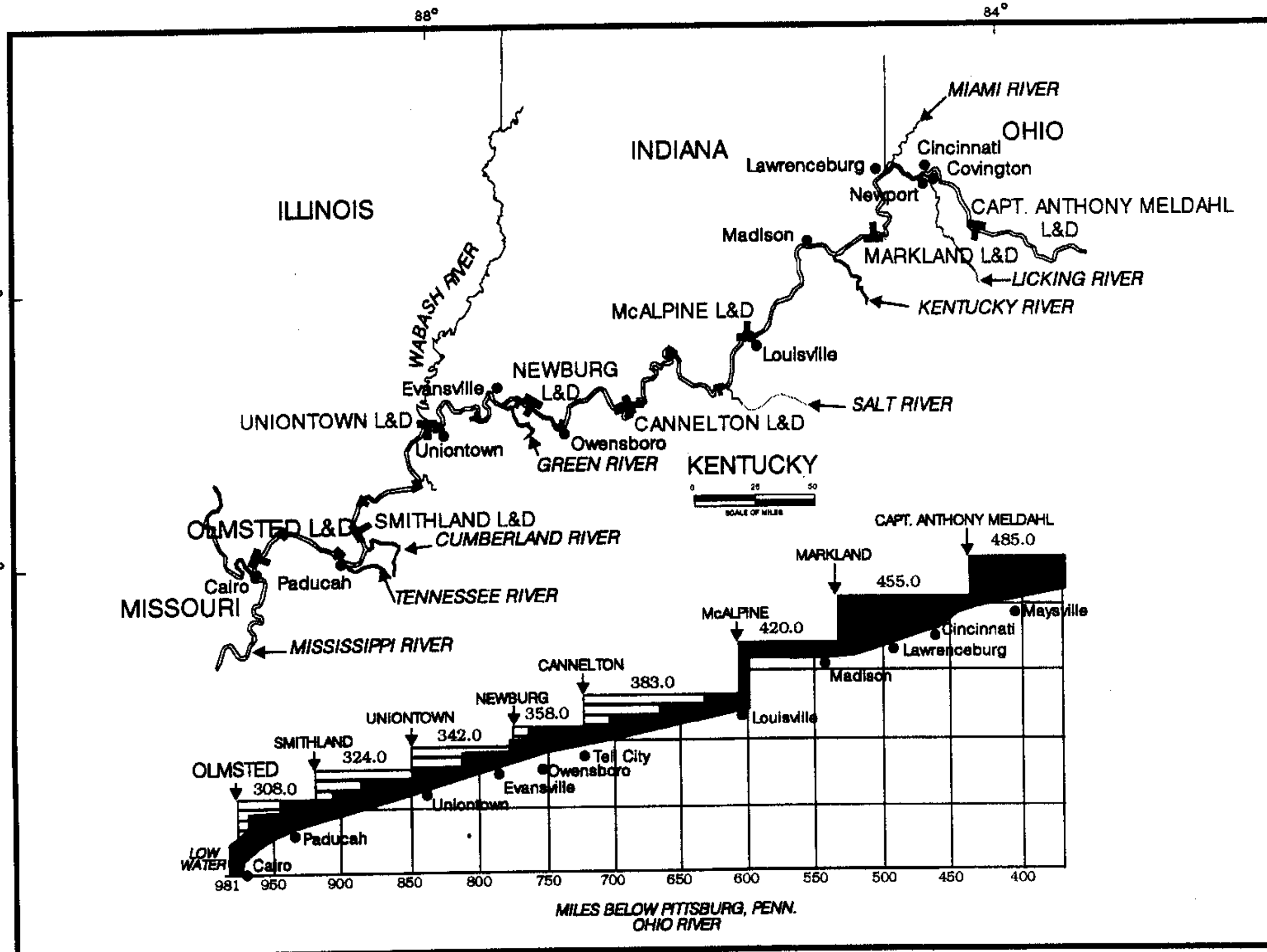

Figure 1. New high-lift dams on the Ohio River.

will be operated to maximize use of the navigable pass and minimize frequency of lockage. Upon completion of the Olmsted Locks and Dam, the existing Locks and Dams 52 and 53 will be dismantled and removed from the Ohio River.

This paper describes the unique application of a multi-transducer acoustic ranging system interfaced with ultrahigh frequency (UHF) radio and Geostationary Operational Environmental Satellite (GOES) telemetry. The sediment deposition monitoring system determines river bed elevations at remote sites and transmits the data to various offices around the country.

Problem: The endangered orange-footed pearly mussel (Plethobasus cooperianus) is an Interior Basin species usually found in medium to large rivers at depths of 10 to 29 ft (U.S. Fish and Wildlife Service, 1993). The mussel buries itself into sand and gravel leaving only part of its shell and feeding siphon projecting above the river bed. The Ohio, Cumberland, and Tennessee River drainages contain the only three known population areas of this mussel remaining anywhere in the historic range of the species. The only population that is known to be reproducing is located in the Tennessee River (U.S. Fish and Wildlife Service, 1993).

The two mussel beds (one population) located in the lower Ohio River near the site of the Olmsted Locks and Dam project are suspected to be reproducing, so a significant adverse affect on this population could threaten the survival of the species. One mussel bed is located upstream of the project, and the other is located downstream of the project. Sediment deposition and erosion patterns that existed prior to construction may change because of the following: bed material lost during dredging for cofferdam construction, creation of a temporary navigational channel, changes in the water-current direction and magnitude, associated river traffic, and riverside development during the construction and operation of the new locks and dam. Changes to the sediment regime could result in water-quality degradation and habitat alteration. The guidelines in the biological opinion (U.S. Fish and Wildlife Service, 1993), set forth by the U.S. Fish and Wildlife Service (USFWS) to ensure protection of the mussels, state that if one sensor indicates an hourly accumulation of 0.787 inches (in.) (2 centimeters) above baseline levels on the mussel bed and if the accumulated sediment remains at the elevated level or increases over another 3-hour period, construction activities will cease and corrective actions will be taken.

The U.S. Geological Survey (USGS), Kentucky District, in cooperation with the Louisville District COE, has designed and installed a multi-transducer acoustic ranging and telemetry system to continuously monitor the changes in elevation of the river bed over the mussel bed located downstream of the construction project.

Monitoring Plans: To ensure continued viability of the mussel beds, the COE implemented a system designed to monitor the mussel populations and record effects of project construction and developed a contingency plan if certain criteria were not met. Biological monitoring, consisting of qualitative and quantitative sampling of the mussels, will be conducted for the first 2 years (1993–94) and in alternate years thereafter for the remainder of the construction and initial operation period of the Olmsted Locks and Dam (U.S. Fish and Wildlife Service, 1993). Physical monitoring will also be conducted by the COE, which includes hydrographic surveys to map the position and extent of the mussel beds; the mapping surveys will provide detailed contours for the development of three-dimensional models of the beds. The USGS, Kentucky District, in cooperation with the Louisville District COE, designed and installed a system to continuously monitor the changes in river bed elevation at the mussel bed located downstream of the project. Construction activities started in September 1993 and the system is currently collecting baseline data during the phase I period scheduled for completion in summer 1995. The system will continue to be operated during construction and during normal lock and dam operation until such time that it is determined that the routine operation of the facility is not adversely affecting the mussel bed by sediment deposition or erosion. To meet the guidelines of the biological opinion issued by the USFWS regarding protection of the endangered mussel species (U.S. Fish and Wildlife Service, 1993), the monitoring system must (1) provide real-time river bed elevation measurements data, (2) detect 0.787 in. of sediment deposition at remote locations on the Ohio River, and (3) provide the data to personnel in various locations.

SYSTEM DESIGN

Physical Configuration: Originally, six transducers were positioned in a "T" configuration (in plan view) with the base of the "T" pointing upstream in each of the four groups; the four groups were all located over the mussel bed. Each segment of the "T" had two transducers equally spaced over a distance of 350 ft (fig. 2). A 5/16-in. diameter steel carrier cable was laid between a mooring pile at the center of the cluster and each of the transducer stands (fig. 3). The steel carrier cable helped secure the transducer cable and was used as a guide for divers to locate the transducer stands. The transducer stand consisted of a 6-in. H-pile driven into the river bed with a 3-ft long I-beam bolted to the H-pile in a horizontal position about 4 ft above the river bed and pointing upstream. The transducers were mounted to a stainless-steel bracket attached to the upstream end of the I-beam. Kevlar[1] reinforced transducer cable, with mating underwater pluggable connectors, was used to connect the transducer to the surface electronics and was attached to the 5/16-in. stainless-steel carrier cable with nylon-wire straps. Each site had a 10 ft diameter by 2 ft high mooring buoy, with a 3 ft by 3 ft steel box mounted on top that housed the acoustic ranging system and telemetry equipment. Each mooring buoy was attached by a 1 3/4-in. steel cable to a 10-in. H-pile that was driven into the river bed at the center of each cluster. Each buoy was equipped with a U.S. Coast Guard approved navigation light. During the high-flow period of 1994 (December 1993-April 1994), it was evident that the existing buoy setup would not be appropriate because of the harsh conditions on the Ohio River. High flow caused the destruction of two buoys and loss of all equipment.

The COE had new buoys designed and built because the original buoys were designed to submerge as the water velocities increased; the new buoys were installed in November 1994. The new buoys have a 12-ft diameter horizontal-deck platform and are 11 ft long. The buoys are designed to withstand velocities of 10 ft per second, have a payload capacity of 2,000 pounds, and the decks extend out of the water approximately 3 ft. They have an adjustable ballast feature. The instrument box enclosure was designed into the construction of the buoys and is located below the platform deck. A specially designed 42 in. by 42 in. waterproof aluminum box rests inside the enclosure and can be easily removed. A spring-balanced aluminum hatch cover allows entrance to the instrumentation enclosure. The buoys are moored by a 5/8-in. steel cable to the 10-in. H-pile driven into the river bed. The buoys have a skid-proof surface, handrails, and a U.S. Coast Guard approved navigation light for safety.

Acoustic Ranging System: Monitoring changes in river bed elevation requires elevation data to be collected at numerous points over the mussel bed. Several technologies were evaluated, and the acoustic ranging systems were found to be the most cost-effective method of monitoring the change in river bed elevation. The equipment had to (1) be rugged, (2) provide the required measurement accuracy over a broad range of environmental conditions with minimal manual adjustment, and (3) operate with low power consumption. To minimize damage caused by submerged debris, all electronics except the transducers had to be located above the water surface. The cable used for the transducers had to be armored to provide strength while maintaining cable flexibility. Each transducer would have a 6 ft pigtail, with underwater pluggable connectors, for ease of installation and maintenance of the transducers. The connector serves as a weak link in the event that debris catches on the transducer cable. Each transducer operates independently to minimize data loss. The minimum and maximum operating range of the system was important and was a factor in how far above the river bed the transducers were mounted. The higher the transducer is mounted, the more likely it is to be damaged by debris; however, if it is mounted too low, the transducer could become buried during extreme sediment deposition. It was decided that the transducers would be mounted about 3.5 ft above the river bed.

Accurate detection of 0.787 in. of sediment accumulation required the acoustic ranging system to have an accuracy of plus or minus 0.394 in. in environmental conditions typical of the Ohio River. Most acoustic ranging systems measure the depth to the nearest object that reflects sufficient acoustic energy to exceed a predetermined energy threshold. The influence of false bottom readings resulting from fish or submerged

[1]The use of trade, product, industry, or firm names in this report is for descriptive or location purposes only and does not constitute endorsement of products by the U.S. Government.

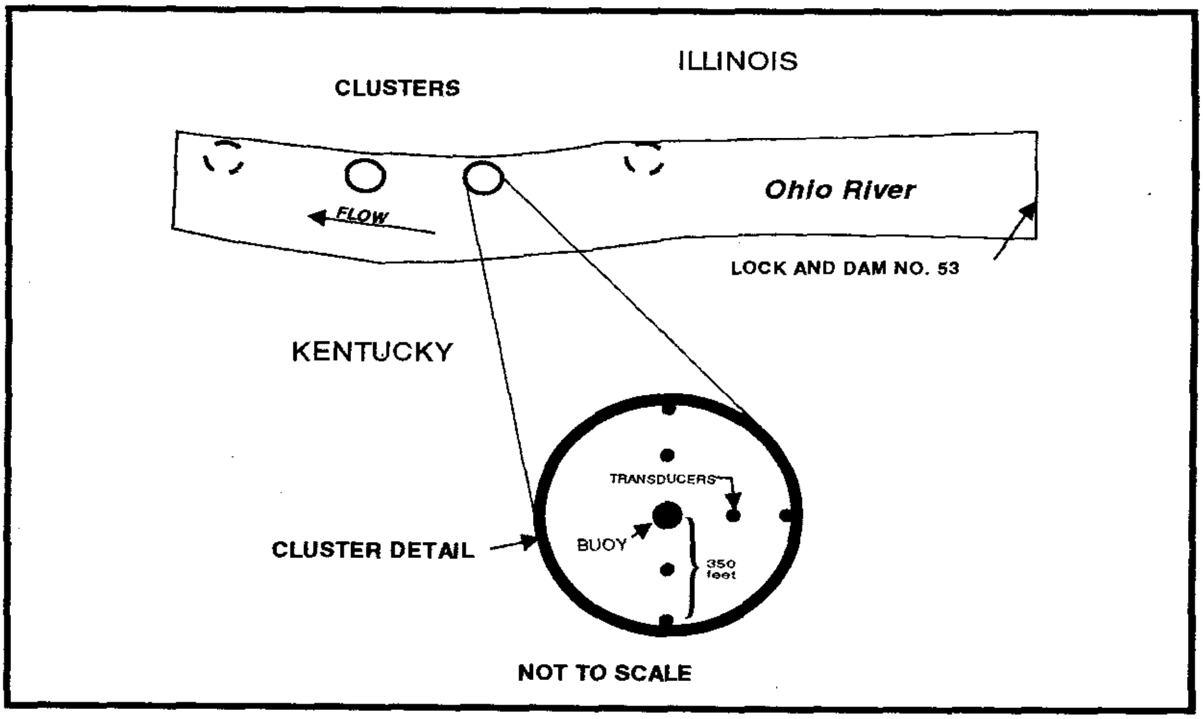

Figure 2. Physical configuration--Plan view.

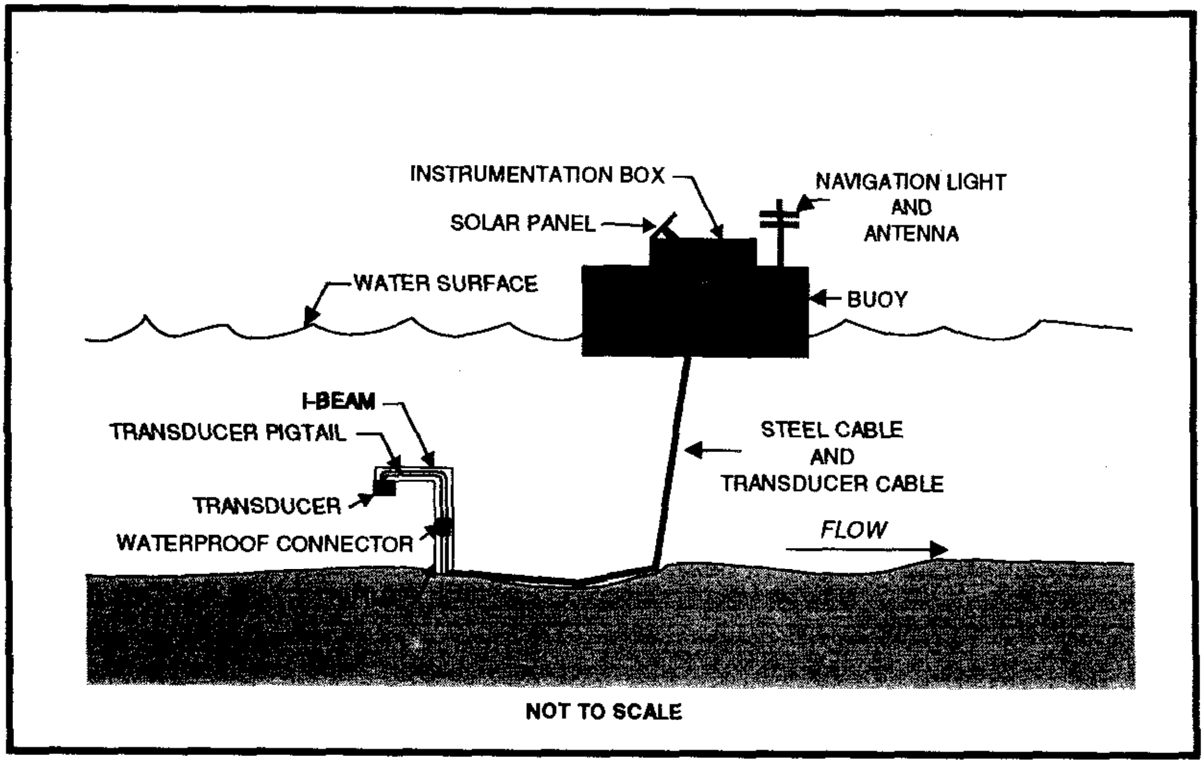

Figure 3. Physical configuration--Profile view.

debris is minimized by the acoustic ranging system which was configured to (1) measure the river bed elevation every 2 minutes; (2) rank the data from minimum to maximum for each hour; and (3) determine the hourly minimum, maximum, and median elevations. The hourly data is monitored for changes in the river bed elevations. The acoustic ranging system was designed to provide internal data storage for 3 to 6 months. A single RS-232 interface was available to download data and to change setup parameters for the instrumentation.

The Model PSA-902[1] Multi-Channel High Resolution Acoustic Ranging System by Datasonics[1], Inc., was selected for this application. The PSA-902 provides internal data storage using a 128K byte memory card and includes an internal-battery backup in the event of external power failure. The transducers operate at a frequency of 200 kilohertz (kHz), and the system has a stated resolution of 0.394 in. (1 centimeter) and a range of 0.98 to 98.4 ft (0.3 to 30 meters). The PSA-902 operates on 24 plus or minus 2 volts direct-current (VDC) at 100 milliamps and provides 12 hours of battery-backup power. The PSA-902 can handle up to 16 different transducers; communication with the PSA-902 is through a personal computer (PC) compatible RS-232 port. Custom firmware was provided by the manufacturer to facilitate the measurement scheme required for this application. Transducer cable was reinforced with Kevlar and can carry the acoustic signal up to 2,000 ft.

Remote Communications: The remote communications had to interface with the PSA-902 Acoustic Ranging System, provide redundant data storage, and provide routine hourly data and battery voltages to various offices through the GOES system.

The Sutron 9000[1] is an expandable multitasking Remote Terminal Unit (RTU) system designed for remote data acquisition and control and was the original system selected for this application. Plug-in modules provided data collection, process control, and data communication between remote RTU's and a central site. The hardware modules have a low power consumption and were designed to operate at temperature extremes typical of the site location. The real-time multitasking operating system is programmable with a Pascal-like programming language, Sutron Data Language (SDL). The original setup used remote units located on each buoy to communicate with the acoustic ranging system through the RS-232 interface, measure battery voltage of the power system, and communicate with a base station using half-duplex (two-way) UHF radios. The base station was similar to the remote units but also included two telephone modem modules that provided dial-in and dial-out capabilities and a UHF satellite radio module that provided concurrent synthesized communication capabilities with the GOES system.

The Handar 555A[1] is a Data Collection Platform (DCP) designed for remote data acquisition that collects and processes environmental data and then can transmit that data to remote locations for analysis in near real-time through the GOES system. The Handar 555A was selected to replace the Sutron 9000 after it was determined that UHF radios were not capable of consistently transmitting the data to the base station. The Handar 555A contains a GOES radio that will transmit the hourly data every 2 hours via satellite. The Handar 555A is the terminal strip version with access to all inputs and outputs. It has a NEMA-4x rated fiberglass enclosure and requires a 12-volt power source. Communication between the Handar 555A and the PSA-902 is done through a PC compatible RS-232 port.

Power System: The power system used for the original sediment deposition monitoring system, consisting of the PSA-902 and the Sutron 9000, included a combination of batteries, solar panels, voltage regulators, and direct current (DC) to DC converters. Each buoy had three 12-volt, 60-amp hour sealed lead-acid batteries connected in parallel. The batteries were recharged by two 50-watt solar panels mounted flat to the instrument box lid. To ensure durability in the remote environment, solar panels constructed without glass were used. The solar panels were connected to a voltage regulator that used a blocking diode to prevent battery discharge through the solar panels. The DC to DC converter was used to convert the 12 volts from the voltage regulator to 24 volts required to power the PSA-902. This power system setup would provide approximately 14 days of power with the batteries operating at 75 percent capacity.

The power system currently used for the current sediment deposition monitoring system, consisting of the PSA-902 and the Handar 555A, includes the combination of batteries, solar panels, voltage regulators, and DC to DC converters. Each buoy has four 12-volt 100-amp hour sealed lead-acid batteries connected in parallel. The batteries are recharged by two 50-watt solar panels mounted at a 45-degree angle. Solar panels constructed without glass are used to ensure durability in the remote environment. The solar panels are connected to a voltage regulator that uses a blocking diode to prevent battery discharge through the solar panels. The DC to DC converter is used to convert the 12 volts from the voltage regulator to 24 volts required to power the PSA-902. This power system setup would provide approximately 21 days of power with the batteries operating at 75 percent capacity.

SYSTEM OPERATION

Acoustic Ranging System: The PSA-902 Acoustic Ranging System was installed in July 1993. The 24 transducers and approximately 6,000 ft of transducer cable were installed by a 4-person diving team in about 2 weeks. A Datasonics field engineer was at the project site to verify adequate installation, programing, and calibration of the PSA-902. Divers verified the PSA-902 readings by physically measuring the distance between the transducer and the river bed. Initial software and procedural problems were quickly corrected with little loss of data. Steel plates mounted on the river bed under one transducer in each cluster were used as quality checks on the acoustic ranging system.

The Datasonics field engineer and a four-person diving team were deployed to the site in November 1993 to check transducers yielding questionable data and to recalibrate each of the PSA-902's after the transducers had become acclimated to the water. No problems attributable to the transducers or system design were evident, but four transducers yielding erratic data were found to be located nearer to the river bed than allowed by the acoustic ranging system operating specifications (<1.0 ft). The problem may have been from the H-piles being driven too far into the river bed or a change in the river bed geometry. The data collected and physical measurements made by the divers indicated that the PSA-902's had met the specified resolution of 0.394 in.

Remote Communications: The Sutron 9000 RTU's were installed at each of the four buoy sites and at the base station located at Lock and Dam 53 in September 1993. As mentioned previously, two buoys were destroyed and all equipment lost during the high-flow period of 1994 (December 1993–April 1994). During the same period, the electronic equipment housed on the other two buoys sustained water damage. The PSA-902's were repaired and returned to the two remaining buoys. The Sutron 9000's were not repaired as it was determined that a change would be made from the UHF radio link to the GOES system. The PSA-902's internal data storage provided by the memory card was extremely valuable and was used during the summer of 1994. Data were downloaded weekly and sent to the COE and USFWS. When the new buoys were deployed, each PSA-902 was interfaced with a Handar 555A, and data were monitored daily through the GOES system. The Handar 555A DCP's were installed in April 1995. Both the Handar 555A and the PSA-902 required custom firmware and software upgrades to facilitate the measurement scheme required by this application. Data have been transmitted using the GOES system on a 2-hour time lag. Because of the movement and rotation of the buoys, an omni-directional antenna was required to prevent the loss of communications. The steel plates used for quality control and data verification were removed from each cluster so that each buoy had six monitoring sites. The new buoys survived the high-flow period in 1995; however, four monitoring sites at one buoy cluster were lost when debris damaged the transducer cables. The cables will be replaced during summer 1995.

Power System: The power system used with the PSA-902 and the Sutron 9000 failed during the 1993–94 winter months because the solar panels were mounted flat and battery storage was insufficient. When the Handar 555A's were installed, the solar panels were moved to a 45-degree angle and larger batteries were also installed. The power system encountered no problems during the 1994–95 winter months. Nearly all data have been received at the COE and USGS offices since these changes were implemented.

SUMMARY

The construction and operation of the Olmsted Locks and Dam may have an affect on two mussel beds located near the project site. These mussel beds contain the endangered mussel species (Plethobasus cooperianus) or orange-footed pearly mussel. Guidelines set by the USFWS, to ensure protection of the mussel beds, state that sediment accumulations cannot exceed 0.787 in. (2 centimeters) above baseline levels. The USGS, in cooperation with the COE, has designed and installed a system to continuously monitor changes in elevation of the river bed over the mussel bed located downstream of the Olmsted Locks and Dam project. The system utilizes a multi-transducer acoustic ranging system to provide river bed elevation measurements accurate to plus or minus 0.394 in. (1 centimeter). Therefore, the acoustic ranging system is providing adequate data for monitoring a 0.787 in. change in river bed elevation. Data from the acoustic ranging system are transmitted every 2 hours using the GOES system. The original system was put into operation in July 1993 using UHF and GOES radios. The UHF radios were dropped from the system in April 1995. The system is currently collecting data to assess the baseline sediment deposition and erosion characteristics of the mussel bed and will continue to be operated during construction and normal lock and dam operations until it is determined that routine operation of the facility is not adversely affecting the mussel bed by sediment deposition or erosion.

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Michael S. Griffin, Hydrologist, U.S. Geological Survey, Water Resources Division, Kentucky District, 2301 Bradley Avenue, Louisville, KY 40217, Phone: (502) 635-8033, FAX: (502) 635-8009.

THE DELINEATION OF FLUID MUD LAYER THICKNESS AND ITS PRACTICAL USE IN DREDGING SURVEYS

By Shawn Hanrahan, Physical Scientist, U.S. Army Corps of Engineers, Philadelphia, Pennsylvania; Anthony DePasquale P.E., Geotechnical Engineer, U.S. Army Corps of Engineers, Philadelphia, Pennsylvania

ABSTRACT

To conduct pre- and post- dredging surveys the utilization of a new multi-frequency surveying technique could result in substantial savings through more efficient dredging practices. An analysis is done on Wilmington Harbor navigation project to determine the magnitude of the potential savings that could be realized by implementing the new surveying technique.

INTRODUCTION

The efficient management of navigational dredging projects is often complicated by the presence of fluid mud which can cause inaccurate readings of the "hard" bottom depth while performing pre- and post- dredging surveys. The difficulty in obtaining accurate survey data can in turn lead to uncertainty in dredge scheduling and in estimating the volume of material to be removed. It has been proposed that the presence of fluid mud can cause the estimated dredging quantities to be overestimated and that in many cases removal of the fluid mud layer is not necessary to improve navigation within the project area (Hanrahan and DePasquale, 1994). Consequently, substantial cost savings could be incurred by delineating the thickness of the existing fluid mud layer in the area to be dredged and establishing a "hard" bottom line for pre- and post- dredging surveys.

The current process utilized by the U.S. Army Corps of Engineers, Philadelphia District for acquiring pre- and post- dredging surveys of project areas only specifies that a 200 kHz fathometer be used to detect the "hard" bottom. This requirement is usually adequate where fluid mud conditions do not normally exist. However, in areas where fluid mud conditions predominate, the use of a 200 kHz fathometer alone may not result in the most economical or efficient dredging of the area. The problem that arises from using only the 200 kHz frequency is that it does not penetrate the fluid mud layer, but instead reflects off of the surface of the fluid mud layer. This results in a false bottom reading that is shallower than the true "hard" bottom. This problem is exacerbated by the disturbance of bottom sediments during dredging operations which places significant amounts of sediment in suspension causing the fluid mud layer to thicken. Subsequently, when post-dredging surveys are performed the thickened fluid mud layer again gives the illusion of a false "hard" bottom. Cases such as this force the overdreging of competent materials in order for the fluid mud line to reach the authorized depth, even though the "hard" bottom may already be well below the authorized depth. Subtraction of the thickness of the fluid mud layer will allow a more accurate determination of the position of the "hard" bottom and cut down on the wasteful dredging due to the presence of the fluid mud layer.

The problem of delineating the "hard" bottom can be overcome to a large extent by the utilization of a multi-frequency acoustic technique which delineates the thickness of the fluid mud layer. In Hanrahan and DePasquale (1994), the authors describe the development of a multi-frequency acoustic technique for use in delineating the thickness of fluid mud layers. The objective in developing the technique was to determine if a multi-frequency acoustic system utilizing both a high frequency, which would reflect off the surface of the fluid mud layer, and a lower frequency, which would penetrate the fluid mud layer and reflect off the surface of the "hard" bottom, could accurately measure these features. The frequencies used were 192 kHz and 50 kHz. If such a multi-frequency system could be developed to be reliable, accurate, easy to use, and be deployed with a minimum amount of time in the field it would be a powerful tool for use in dredging management.

The purpose of this paper is to discuss the potential savings that may be realized from using the proposed multi-frequency acoustic technique in an existing project area within the Philadelphia District where fluid mud is known to exist. The area chosen for this discussion is Wilmington Harbor, Wilmington, Delaware.

WILMINGTON HARBOR

The Philadelphia District is responsible for the operation and maintenance of the Wilmington Harbor navigation channel. The Wilmington Harbor navigation project is located in Wilmington, Delaware, and is situated on the Christina River. The Christina River is a tributary to the Delaware River and is located approximately 70 miles upstream from the Atlantic Ocean. Wilmington Harbor is the first inbound deep draft general cargo port on the Delaware River and is critical to the commerce and economy of the Mid-Atlantic region.

Currently within the project area (figure 1), the pre-dredging surveys, which employ only a single 200 kHz fathometer, commonly detect channel depths ranging from 27 to 30 feet with no significant hinderance to ships navigating and docking in the Wilmington Harbor Marine Terminal, even though these ships frequently draft from 33 to 35 feet. This in effect verifies the presence of a fluid mud layer which was known to exist from earlier work in the project area. In addition, the overdepth dredging method is not utilized for the Wilmington Harbor navigation project which would ensure a channel depth greater than the 35 to 38 foot authorized channel depth. While the presence of a fluid mud layer is not the preferred condition for the pilots or owners of the ships utilizing Wilmington Harbor, the day to day operation of the port continues nonetheless.

The Wilmington Harbor navigation project requires the removal of approximately 800,000 cubic yards of sediment every nine months in order to maintain the navigation channel at the authorized depth of 35 to 38 feet. The contract cost for this dredging program has recently ranged from $1.5 to $4.0 million per nine month cycle. From previous work in the project area, it is conservative to assume that a fluid mud layer 2 feet thick exists over the project area (Approx. 3.4 million sq ft) at any given time. If fluid mud is excluded from the dredge quantities the reduction in maintenance dredging will exceed 250,000 cubic yards per nine month cycle. This amounts to an annual potential savings of $400,000 to $1 million. Over the 50 year project life, estimates of the potential savings range from $20 to $50 million. In addition, due to the decrease in the amount of material being dredged during each nine month cycle, the life of the project disposal areas would be extended by approximately 10 years. With the cost of constructing a new 200 to 300 acre disposal area estimated

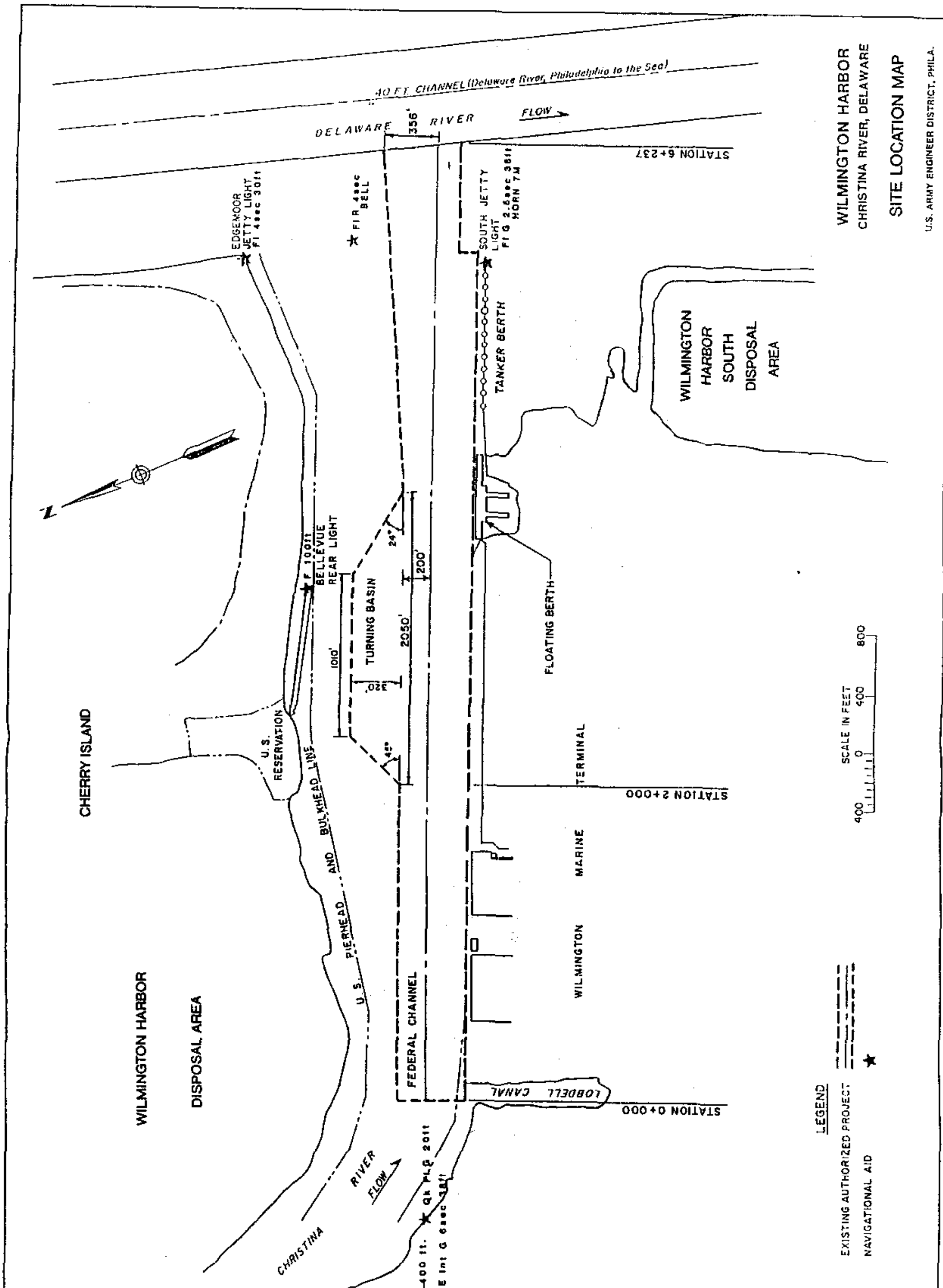
WILMINGTON HARBOR
CHRISTINA RIVER, DELAWARE
SITE LOCATION MAP
U.S. ARMY ENGINEER DISTRICT, PHILA.
40 FT. CHANNEL (Delaware River, Philadelphia to the Sea)
DELAWARE RIVER
FLOW
356'
STATION 6+237
EDGEMOOR JETTY LIGHT
SOUTH JETTY LIGHT
TANKER BERTH
WILMINGTON HARBOR SOUTH DISPOSAL AREA
FLOATING BERTH
BELLEVUE REAR LIGHT
TURNING BASIN
1010'
2050'
200'
320'
24°
42°
CHERRY ISLAND
U.S. RESERVATION
U.S. PIERHEAD AND BULKHEAD LINE
WILMINGTON HARBOR
DISPOSAL AREA
FEDERAL CHANNEL
WILMINGTON MARINE TERMINAL
STATION 2+000
STATION 0+000
LOBDELL CANAL
CHRISTINA RIVER
FLOW
400 ft.
SCALE IN FEET
400 0 400 800
LEGEND
EXISTING AUTHORIZED PROJECT
NAVIGATIONAL AID

Figure 1

to be between $20 and $35 million, the extension of the life of the disposal area would be invaluable to the project.

It can be seen that the potential benefits of a more accurate determination of the thickness of the fluid mud layer, and hence the depth of the "hard" bottom, can result in improved efficiency of maintenance operations through better determination of what areas actually require dredging, what has been dredged, dredging priorities, and dredge scheduling (Teeter, 1994).

CONCLUSION

It is proposed that a multi-frequency acoustic technique be utilized during pre- and post- dredging surveys to determine the thickness of the fluid mud layer in the Wilmington Harbor project area. Utilization of the proposed multi-frequency surveying technique will allow the Corps to determine the thickness of the fluid mud layer and the depth of the "hard" bottom. In addition, employment of the proposed surveying technique will provide the ability to more accurately determine how much material is required to be removed from the navigation channel.

For the Wilmington Harbor navigation project there is assuredly some intermediate dredging depth and schedule that can be determined that takes into account the interests of the Corps, pilots and ship owners. Given the amount of fluid mud that is present in Wilmington Harbor, there is a need to further investigate the quality and quantity of the bottom material at this location. It is the opinion of the authors that by utilizing the multi-frequency surveying technique described in Hanrahan and DePasquale (1994) and collecting in situ density measurements during the pre- and post- dredging surveys, a more efficient and reliable dredging quantity and interval can be developed for the Wilmington Harbor navigation project. The authors feel that the proposed surveying process could be used by the Philadelphia District at the present time, if necessary on an experimental or trial basis, and that the use of such a system is economically and engineeringly feasible.

It is anticipated that in the near future a program will be initiated to utilize the proposed multi-frequency surveying technique in the Philadelphia District, possibly on an experimental basis. The authors hope that this will result in a new, more efficient approach to dredging and dredged material management.

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DESIGN ANALYSIS OF SEDIMENT-EXCLUDING OFF-STREAM RESERVOIR, RIO FAJARDO, PUERTO RICO

Gregory L. Morris, P.E., Ph.D., Principal, Morris & Assoc.
P.O. Box 5635, San Juan, Puerto Rico 00902, USA

__Abstract__. Conventional reservoir design is based on constructing a large impoundment with a sediment storage pool capable of storing at least 100-years of sediment. However, application of this design in Puerto Rico, with high sediment yields, results in large impoundments and non-sustainable water supplies. These problems can be overcome to a large extent using an off-stream reservoir designed to minimize sedimentation.

This paper reports on a daily simulation analysis of water and sediment to compare the yield and sedimentation characteristics of a conventional on-stream and an off-stream reservoir on Río Fajardo, Puerto Rico. It is shown that an off-stream impoundment can reduce sediment load on the impoundment by 89% while developing a firm yield equal to 50% of the mean annual streamflow, and is a very attractive alternative to a conventional reservoir.

INTRODUCTION

Although most of Puerto Rico has a humid climate, receiving over 2000 mm (80 inches) of annual precipitation, the island's 88675 km^2 (3350 mi^2) area is drained by more than 30 rivers and no river has a large base flow. Population density is high, exceeding 390 persons/km^2 (1000 persons/mi^2), and many communities rely on run-of-the-river stream diversions from the smal streams, which have inadequate yield to meet urban demands during dry periods. Water supplies could be increased by constructing storage reservoirs.

Conventional reservoir design is based on constructing a large impoundment with a sediment storage pool capable of storing at least 100-years of sediment. However, application of this design in Puerto Rico, with high sediment yields, results in large impoundments and non-sustainable water supplies. The resulting sediment storage pool is quite large and costly since it has to be sized to store both water and sediment. Furthermore, development of a reservoir that is designed to continuously trap sediments until abandonment also does not represent a sustainable water resource development strategy. Dredging is a very costly alternative, and large-volume disposal sites are in extremely limited supply.

alternative, and the author knows of no performance comparisons of on-stream vs. off-stream impoundments. Such a comparison is presented herein.

STUDY AREA DESCRIPTION

Río Fajardo drains eastward from the Luquillo Mountains, at the eastern end of the Island of Puerto Rico (Figure 1). The watershed is moist, receiving an average annual rainfall of 2500 mm/yr (95 in./yr). Rainfall is rather well-distributed throughout the year; January through March is relatively dry but no month is without rainfall. A existing filtration plant with an extraction rate of about 0.25-0.30 m^3/s (9-10 cfs) has an intake a few hundred meters upstream of USGS gage station 50071000, used in this analysis.

Reservoir surveys at 14 sites islandwide, with between 12 and 72 years between construction and the most recent survey, produce sediment yields ranging from 680 to 2400 $t/km^2/year$ (Morris, 1995). At Río Fajardo the USGS measured suspended sediment during water years 1983 through 1986 and computed total sediment load. The total discharge during this period was 125,740 tons from the 38.6 km^2 drainage area tributary to this gage station, for a specific yield of 814 $t/km^2/yr$. The discharge of sediment over time is high irregular: over the four years of sediment record only 1% of the days accounted for 57% of the total sediment discharge and 15% of the water discharge (Table 1). This high concentration of sediment yield in a few days per year is typical of streams in Puerto Rico.

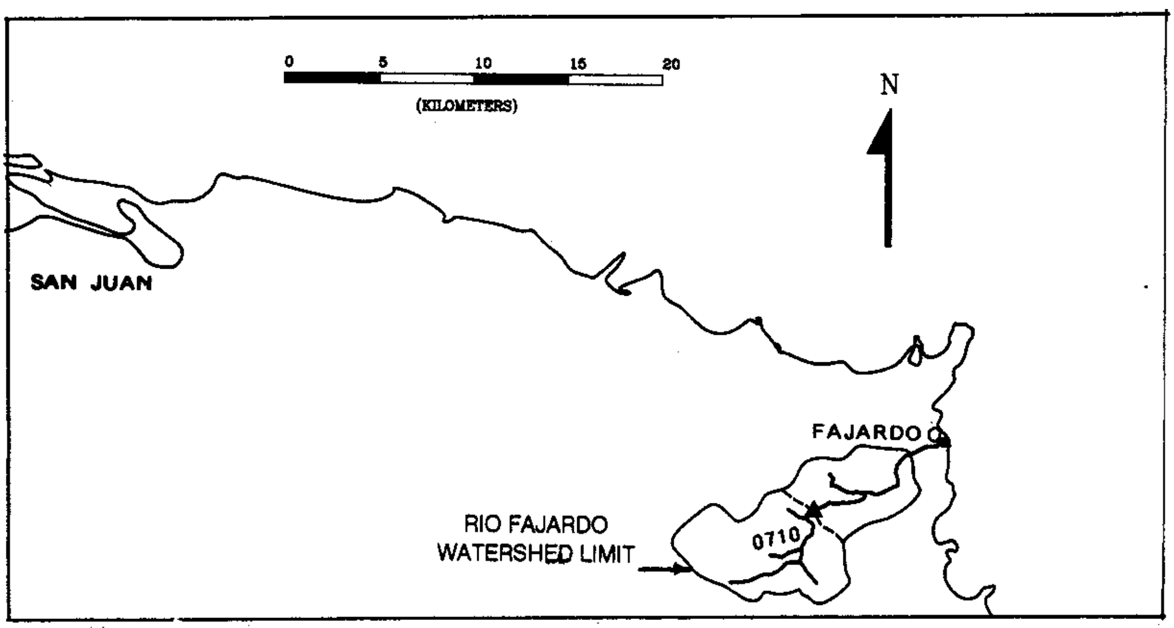

Figure 1: Location map for Río Fajardo, Puerto Rico.

TABLE 1: Water and Sediment Discharge at Río Fajardo, USGS Gage 50071000, Water Years 1983-1986.

Sorted on Water			Sorted on Sediment		
% of Days	% of Sediment	% of Water	% of Days	% of Sediment	% of Water
1	57	15	1	57	14
2	69	24	2	77	22
3	78	30	3	80	28

Computed from USGS data as published in CD-ROM format by EarthInfo, Boulder, Colorado.

The high concentration of the total sediment load in only a few days reflects the large influence of short-duration flood events. With the major part of the sediment load concentrated in so little time, and in a relatively small percentage of the total annual runoff, reservoir design can focus on the routing of sediment-laden water through or around the impoundment. One such strategy is to construct an off-stream reservoir, conveying water supply to the reservoir by a pipeline with an inlet in the river, and allowing sediment-laden flood flows to continue downstream. Another strategy is to lower the reservoir pool during the short-duration flood events, and to refill the reservoir using water from the recession portion of the hydrograph. The off-stream reservoir alternative was analyzed in detail and compared to the performance of a conventional on-stream impoundment on Río Fajardo.

METHODOLOGY

Liquid and Sediment Discharge. The analysis was performed using 21 years of daily streamflow data starting in October 1984, as published by the USGS and available in CD-ROM format from EarthInfo, Boulder, Colorado. The four years of sediment discharge data described previously was divided by mean daily flow to obtain a value of average daily sediment concentration. The concentration values were plotted against discharge and a relationship was fitted to the data (Figure 2) having the following form:

$$CONC(mg/l) = 31 * Q(m^3/s) \wedge 1.5$$

For mean daily discharges in excess of 25.5 m^3/s (900 cfs) a maximum concentration of 4,000 mg/l was assigned. The resulting relationship was checked against the sediment discharge computed by the USGS during the four years of measurement, resulting in an error of less than 3%. Application of this rating relationship to the 21-year streamflow series used in the simulation resulted in a total sediment discharge of 1,174,000 metric tons, equivalent to an average annual sediment load of 55,900 t/yr or 1,450 t/km^2/yr. These values are very reasonable compared to date from other island streams.

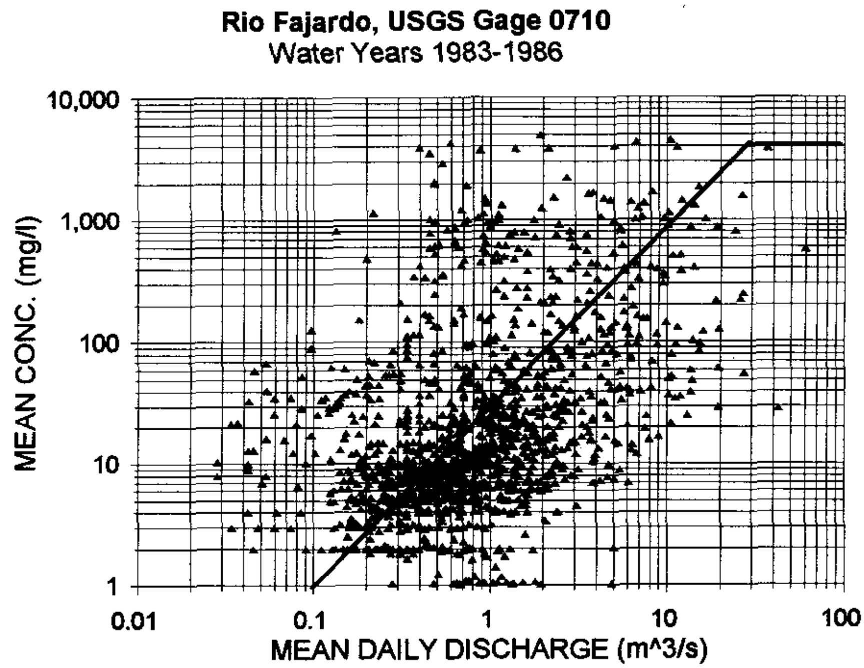

Figure 2: Relationship between mean daily discharge and mean daily sediment concentration used in the simulation analysis.

Because the gage station is located just downstream of a water supply intake the gaged flow is not entirely natural. The filter plant withdrawal is essentially constant year-around, and is probably of a similar order-of-magnitude to a required low-flow release. Thus, while the gaged flow does not represent the total flow of the river, it probably reflects in a reasonable manner the actual amount of water that may be available for development at this site.

For the purpose of comparison of reservoir yields with an unregulated stream diversion at this same site, I have defined the "firm yield" for a run-of-the-river intake as the flow equalled or exceeded on 99% of the days of record. At this gage station this was equivalent to 0.110 m^3/s (3.9 cfs), or 5.7% of the mean flow of 1.93 m^3/s (68.2 cfs). In the case of the reservoir the "firm yield" was taken as the maximum continuously sustainable flow during the simulation period.

__Conventional Reservoir__. A conventional reservoir consists of a dam constructed across the river with an overflow spillway capable of passing the design flood. It would be designed with a 100-year sediment storage pool. Extrapolating from the 21-year series, the 100-year sediment discharge will be $5.59x10^6$ tons. Assuming that the reservoir will have a capacity:inflow ratio in excess of 0.17, as a first approximation we may assign a trap efficiency of about 90% based on Brune's relationship (Brune, 1953). About $5.03x10^6$ m^3 of sediment will be trapped during 100-years, and using an average deposit density of 0.9 t/m^3 (based on borings data in the Loíza reservoir which is in a climatically and geologically similar zone), the trapped sediments will occupy about $5.6x10^6$ m^3 (4,531 acre feet) of storage volume.

A storage-yield relationship for the conventional reservoir was developed by routing the daily discharge through impoundments of various sizes, to determine the maximum rate of constant-rate withdrawal that can be sustained without depleting the conservation pool during the historical period. The resulting storage-yield curve is presented in Figure 3.

Off-Stream Reservoir. In an off-stream reservoir flow is diverted from the stream into an impoundment which is located on a small tributary or within a diked basin. For the purpose of this analysis it is assumed that the only sediment inflow into the off-stream reservoir is derived from the diverted water.

Hydraulic and sediment routing into the reservoir were performed using the same 21 years of daily streamflow used to analyze the conventional reservoir. The flow rate into the off-stream impoundment is limited by the hydraulic capacity of the stream intake. If streamflow is lower than the intake capacity then reservoir inflow is equal to the streamflow, but if streamflow exceeds the pipe capacity then inflow is limited by the intake capacity. The volume of water diverted into the reservoir is also limited by the storage deficit, and in wet periods when the reservoir is full the inflow will not exceed the rate of withdrawal. The sediment rating curve in Figure 2 was used to determine the concentration of sediment in the stream each day, and this concentration was applied to the water volume diverted into the reservoir to determine the total sediment load on the reservoir. As in the case of a conventional reservoir, yield varies as a function of reservoir volume. However, in the case of the off-stream reservoir yield is also influenced by the intake capacity. A larger intake allows the reservoir to refill more rapidly, but also admits more sediment because a greater percentage of the total inflow consists of sediment-laden flood flow. In the case of the off-stream reservoir, both reservoir volume and intake capacity influence the sediment loading.

RESULTS AND DISCUSSION

The simulations produced values of reservoir yield and sediment loading, which were expressed in dimensionless units based on the Average Daily Flow (ADF) over the 21-year simulation period. Conservation pool storage volumes from 5 to 60 days ADF were simulated, yield was expressed as a fraction of ADF, and sediment load on the reservoir was expressed as percentage of the total sediment discharge. In the conventional reservoir trap efficiency is expected to run about 90% for 60-days of total storage volume, consisting of the conservation pool plus the sediment storage pool. The 100-year sediment storage pool of 5.6×10^6 m^3 is equivalent to 33-days of storage at Average Daily Flow. Trap efficiency in the off-stream reservoir will be essentially 100%, acting as an efficient pre-sedimentation basin for a downstream filter plant. Smulation results are summarized in Table 1. The yield curves for the conventional reservoir (case "A"), and the off-stream reservoirs (case "B", "C" and "D") are compared in Figure 3. Yield curves "A" and "B" are virtually indistinguishable.

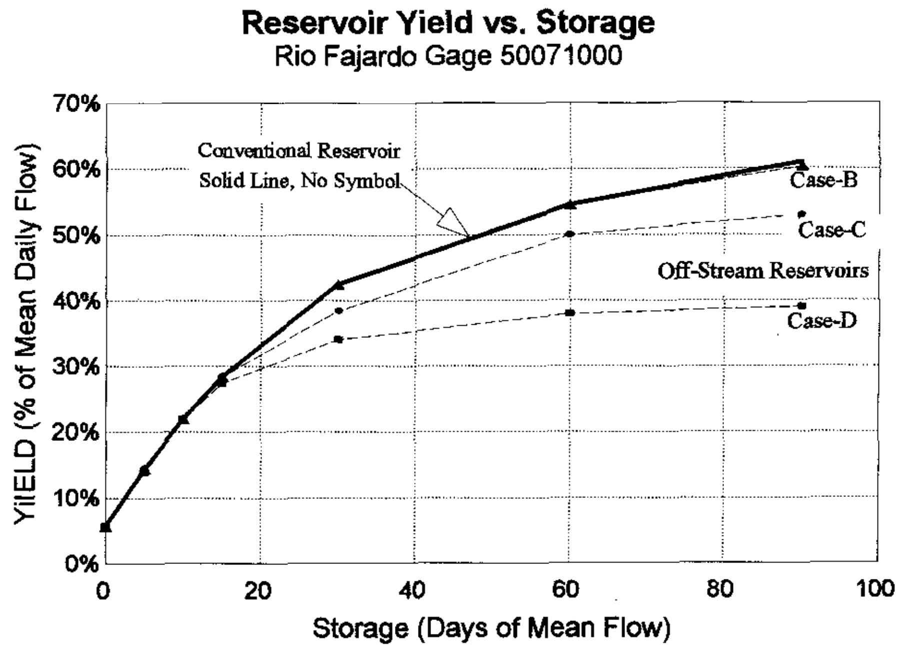

Figure 3: Curves of reservoir yield vs. storage volume for a conventional on-stream reservoir and three off-stream reservoir configurations.

Table 1: Results of Water and Sediment Routing Simulations for A Conventional (On-Stream) and an Off-Stream Reservoir, Río Fajardo, Puerto Rico.

Storage Volume (Days @ ADF)	Reservoir Configuration **A** Yield (ADF)	**B** Yield (ADF)	**B** Load (%)	**C** Yield (ADF)	**C** Load (%)	**D** Yield (ADF)	**D** Load (%)
5	.145	.145	2.1	.145	2.1	.140	2.1
10	.220	.220	3.5	.220	3.5	.220	3.5
15	.285	.285	5.2	.285	4.9	.275	4.6
30	.425	.425	10.1	.385	7.7	.340	5.9
60	.545	.545	16.3	.500	11.1	.380	6.7
90	.610	.605	20.5	.530	12.0	.390	6.8

Notes: Storage volume expressed in days of discharge at Average Daily Flow. ADF=1.93 m^3/s=68.2 cfs.
A = Conventional reservoir, sediment inflow is 100% of river load, 90% trap efficiency.
B = Off-stream reservoir, inlet capacity = 3.0 * ADF.
C = Off-stream reservoir, inlet capacity = 1.0 * ADF.
D = Off-stream reservoir, inlet capacity = 0.5 * ADF.

Discussion. Surprisingly, for reservoirs with storage volumes up to 90 days of mean flow (25% of mean annual runoff), there was essentially no difference in yield between a conventional on-stream reservoir and an off-stream reservoir with an inlet capable of delivering 3 times average daily flow. Although use of a smaller inlet capacity, Q=1*ADF, had a small effect on yield, it reduced sediment inflow by almost half compared to the larger inlet. The smallest inlet, 0.5*ADF, had a significant impact on yield for larger storage volumes but not for smaller.

Droughts in Puerto Rico consist of prolonged periods of below average streamflow, well below the Average Daily Flow. When the drought ends the streamflow returns to a normal levels, which is still usually less than the mean discharge. The long-term average daily flow is exceeded only 22% of the time in Río Fajardo. This explains why, on this stream, the gain in yield achieved by increasing inlet capacity is not large. However, larger inlet capacity significantly increases sediment loading because the reservoir is refilled using a higher percentage of sediment-laden flood flow as compared to the smaller inlet configuration.

The yield analysis reported in this paper illustrates that a dramatic reduction in sediment loading can be achieved using an off-stream reservoir, without a significant penalty in terms of firm yield. This yield analysis is preliminary in nature, and more detailed studies will be required as the basis for design of a project.

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The author may be contacted at tel. (809) 723-8005, fax (809) 721-3196.

BATHYMETRY OF THE MISSISSIPPI RIVER IN 3D FOR RIVER ENGINEERING ANALYSIS

By Robert Davinroy, District Potamologist, Potamology Section, US Army Corps of Engineers, St. Louis, Missouri; and John Naeger, Engineering Technician, Potamology Section, US Army Corps of Engineers, St. Louis, Missouri

Abstract. River engineers of the past have faced great limitations in their ability to study and analyze the dynamic changes of the river bed of the Mississippi River. Recently, this shortcoming has been drastically improved by the application of bathymetric, 3D digital terrain models developed in the computer aided drafting environment. These models, when combined with more intensified, prototype data collected from channel sweep and multi beam swath technology, enable engineers to visually and quantitatively analyze changes in the sediment response of the river. The changes may be the result of natural, morphologic effects, or the result of man induced effects including dredging, dikes, bendway weirs, etc. Selected output of these 3D models and a synopsis of the engineering information gained from them are addressed in this presentation.

INTRODUCTION

Standard Hydrographic Surveys. Historically, the sediment transport characteristics of the Mississippi River have been analyzed by the use of standard hydrographic surveys. Standard hydographic surveys are defined as sounding ranges spaced every 1000 feet along the thalweg of the river. Each sounding point is collected at approximately 50 foot lateral intervals (Figure 1). The soundings are referenced to NGVD and plotted on Missouri east zone standard Latitude/Longitude aerial maps. Contours are generated by visual interpolation. These surveys have traditionally been conducted by the St. Louis District on an annual basis, surveying 33 percent of 300 miles of the Mississippi River (Saverton, Missouri to Cairo, Illinois) each year. The finished product, as illustrated in Figure 1, gives river engineers the overall bed configuration of the river.

The surveys have served as an invaluable method of studying overall trends of the resultant bed configuration at low water. However, detailed scour and depositional patterns at both natural and man induced areas cannot be interpreted from this data. For example, an important scour and depositional pattern that may occur at the apex of a bend or off the end of a dike may easily lie between the 1000 foot ranges of the standard survey and go completely undetected.

In 1989, the new Bendway Weir concept was implemented by the St. Louis District in the Mississippi River (Davinroy, 1990, 1994). Because the concept was radically different as compared to traditional dike structures, river engineers needed the ability to examine the river bed in greater detail. Bendway Weirs, unlike dikes, would always be submerged. Initially, side scan sonar technology was used (Davinroy 1990) as a way to analyze sedimentation effects. Yet this technology had its limitations. It gave an excellent graytone picture of the river bottom and both scour and depositional patterns could be observed. However, the data was purely qualitative because it could not be fixed or correlated to a vertical or horizontal datum.

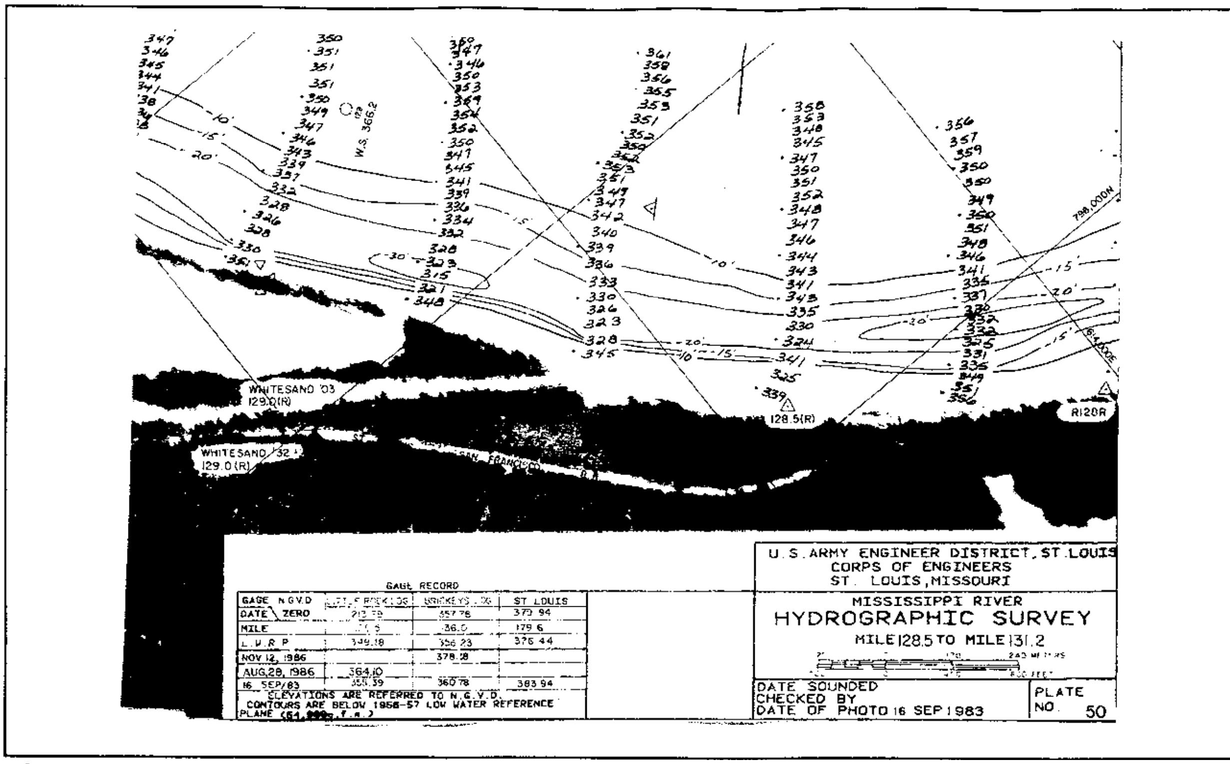

Figure 1. Standard Hydrographic Survey of the Mississippi River

Application of the multi swath sounding technology in 1989 was a river engineer's dream. Initially, the St. Paul District's Launch 19 channel sweep system was used for Bendway Weir monitoring. For the first time, thousands of data points or soundings could be collected in near real time (Leckner 1990). The processing and management of this data would be a major challenge. This challenge was met by application of the computer aided drafting environment.

HISTORICAL DEVELOPMENT OF CADD IN THE ST. LOUIS DISTRICT

Structural Design Application. The construction of the Melvin Price Locks and Dam on the Mississippi River, one of the largest and most complex civil works projects ever attempted on the Inland Waterways System of the United States, forced engineers and technicians of the St. Louis District to become pioneers in the use of Computer Aided Design and Drafting (CADD) systems. The first CADD system was delivered to the district office in April of 1981. During those early years, CADD was used as a two-dimensional drafting tool for structural design. As sophistication developed, CADD became the primary source for producing final design drawings. Although the hardware improved significantly over the years, the improvement in software was not nearly as dramatic. There were great limitations on the ability to post process raw data.

In 1990, a transition in personnel between the newly formed Geodesy, Cartography and Photogrammetry Section and the Structural Design Section set a precedence for new river engineering design potential within the St. Louis District. The Geodesy Section had always worked in close liaison with the river engineers of the Potamolgy Section, serving as the source for all surveys performed on the river. Now, with the Geodesy Section acquiring key CADD experts from the Structural Design Section, the potential for innovative post processing of the enormous amount of channel sweep sounding data coming in from the field was tremendous. This unique marriage of technical expertise and new surveying techniques proved to be a stepping stone for the advancement of river engineering for years to come.

The forming of this technical marriage couldn't have been more timely. Great advances in three dimensional software application packages enhanced the CADD expert's ability to create digital terrain models. This meant that theoretically, the channel sweep data from the field could be post processed and enhanced both qualitatively and quantitatively in a manner like never before. New graphical terms such as "imaging" and "rendering" have become intricate parts to usable engineering output. The burden now falls on the river engineer's imagination toward establishing the proper ergonomics of the final product.

The Final Product. Figures 2 and 3 are two examples of digital terrain modeling used in analyzing the bed configuration of the Mississippi River. Each output involves a different application. Figure 2 contains a model of a Bendway Weir field through Prices Bend, Mile 30.5 to Mile 29.0. This model, besides showing the effects of the structures on the river bed and navigation channel, brought to the attention of engineers that structural degradation of one of the weirs had occurred after the great flood of 1993. The graphics (the gray scale generated for this paper does not fully enhance the effects of color on the computer) clearly depicted that a piece of Weir No. 30.5 had degraded approximately 30 percent from the original "as built" section. These models have proven to be a vital tool for the assessment of maintenance measures on other Bendway Weir fields within the District.

Figure 3 is a model depicting a dredge cut on the Mississippi River (Mile 7.0 to Mile 5.0). Again, by collecting multi swath data, details in the river bed can be defined. Digital terrain models are now used in this manner as a way to graphically view and calculate the sediment transport response of the river before, during, and after maintenance dredging.

Data Collection Methodology and Procedure. A brief outline is described on the methodology and procedure of developing the digital terrain models. Hydroacoustic data is first collected in the field by use of a multi swath system combined with a digital global positioning system (DGPS). The data are output as ASCII format files. These files are then further processed in the office using custom post-processing software. The software strips the headers from the data fields and then merges and thins the data. The end results are simple, ordered triplet X,Y,Z point files.

The data must be thinned due to the over abundance of collected survey points. The channel sweep system or other type multi swath systems are capable of collecting hundreds of thousands of data points over a very small reach of river. The files can become quite large. Through experimentation, Geodesy CADD personnel have found that the data from these files may be thinned by as much as 30 percent. File integrity is still retained for the production of extremely detailed terrain models. Is the old adage "one can never obtain enough data" incorrect? Or will the more powerful processors handle this problem in the future?

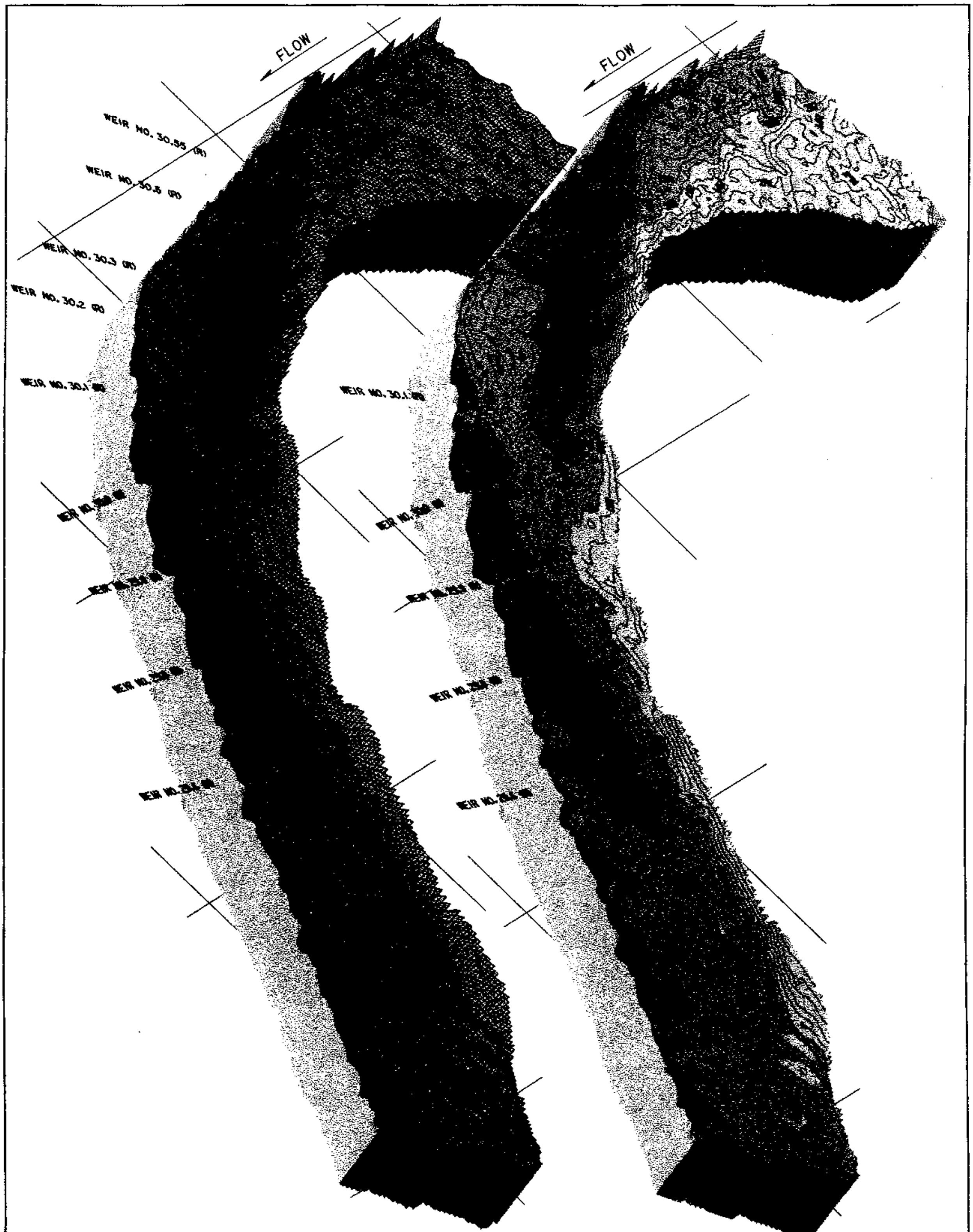

Figure 2. Digital Terrain Models of Mississippi River Bed at Prices Bend, Mile 30.5 to Mile 29.0, Illustrating Bendway Weir Effects

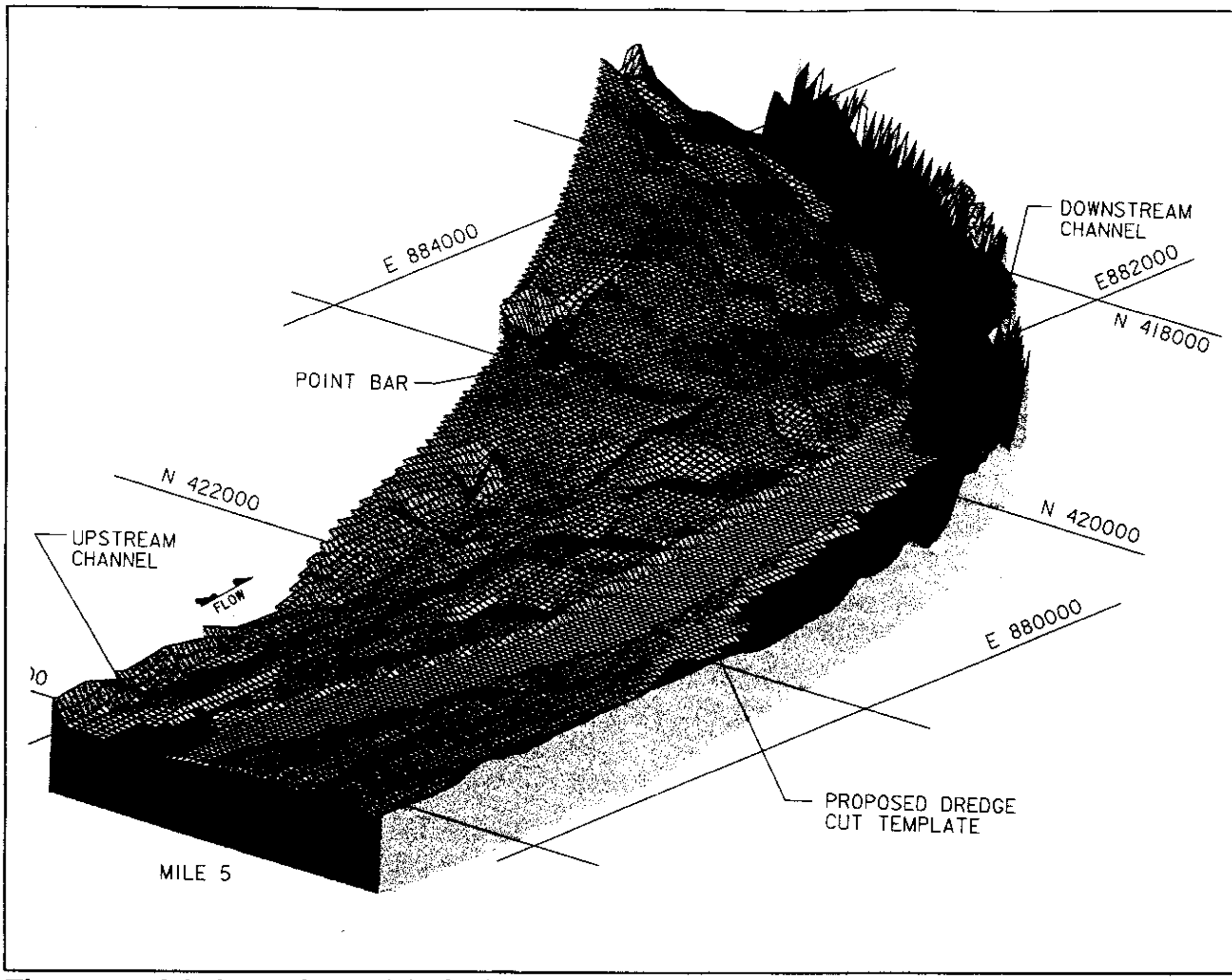

Figure 3. Digital Terrain Model of Mississippi River Bed, Mile 7.0 to Mile 5.0, Pre Dredge Survey With Dredge Cut Template

The post processed files are input into CADD. A 3D digital terrain model depicting the bathymetry or bed configuration of the river is created using either Intergraph's Inroads or Terrain Analyst software packages. Surfaces are prepared by producing triangulated topological network files (TTN). Grid models are then prepared from the TTN file. The grid model is a representation of elevation data comprised of user specified grid spacing. The grids are used for generation of contours, color shading, shadow and shaded relief enhancement, etc. The result is the production of color dramatic 3D images which may then be output on a color plotter (Berman and Clouse, 1995).

SUMMARY AND CONCLUSION

The use of the personal computer and the CADD application software environment has ushered a new era in river engineering. Clearly this is the wave of the future. River engineers now have the ability to examine details of scour and deposition in the river like never before. The possibilities of detailed analysis of the prototype are endless. The actual dynamics of sediment transport of the river can be captured graphically using the methods and examples described herein. If detailed, periodic field surveys are collected using multi swath technology, engineers can quantitatively and qualitatively analyze the complete sediment response of the river through the course of an entire hydrograph. The main challenge lies in the orderly management of this enormous amount of prototype information which will be accomplished during the geographic information era in the years to come.

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MEASURING STREAM-CHANNEL CROSS SECTIONS WITH GROUND-PENETRATING RADAR

By Kurt R. Spicer, Hydrologic Technician, U.S. Geological Survey, Vancouver, Washington; John E. Costa, Research Hydrologist, U.S. Geological Survey, Vancouver Washington; and Gary Placzek, Electrical Engineer, U.S. Geological Survey, Hartford Connecticut.

Abstract : Accurate and timely determination of riverbed elevations is important to sedimentation studies involving unstable river channels. Standard sounding techniques often fail or are inadequate when river channels are most active. Field experiments were conducted to test the ability of ground-penetrating radar (GPR) to measure stream-channel cross sections at high flows without the necessity of placing instruments in the water. Experiments were conducted at four sites: The Cowlitz River at Castle Rock, Wash. (from a bridge); the North Fork Toutle River near Kid Valley, Wash.; the Toutle River at Tower Road near Silver Lake, Wash.; and the Muddy River below Clear Creek near Cougar, Wash. (from cableways). With the GPR antenna suspended by cable above the water surface, traverses were made across stream channels to collect radar profile plots of the streambed. Additional tests were conducted to verify water surface position on the radar plot. Subsequent measurements of water depth were made using conventional sounding equipment, and were used to calculate radar signal velocities. Other streamflow-parameter data were collected to examine their relation to radar signal velocity and to clarity of streambed definition. These initial tests indicate that GPR is capable, under some conditions, of producing a reasonably accurate (+/- 20%) stream-channel profile quickly (approximately five minutes for a 50 meter traverse), while avoiding the problems and hazards associated with placing instrumentation in the water.

INTRODUCTION

To be of value, sedimentation studies involving unstable-bed channels require accurate channel-geometry measurements. Knowledge of stream-channel cross-sectional area is a critical component of any direct estimate of water discharge at flood stage, and, by extension, of any calculation of suspended sediment discharge or bedload transport rate for the same peak flow. Sequential profiles of channel geometry can help define the active zone of bedload transport (to assist in the design of a sampling program), as well as aid in the indirect computation of bedload transport rates by developing a relation between bedform volume and celerity, and bedload discharge (Mahmood and Mehrdad, 1991). Typically, however, the conditions that result in the greatest movement of sediment and the greatest variability in channel geometry are also those that most challenge standard measuring techniques. Rivers at flood stage are dangerous to gage because of high velocities and drift (logs, stumps, debris); and traditional depth sounding equipment is increasingly subject to error and/or failure as stream depth, velocity, and bed instability increase (Sauer and Meyer, 1992). Technology that allows non-contact monitoring of stream bed changes during high flow conditions is needed to avoid such problems, and to provide a safe way to obtain flow data that would otherwise be missed.

One measurment technology that may help improve the acquisition of channel-geometry data during high flow periods is ground-penetrating radar (GPR). Ground-penetrating radar is a geophysical technique that produces high-resolution profiles of the subsurface by measuring the traveltime of an electromagnetic pulse between a transmitter, a reflective boundary, and a receiver. The velocity of an electromagnetic pulse varies with the electrical properties of the penetrated material (Davis and Annan, 1989). It is therefore necessary either to calibrate signal traveltime to a known distance traveled in order to infer distance from the recorded traveltime, or to use a known velocity through a material to calibrate the instrument.

Applications of GPR in hydrogeologic studies have shown that GPR can discern water/sediment boundaries. Ground-penetrating radar studies on lakes and rivers have shown that when a low-frequency (100 MHz) antenna is towed across relatively low conductivity (400S/cm) water, GPR can be used to map water depth up to about ten meters with resolution on the order of 10cm. GPR has been used to detect the water/streambed interface on a river and a lake in Connecticut (Beres and Haeni, 1991), and to profile a lake bed in Arizona (Sensors and Software newsletter, Oct., 1994). These studies, and the fact that a radar pulse can travel through both air and water (Davis and Annan, 1989), suggest that GPR can be used to obtain estimates of water depth in streams and rivers when conditions make conventional stream gaging difficult or dangerous. The following report is a description of field tests conducted to assess this possibility.

OBJECTIVES AND METHODS

The purpose of the tests described here was to evaluate, under field conditions, the suitability of GPR to the measurement of stream-channel cross-section geometry. Three basic questions were posed: 1) Can ground- penetrating radar profile a stream bed when the radar antenna is suspended above the stream surface?; 2) Is the radar-signal velocity sufficiently reliable to provide reasonable confidence in the accuracy of depth estimates based on signal traveltime? (in other words, can worthwhile estimates of channel geometry result from GPR profiles?); and 3) Is GPR equipment compatible with typical U.S. Geological Survey streamgaging infrastructure?

GPR equipment is expensive ($15,000 to $100,000 per system) and therefore of limited availibility. A GSSI (Geophysical Survey Systems Inc.)10 ground-penetrating radar unit, with thermal printer, magnetic tape recorder, and 60-300MHz transceiving antennas, was borrowed from the Branch of Geophysical Applications and Support, Office of Ground Water, U. S. Geological Survey. (Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U. S. government.) Field tests were conducted at four sites on rivers draining Mount St. Helens in southwestern Washington: Cowlitz River at Castle Rock (bridge site); Toutle River at Tower Road (cableway site); North Fork Toutle River at Kid Valley (cableway site); and Muddy River below Clear Creek (cableway site). Initial tests were made to determine appropriate radar signal-processing settings (gain and filters), data-collection parameters (data samples per scan, scans per second, and recorded time range), and optimal antenna frequency. The optimal radar/data collection configuration was: 40 watt 100 MHz transceiving antenna; vertical Infinite Impulse Response bandpass filters set to pass 25-200 MHz; auto-set signal gain; 1024 samples per scan; and approximately 30 scans per second. The 100 MHz antenna represented the best compromise between resolution and penetration. With resolution defined as one-third the radar wavelength (Beres and Haeni, 1991), the 300 MHz antenna (approximate wavelength in water: 10 cm) theoretically provides three times the resolution of the 100 MHz antenna (approximate wavelength in water: 34 cm). However, the shorter wavelength of the 300 MHz antenna also limits penetration. The 60 MHz antenna signal will penetrate greater depths than the 100 MHz or 300 MHz antennae signals, but the longer wavelength results in reduced resolution.

Radar cross-section profiles were made by suspending the radar antenna (the 100MHz transceiver housed in a .30m X .61m X 1.2m fiberglass box) over the stream using a standard USGS sounding reel (model A, B, or E) and cable. The antenna was first positioned near the center of the stream channel, approximately .5 meter above the water surface, and radar signal gains were set to achieve optimal recognition of the water/streambed boundary. The antenna was then repositioned to the edge of the stream and towed from bank to bank at a rate of approximately .15 meters per second. Radar data were output to the thermal printer and to magnetic tape. Cableway and/or bridge stationing was marked in the GPR data file to indicate antenna location relative to stream cross-section position. To assess radar signal consistency, subsequent lead-weight depth soundings were collected at the cross-section stationing marked on the radar plots to enable calculation of radar signal velocity at those points. Equipment setup time typically was two hours, which included mounting the radar antenna to the cable car or bridge cart, positioning the radar unit on bridge or cableway, and making preparatory settings tests. Equipment breakdown time was about one hour.

At the Cowlitz River at Castle Rock site, an additional test was made to verify water surface position on the radar plots. Position verification was used to help derive channel cross-section plots.

Stream water conductivity, suspended sediment concentration, bed material, and water temperature were collected at selected sites to examine their effects on radar signal velocity and clarity of boundary reflectivity (how clearly the radar plot shows the water/streambed boundary).

DISCUSSION OF FINDINGS

Results indicate that GPR can provide an image of a stream-channel cross section when the radar antenna is suspended above the water surface. Construction of a stream-channel cross-section plot from an unprocessed radar plot requires visual definition of both water/streambed and air/water interfaces. Unprocessed radar plots show the water/streambed boundary as an intersection of a darker, more chaotic section (representing underlying sediments) overlain by a lighter, more uniform section (representing the water column). Less distinctly shown, due to the radar's greater wavelength in air (and thus lesser resolution), is the air/water boundary. Traverses in which the antenna height above water varied with cableway sag show a curved band visible near the top of radar plots. This band, which represents the water surface, is curved because the varying antenna height above the water results in varying signal traveltime. To confirm that this curved band represents the air/water boundary, and to increase our confidence in interpretation of records for which antenna height was constant (such as from a horizontal bridge deck), a data set was collected in which the antenna height was alternately raised and lowered by 30 cm over several 15 m intervals of the transect. This data set verified that the air/water boundary is represented by the same band that is curved when antenna height above water mirrors cableway curvature. By confidently placing the location of the air/water boundary in the radar record, derivation of a channel cross-section plot becomes straightforward, although somewhat subjective. Error due to subjective differences in the interpretation of the radar record was not assessed for this report. Figure 1 shows an example of an unprocessed radar plot, and a comparison of the cross-section plot derived from the radar plot with a cross-section plot obtained by conventional sounding methods. At all sites, under a variety of field conditions, it was possible to determine basic channel shape from unprocessed radar plots.

To determine the consistency of this methodology, radar-signal traveltime between the water surface and bed sediments was plotted against weight-sounded water depth for the four sites (figure 2). Linear regression returned coefficient of determination (r^2) values of greater than .84 for all four sites (greater than .94 for three of the sites), while the all-sites composite regression r^2 value was .97, indicating that most of the variation in radar-signal traveltime was a

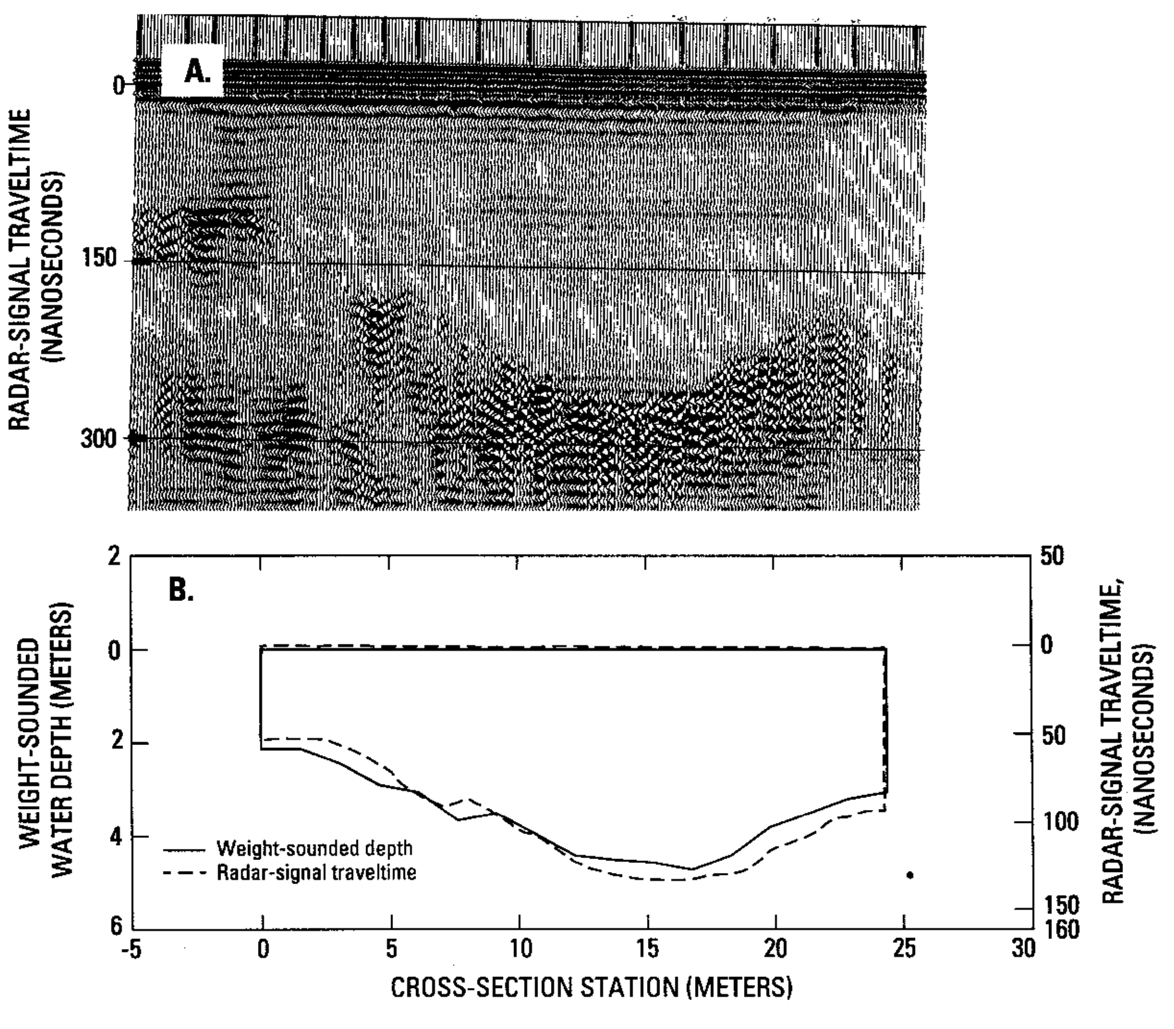

Figure 1. A) Unprocessed GPR plot of stream channel at Muddy River. (Plot shows signal traveltime from surface to bed and back.) B) Shape comparison of gpr-extracted cross-section plot (signal traveltime from surface to bed only) and weight-sounded cross-section plot.

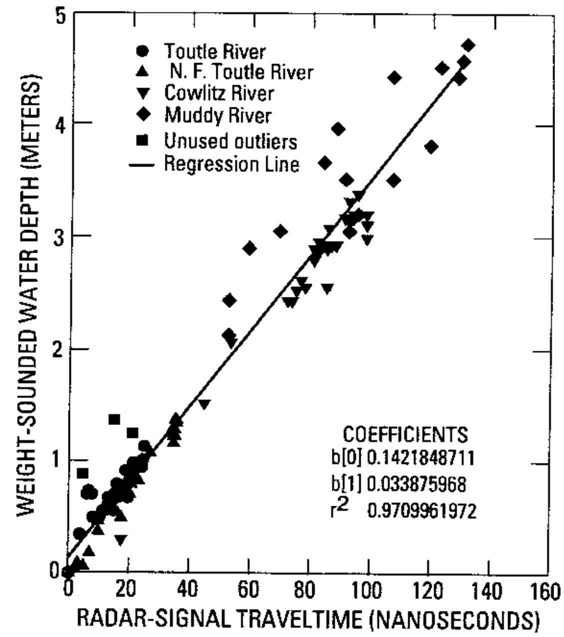

Figure 2. Radar-signal traveltime vs. weight-sounded water depth at four sites, and linear regression.

Table 1. Approximate values for electromagnetic properties of selected materials. [Modified from Geophysical Survey Systems, Inc., 1987; μ S/cm, microsiemens per centimeter at 25 degrees Celsius; m/ns, meters per nanosecond.]

Material	Specific Conductance (μ S/cm)	Relative dielectric permittivity (Er) (dimensionless ratio)	Velocity of electromagnetic energy, Vm (m/ns)
Air	0	1	.305
Dry sand	0.001-10	4-6	0.127-0.152
Fresh water	1-300	81	.034
Saltwater	40,000	81	.034
Saturated sand	1-100	30	.055
Saturated silt	10-100	10	.098
Saturated clay	1,000-10,000	8-12	.092-.114

result of the depth of water traversed. Remaining variation in traveltime is probably influenced by suspended-sediment concentration; as sediment concentration increases, the velocity of the radar signal should also increase (an assumption based on the known values in fresh water and in saturated sand) from approximately .034 m/ns to approximately .055 m/ns (table 1). Stream-parameter data collected during these tests (table 2), however, show no strong relation between signal velocity and suspended-sediment concentration. Other possible sources of signal velocity variation may include: height of the antenna above the water surface; angle of the river bed relative to the radar antenna; and inaccurate interpretation of the radar record. The greatest differences between GPR-estimated depths and weight-sounded depths consistently occur near stream edges, in the part of the cross section where antenna-height-above-water variation and riverbed angles were of greatest magnitude. More testing is required to determine the cause(s) of the unexplained variation in signal traveltime. Although the source of this variation is unclear, it is apparent that it is at least partly site/time related, because observations for a given site are grouped on the plot shown in figure 2. The plotted data also suggest that the relation between radar-signal traveltime and sounded water depth

Table 2. Stream parameter data. m^3/s, cubic meters per second; μ S/cm, microsiemens per centimeter; mg/L, milligrams per liter; m/ns, meters per nanosecond.

Site	Date	Computed Flow m^3/s	Conductivity μ s/cm	Susp. Sed. Conc. mg/L	Water temp. degrees Celsius	Bed Condition	Remarks
Cowlitz R. at Castle Rock	Apr. 21, 1994	230.5	Est. 100	--	--	Sand, gravel	Low flow
Cowlitz R. at Castle Rock	Jan. 10, 1995	487.1	--	--	--	Sand, gravel	Medium flow
Cowlitz R. at Castle Rock	Jan. 26, 1995	239.6	92	184	6.5	Sand, gravel	Low flow sig. vel.=.034 m/ns
N.F. Toutle R. at Kid Valley	Apr. 19, 1994	43.9	--	47	--	Gravel, cobble	Medium flow
N.F. Toutle R. at Kid Valley	Jan. 12, 1995	Est. 51.0	262	324	--	Gravel, cobble	Medium flow sig. vel. =.038 m/ns
Muddy R. below Clear Creek	Jan. 31, 1995	325.7	26	10,000	--	Sand, gravel, cobble	High flow
Muddy R. below Clear Cr.	Feb. 1, 1995	249.2	32	4060	6	Sand, gravel, cobble	High flow sig. vel. =.037 m/ns
Muddy R.below Clear Cr.	Feb. 24, 1995	51.8	--	100	--	Gravel, cobble	Medium flow
Toutle R. at Tower Rd.	Jan. 24, 1995	59.8	210	222	7	Gravel, cobble	Medium flow sig. vel. =.044 m/ns

may not be best described by a straight line. In view of the limited size of the data set, and the desire to assess the practicality of using GPR as a field data collection technique, this analysis used first order linear regression only. Data collected for this study show that radar-signal traveltime is largely correlated with water depth; that site specific conditions influence the signal velocity; and that a single signal velocity may not be sufficient to completely describe the relation between radar-signal traveltime and sounded water depth.

Three methods were used to evaluate the usefulness of GPR-based cross-section plots: comparison of water depths and stream-channel cross-sectional areas obtained by GPR and computed by conventional measurement methods; comparisons of GPR-based discharge estimates with a stage-discharge rating curve; and comparison of two sequential profiles.

Based on the signal traveltime data shown in figure 2, a single value (.04 m/ns) was selected as the most representative signal velocity in impure fresh water. (Least squares regression for the four sites were run through the origin, and the resulting slope values averaged.) This value was then used to calculate depths at those points in the radar plot corresponding to the points where lead-weight depth soundings were obtained. Using .04 m/ns as a conversion factor, 80% of the GPR-based depth estimates fell within 20% of the weight-sounded depth. Cross-sectional area was then calculated using the USGS standard midpoint method (Rantz, S. E., and others, 1982). Approximate processing time per cross-section was one hour. Data were available to perform such calculations for eight different transects at the

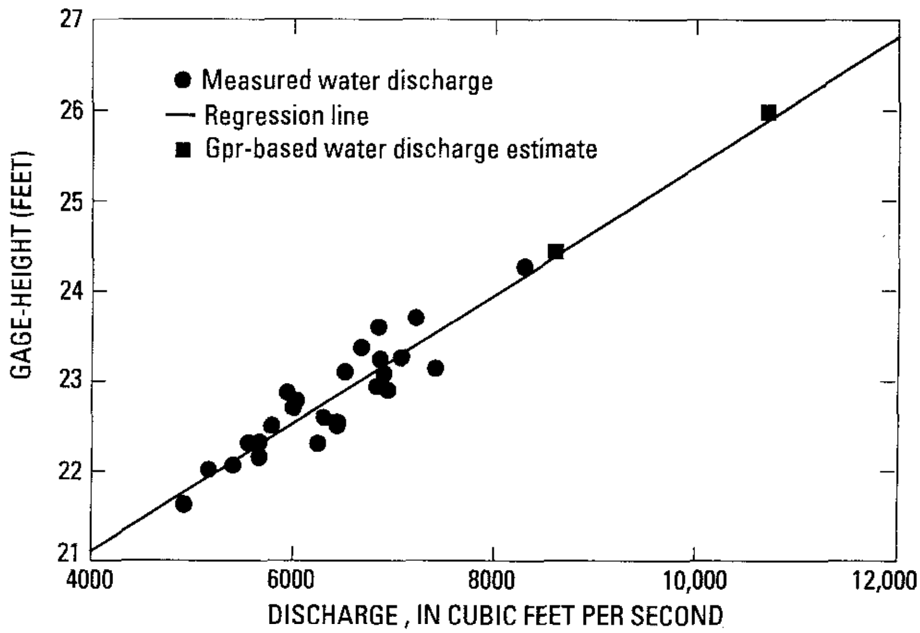

Figure 3. Linear regression through all discharge measurements above 4900 cfs, and gpr-based discharge estimates, Muddy River below Clear Creek.

four study sites. These comparisons show that when a single signal velocity is used, areas computed from GPR plots differ by +/- 18% from areas computed by conventional sounding techniques. Better results are achieved when signal velocities based on calibrations specific to each cross section are used to calculate areas. When this approach is used, areas computed from soundings and GPR plots differed by less than 10%, (with the exception of one test at Muddy River, when only 4 signal velocity calibrations were available). Site-specific calibrations, which may be difficult to acquire, appear to be a requirement to significantly improve confidence in GPR-based estimates of depths and cross-sectional areas.

GPR-based discharge estimates were also compared against a stage-discharge rating curve. GPR data were collected at Muddy River during a flood peak, having an approximately 20 year recurrence interval, on January 31 and February 1, 1995. Surface velocities were estimated by timing drift. Cross-sectional area was estimated from the GPR plot using 0.13 ft/ns to convert to units of square feet. (English units were used for this comparison to agree with units used for previous discharge measurements.) Mean water velocity was estimated by applying a coefficient of 0.80 (estimated from previously collected discharge measurement data) to the timed surface velocities. The two estimated discharges were then compared with a regression line based on all measured discharges above 4900 cfs. As shown in figure 3, the two GPR-based discharge estimates fall close to the regression line (<2%). Although this portion of the rating is not defined by direct measurements, the vertical bedrock walls of the channel support extension of the regression line in the manner shown. Determination of mean stream velocity, radar signal velocity, and appropriate rating extension all represent sources of error; nevertheless these results indicate that GPR radar plots can provide useful information about channel geometry and discharge at high flow.

Two radar cross-section plots obtained five minutes apart during high flow at Muddy River demonstrate the ability of GPR to improve knowledge of channel geometry in unstable-bed conditions (figure 4). These two images record a significant change in channel geometry within a five minute time span; such information is not obtainable using conventional methods.

These investigations show that GPR can provide useful water-channel-geometry information not obtainable by conventional methods. Although improved accuracy probably requires undesirable site/time-specific calibrations, the ability to profile a stream bed rapidly under high flow conditions makes GPR a potentially valuable addition to currently available measuring equipment.

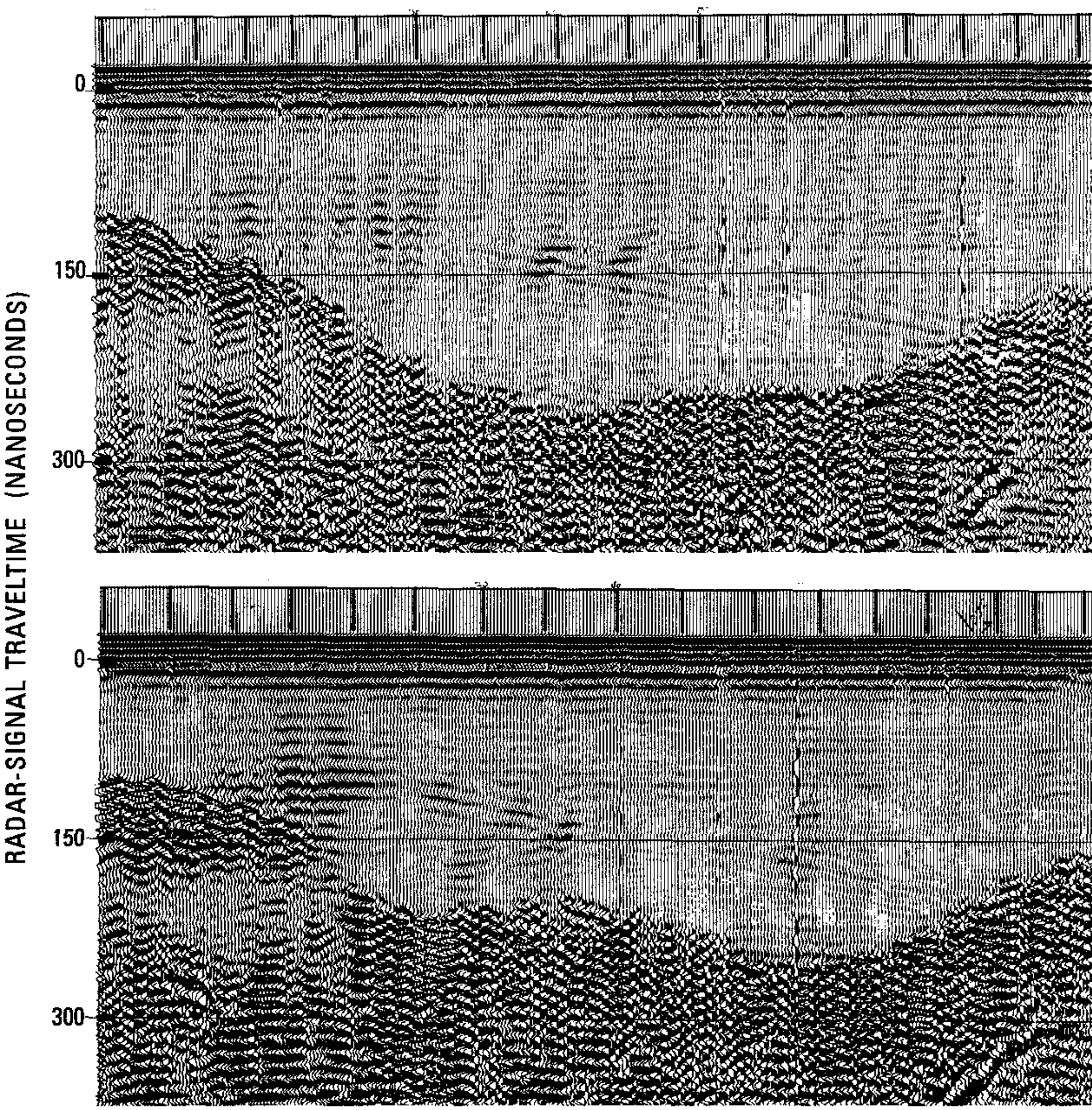

Figure 4. Sequential ground-penetrating radar cross-section profiles at Muddy River on February 1, 1995, showing rapid change in channel geometry.

Experience with GPR equipment shows that it is compatible with standard USGS equipment and procedures. Radar plots were successfully collected from both bridge and cableway over rivers up to 90 m wide (Cowlitz River at Castle rock), and up to 4.5 m deep with velocities exceeding 3 m/sec (Muddy River), using standard reels and suspension cable. The light weight of the radar antenna and the rapid data-acquisition ability of the GPR equipment increases the safety and speed of cross-section measurement in hazardous flows. Because the radar antenna weighs only 11 kilograms, and does not contact the stream, risk of injury to personnel and equipment is lessened. The most significant problems encountered using GPR with standard USGS equipment were: radar antenna rotation, sway and bounce, and logistical constraints posed by a fixed antenna cable length. Suspending the antenna with a cable from a single point made it sensitive to wind gusts and conveyer-induced vibration. Vertical oscillation of the radar antenna caused by cable-car bounce is the likely cause of undulations in the water/streambed boundary in the left side of the top radar plot shown in figure 4. The fixed length of the cable connecting the antenna to the control unit meant that a complete cross-section plot of a wide river required transporting all the radar equipment across the river. Data acquired during these field tests showed that available GPR equipment can be used with standard USGS streamgaging facilities to profile stream channels. However, improvements in both GPR equipment and data collection technique are possible. Such improvements could include: 1) reducing size and weight of GPR equipment; 2) increasing stability of GPR antenna (possibly using a lightweight, rigid frame attached to the cable car); 3) improving regulation of antenna travel rate; and 4) reducing or automatically correcting for changes in antenna height above water surface. These changes would almost certainly result in better quality radar plots

SUMMARY

We conclude from field tests that GPR is a viable technology for mapping stream-channel profiles at high flow, particularly under conditions in which conventional methods are either unsafe or inadequate. Radar plots collected in the field under a variety of conditions show, to varying degrees, the water/streambed interface, as well as the water/air interface. It appears possible to estimate channel cross-sectional area to within +/- 20% using a radar velocity of .04 meters per nanosecond. The data suggest that if sufficient effort is made to calibrate the radar signal to a specific site and time (a difficult task under high flow conditions), better results are possible. These tests have shown that currently available GPR units can be used successfully from cableways and bridges. Lastly, we note that these field tests represent an initial effort with new equipment and techniques, and that sophisticated post-acquisition data processing techniques were not used in the data analysis.

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IN-CHANNEL SEDIMENT BASINS: AN ALTERNATIVE TO DAM-STYLE DEBRIS BASINS

Wendy S. Gist, Hydraulic Engineer, Corps of Engineers, Los Angeles CA;
Scott E. Stonestreet, Hydraulic Engineer, Corps of Engineers, Los Angeles CA;
Ronald R. Copeland, Research Hydraulic Engineer, US Army Waterways Experiment Station, Vicksburg, MS

Abstract: In-channel sediment basins were designed, in lieu of a traditional debris basin, to capture large sediment loads at the upstream end of a proposed flood control channel. A numerical model, HEC-6W, was used to size the basins.

INTRODUCTION

General: The US Army Engineer District, Los Angeles (USAEDLA), has proposed to improve a portion of San Timoteo Creek located in San Bernardino, California (USAEDLA 1990, 1991). The proposed channel improvement will convey the 100-year flood of 19,000 cfs with a concrete-lined, supercritical flood control channel. The San Timoteo Creek watershed has the potential to supply a large amount of sediment during a storm event due to sparse vegetation, steep slopes, and easily eroded soils. Therefore, to assure that the proposed channel would function as designed, a debris basin would be required.

Description of Study Area: The San Timoteo Creek watershed comprises about 126 square miles and is located southeast of the City of San Bernardino, California, in Riverside and San Bernardino counties. The creek is formed by Yucaipa, Wilson, and Noble Creeks and is itself a tributary to the Santa Ana River.

The proposed improvement includes the lower 5.2 miles of the creek as it flows from the foothills across an alluvial plain to the Santa Ana River. Upstream from the proposed channel improvements the bed is composed primarily of coarse sand with some gravel. The channel width varies due to extensive bank erosion, generally ranging in width between 100 and 300 ft. Average bed slopes through San Timoteo canyon range from 0.0131 ft/ft (69 ft/mi) near the proposed in-channel basins to 0.0145 ft/ft (77 ft/mi) in the sediment supply reach. The overall thalweg profile, in the study area, of San Timoteo and Yucaipa Creek is shown in Figure 1.

Debris Yield: An analysis was made to estimate the volume of debris delivered to the upstream end of the proposed project from the watershed. The debris yield was determined using the methods outlined in USAEDLA (1989). This method uses predictive regression equations which are based on watershed parameters and the combined probability of wildfire and flood.

This analysis indicated that the single-event, 100-year-frequency debris estimate would be 700 acre-feet. Preliminary sediment transport analyses indicated potential problems with the channel inlet and outlet due to this large volume of debris.

Traditional Debris Basin Alternative: Initially, a traditional dam-style debris basin was designed to control debris and limit sediment inflow to the supercritical channel. However, due to the narrow canyon and further confinement by a railroad alignment, this structure had an embankment that was a maximum of 68 ft above the channel invert and was over 2 miles long. The spillway, designed to meet Corps probable maximum flood (PMF) criteria for dams, resulted in a 400-ft-wide spillway with a crest approximately 43 ft above the channel invert.

The local residents and flood control agency found this design unacceptable aesthetically and raised many concerns about dam safety. Thus, an alternative solution to the dam-style debris basin was sought.

In-Channel Sediment Basin Alternative: In-channel sediment basins were designed as the alternative. As shown in Figure 2, the in-channel alternative consists of a total of six sediment basins in series. Five basins are excavated 11 feet below the channel invert and one basin is excavated 30 feet below the invert. Grouted stone

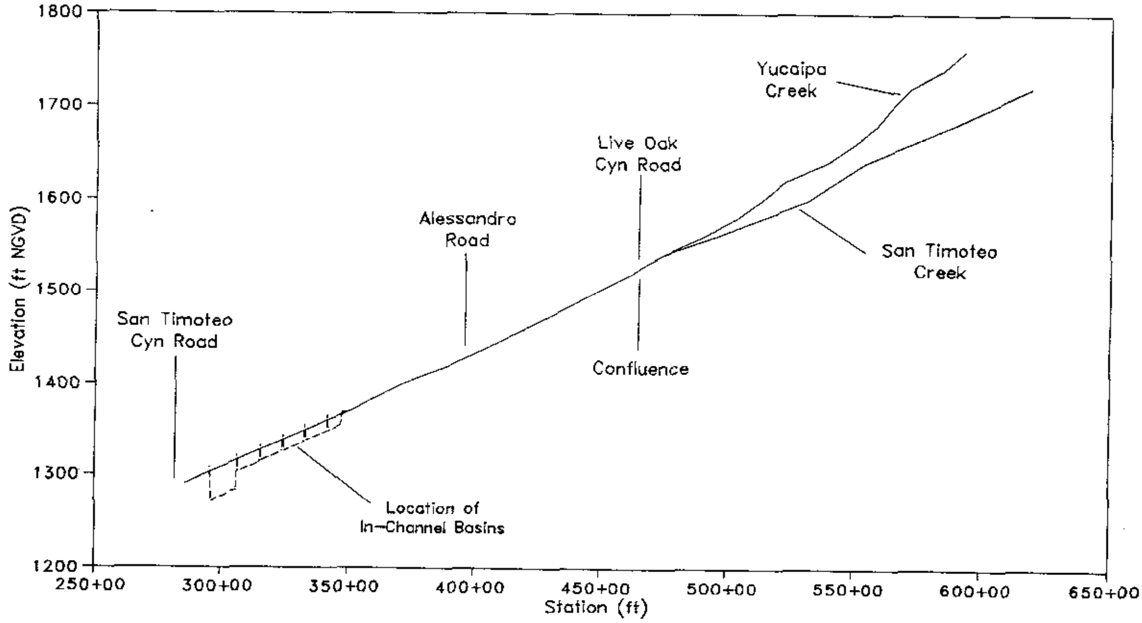

Figure 1. Thalweg Profile of San Timoteo and Yucaipa Creeks

stabilizers are located between the basins and rise to a height of 6 ft above the existing channel invert. The in-channel basins range in width from 300 to 550 feet and in length from 500 to 1100 feet. The alignment of the basins generally follows that of the creek bed.

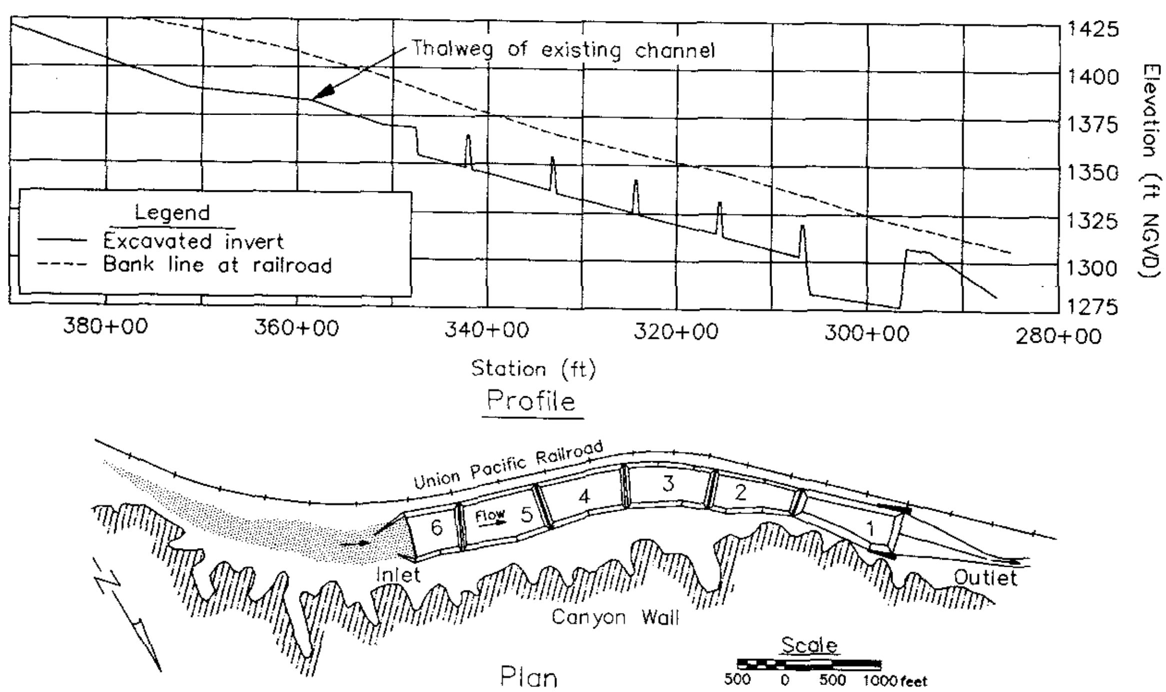

Figure 2. Plan and profile of in-channel basins

The proposed in-channel sediment basins for this project were designed to function basically the same as a larger, dam-style, single debris basin. With a single debris basin, sediment-laden flows are detained with a combination of above-grade embankment and below-grade excavation. The flow detention causes significant reduction in velocity, greatly reducing the sediment transport capacity of the flow and inducing deposition of most of the bed-material load. Only the wash load and a relatively minor amount of bed-material load are passed over the spillway of the debris basin.

The main difference from the concept involving a single debris basin is that instead of a combination of below-grade excavation and a substantially above-grade embankment, these in-channel debris basins are equally above and below grade. The height of the stabilizer at the downstream end of each basin was limited to 6 ft above the existing channel invert to keep it below the classification of a dam.

The system of in-channel sediment basins would significantly reduce the inflow velocities. At the design discharge for the existing natural channel above the project inlet, the flow velocities range from 12 to 18 fps, while the velocities within the basins would range from 3 to 8 fps. The design length of the basins would result in a typical detention time of 4 minutes, which is sufficient time to settle out even the finest classification of sand.

The uppermost basin (basin 6 in Figure 2) will provide the initial trapping of sediment during the beginning of the design flood. As the basin fills up to the crest of the stabilizer, a condition of relative equilibrium will be attained between the rate of sediment inflow to the basin and the sediment transport capacity of the detained flow within the basin. Once the sediment storage capacity of the basin has been exceeded, all additional sediment inflow will be transported to the next downstream basin. The process will be repeated sequentially through each of the basins. The series of basins is designed to provide a total sediment storage capacity equal to the entire volume of sediment expected during the design flood, plus an allowance for sediment from antecedent flows.

Because San Timoteo Creek is well entrenched in the canyon bottom, levees or other flow containment structures are not needed to line the basins. In most cases, the stabilizer crests between basins would be well below the banks of the channel. A small berm would be required along the downstream end of basin 1 (see Figure 2) to make sure the flows enter the basin outlet structure.

Although the concept of utilizing several small sediment basins in series may seem rather unorthodox at first, it actually constitutes only relatively minor variations of the same proven concept used in the USAEDLA, for many years to exclude large amounts of bed-material-sized sediment and debris from downstream channel improvements.

SEDIMENT TRANSPORT ANALYSIS

General: Numerical modeling using HEC-6W, a research version of the one-dimensional sediment transport model HEC-6, was performed by the USAEDLA, and the US Army Engineer Waterways Experiment Station (USAEWES) to ensure that the debris basins would function as designed during a design flood. The numerical model was able to simulate the sequential filling of the basins, the variation of deposition rate as each basin filled, the size class distribution of the sediment that passed through the basin, and the slope of the deposited sediments. The one-dimensional model does not account for variation in deposition due to eddies or increased turbulence at the basin inlets.

Sediment Gradation: Initial bed material gradations for the model were based on an extensive bed and bank sampling program that included over 100 samples. Most of the samples were taken in a representative supply reach upstream from the proposed sediment basins. Sufficient samples were taken to determine if there was any lateral, vertical, or longitudinal variation in the bed. The maximum size of material was about 64 mm with an average D_{50} of about 0.9 mm. An average normalized bed gradation was determined from the bed samples for use in the model (Figure 3).

Transport Function: Yang's unit stream power function was used for this study. This function is desirable since it has proved applicable for medium to coarse sand-bed streams located in the USAEDLA. Silt transport and

Figure 3. Bed material gradation

deposition is computed by HEC-6W based on an equation developed by Krone (1962) for silt and clay deposition in a recirculating flume.

Additional transport functions were used in the numerical model and tested for sensitivity. These functions included Madden's (1985) modification to Laursen's (1958) function and Copeland's (1989) modification to Laursen's (1958) function. Madden's 1985 modification of Laursen's function adapted Laursen's function for higher Froude numbers and included Toffaleti's river data and Guy, Simons, and Richardson's flume data. Copeland's modification to Laursen's (1958) function included Brownlie's data and incorporated data for transport of gravels in addition to the sand data used to develop the original Laursen function. The Laursen-Copeland function is very sensitive to the fraction of fine and very fine sand present in the bed. This function is best used when measurements of suspended sediment are available to confirm calculated concentrations of fine material.

__Sediment Inflow__: Measurements of suspended or bed-load sediment do not exist for San Timoteo Creek. Therefore, sand and gravel inflow to the numerical model was calculated assuming equilibrium sediment inflow using average hydraulic parameters in the supply reach and the average normalized bed material gradation. By using the average bed gradation, the computations ignore the effect of armoring and the inflow curves tend to be high especially with a multiple-grain size transport function. Specifically, sediment transport capacities were computed with the sediment transport module of the Hydraulic Design Package for Flood Control Channels (SAM) developed at WES (Thomas et al, 1995). Silt inflow was estimated to be 20 percent of the total sand inflow. This percentage corresponds roughly to the average percentage of silt from bank samples.

__Results__: Results of this analysis are shown in Figure 4. The model was run for the 3-day, 100-year design flood using Yang's transport function. The initial bed elevations were assumed to be at the design levels. Due to the rapid change in cross-section shape at the sediment basins, the numerical integration scheme in the model was set to use "at-station" values for hydraulic parameters. Although the use of at-station values can decrease model stability, the time-steps used for the flood simulations were short enough to prevent model instability problems.

By the peak of the 100-year flood an accumulated total of 340 acre-feet of sediment was delivered to the basins from the supply reach. Approximately 256 acre-feet of sediment was deposited in the basins and an additional 84 acre-feet of sediment by-passed the basins. The by-passed sediment included 61 acre-feet of silt and 23 acre-

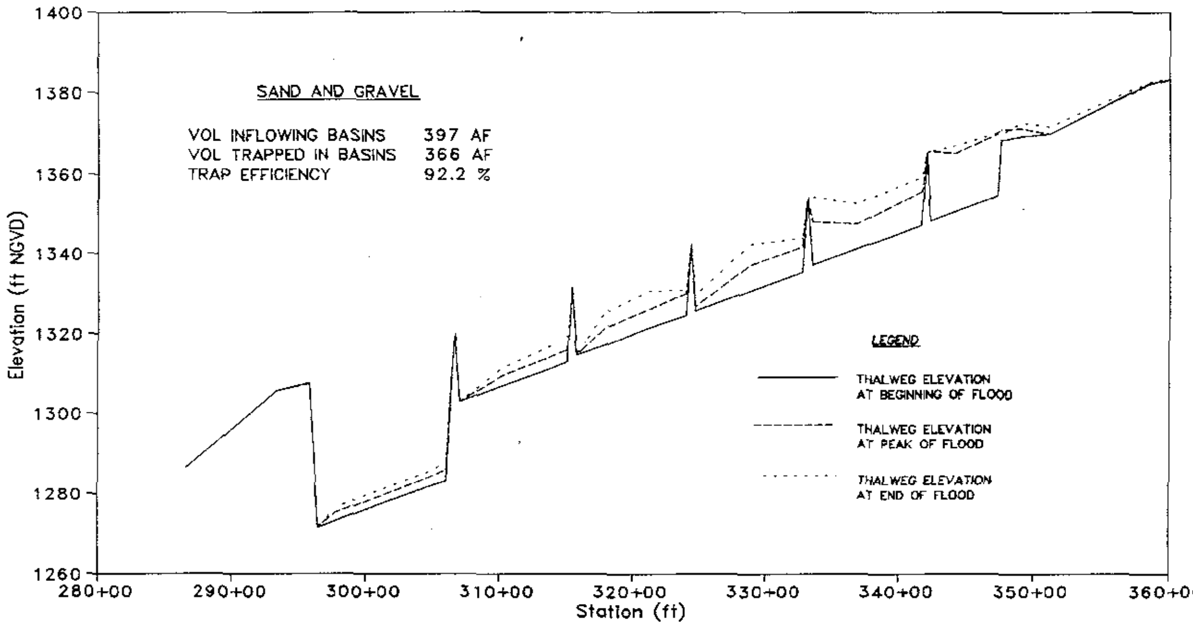

Figure 4. Thalweg profile for Yang function

feet of sand (mostly very fine and fine sand).

At the end of the design flood, a total of 508 acre-feet of sediment was delivered to the basins. 382 acre-feet of sediment was deposited in the basins and 126 acre-feet of silt and sand (95 acre-feet of silt and 31 acre-feet of sand) had by-passed the basins. The trap efficiency for the total sediment load (i.e. silt, sand, and gravel) was 75.2 percent and the trap efficiency for sand and gravel was 92.2 percent.

The numerical model was able to simulate the sequential filling of the basins, the variation of deposition rate as each basin filled, the size class distribution of the sediment that passed through the basin, and the slope of the deposited sediments. The one-dimensional model does not account for variation in deposition due to eddies or increased turbulence at the basin inlets.

Sensitivity Analysis: It was especially important to determine the model's sensitivity to sediment inflow due to the lack of prototype sediment inflow data. Simulations of the design flood were conducted using three sediment transport equations. As expected, different transport equations produced different deposition rates and quantities. Since suspended sediment data was not available for comparison with calculated transport rates, numerical model results were interpreted considering the model's sensitivity to the transport function. Additional sensitivity tests were conducted which included running the hydrograph twice to evaluate possible effects from the imposed initial conditions and increasing the sediment inflow of silt by one standard deviation. The results of the transport function analysis are discussed below.

Transport Function: In general, results from the Laursen-Madden function were similar in magnitude to those computed with Yang's. At the end of the design flood, the volume of sediment delivered by the supply reach was 397 acre-feet and the volume of sediment trapped in the basins was 312 acre-feet (Figure 5). The trap efficiency for the total sediment load (i.e. silt, sand, and gravel) was 78.4 percent and the trap efficiency for sand and gravel was 96.4 percent.

In contrast, results from the Laursen-Copeland function varied significantly compared to those computed with Yang's. At the end of the design flood, the volume of sediment delivered by the supply reach was 1675 acre-feet and the volume of sediment trapped in the basins was 763 acre-feet (Figure 6). The trap efficiency for the total

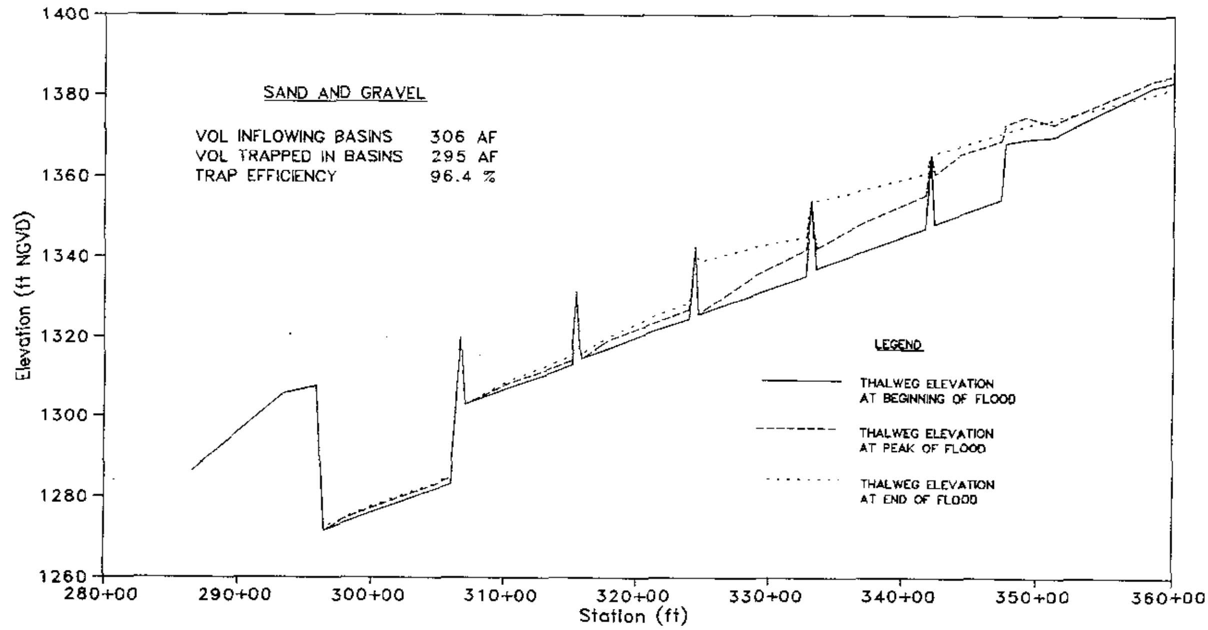

Figure 6. Thalweg profile for Laursen-Madden function

sediment load was 45.6 percent and the trap efficiency for sand and gravel was 56.3 percent.

Performance of In-Channel Basins: Overall, results from the sensitivity studies indicate that the in-channel sediment basins will function adequately. As expected, application of different transport functions resulted in computed trap efficiencies for sand and gravel ranging from 56.3 to 96.4 percent when silt is included in the model. When silt is omitted from the computations, trap efficiencies for sand and gravel ranged from 62.2 to 98.2 percent. In either case, the basins trapped most of the coarse, bed-load material and passed the fine sand and silt on to the concrete channel.

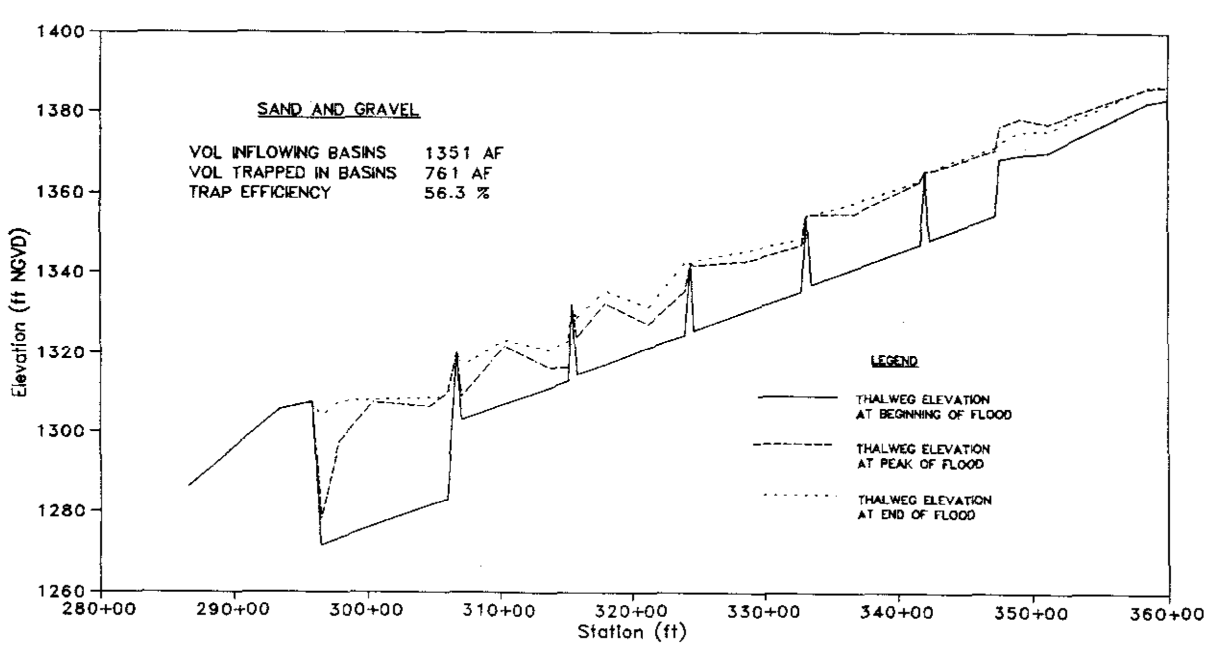

Figure 6. Thalweg profile for Laursen-Copeland function

Design Optimization: As discussed above, the numerical model was initially run for a six-basin configuration which had a total storage volume of 700 acre-feet. However, based on the results of the HEC-6W modeling, it was determined that the stream was transport limited. A design which used eight smaller basins was developed as shown in Figure 7. This design was incorporated into the numerical model and tested for reliability using Yang's transport function. As a result of the model study, the design volume of the sediment basins was reduced to 470 acre-feet.

The total calculated trap efficiency of the eight sediment basins for the 100-year hydrograph was 73.9 percent. Trap efficiency for sands was 94 percent, and for silts was 3.6 percent. 92 percent of the sand passing through the basins was smaller than 0.125 mm. Material passing through the basins would easily be transported in the high-energy concrete channel. The end of flood bed profile for this design is shown in Figure 7.

CONCLUSIONS AND RECOMMENDATIONS

Numerical modeling, using a research version of the one-dimensional sediment transport model HEC-6W, was performed by the USAEDLA and WES to ensure that the in-channel debris basins would function as designed during a design flood. The numerical model was able to simulate the sequential filling of the basins, the variation of deposition rate as each basin filled, the size class distribution of the sediment that passed through the basin, and the slope of the deposited sediments. The one-dimensional model does not account for variation in deposition due to eddies or increased turbulence at the basin inlets.

Results of this analysis concluded that the in-channel basins performed satisfactorily for a relatively wide range of conditions. A series of sensitivity tests were conducted to verify the design given the lack of measured or prototype data. For a case like this, it is important that several techniques be incorporated into the overall analysis to minimize uncertainty and risks. This analysis included results based on the USAEDLA debris yield method and a sediment transport-based HEC-6W numerical model study.

A sediment gaging station and sampling program should be developed and implemented in order to reduce uncertainty and risks in the design. Prior to construction, sediment sampling would provide insight to the

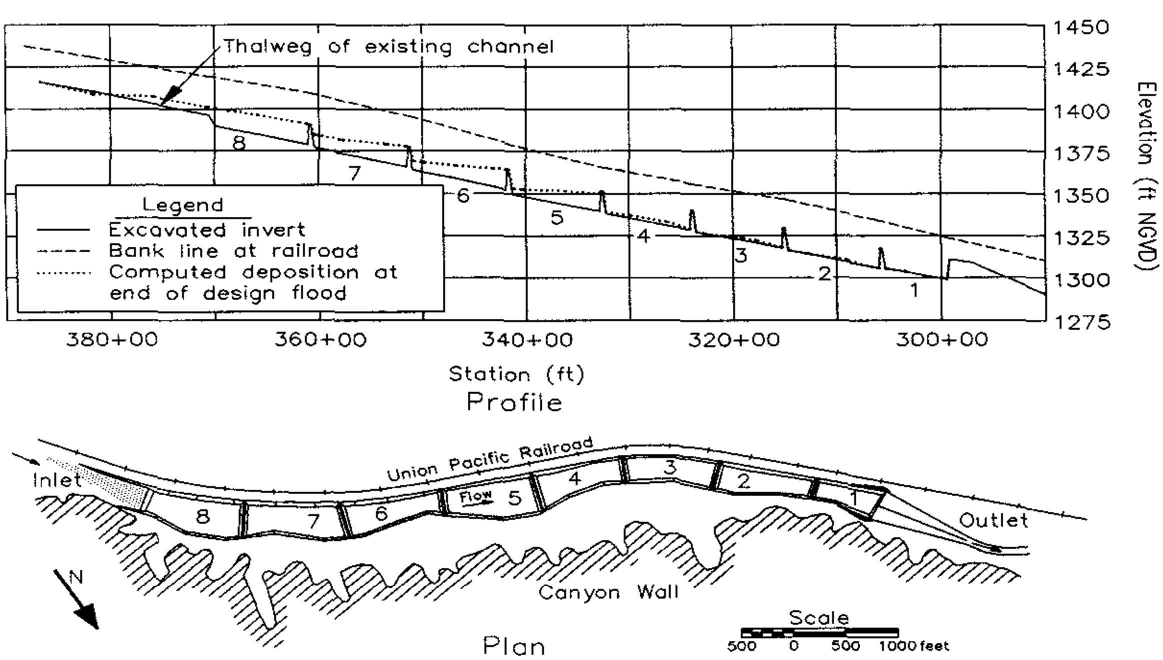

Figure 7. Plan and profile of in-channel basins

reasonableness of the sediment transport rates and volumes discussed herein. After construction, detailed operation and maintenance records should be maintained regarding the material removed from the basins and should include the volume, size (i.e. gradation information if possible), and type of material (i.e. organic versus inorganic). This information would provide the basis for determining the effectiveness of the prototype basins.

The design of the in-channel basins was optimized by reducing the total storage volume and by using basins with a depth of six feet as opposed basins ranging from 11 to 30 feet deep. This reduction in depth was required due to a high ground water table discovered during detailed site investigations. It is conceivable that further optimization could reduce the required storage volume of the in-channel basins.

The San Timoteo Creek flood control channel is currently under construction. Construction of the in-channel sediment basins is scheduled to begin in 1996.

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