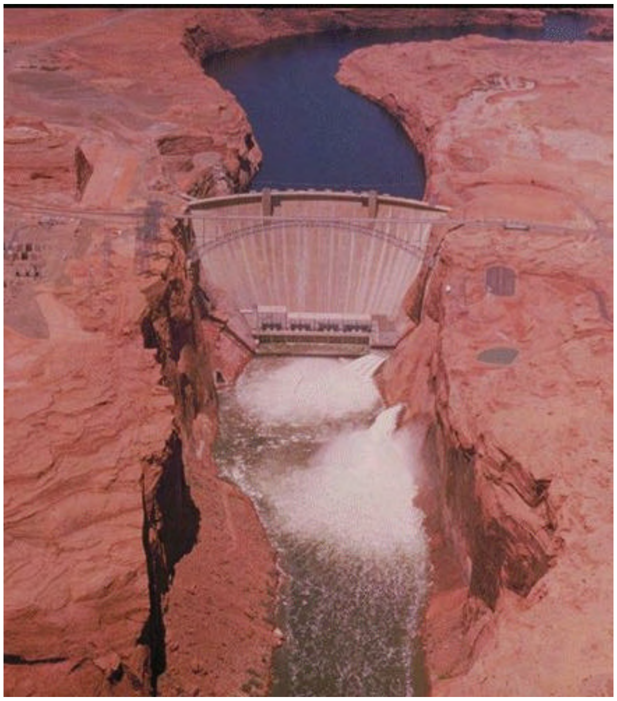
## Volume 2

# IX. Reservoirs



# IX. Reservoirs

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# USE OF GLOBAL POSITIONING AND GEOGRAPHIC INFORMATION SYSTEMS IN THE HUNTINGTON DISTRICT RESERVOIR SEDIMENTATION INVESTIGATIVE PROGRAM

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**Abstract:** The Huntington District Corps of Engineers is responsible for a geographic area that encompasses southern and central West Virginia, eastern Kentucky, western Virginia, northwestern North Carolina and southeastern and central Ohio. The topography of this area varies from the hills and mountains of West Virginia to the rolling plains of central Ohio. Within this region, the District operates and maintains 35 flood control reservoirs that control approximately 34% of the 45,000 square mile drainage area. Several of these flood control reservoirs have been in operation for over 60 years and are beginning to experience adverse impacts upon authorized project purposes due to sediment accumulation.

In 1972, the Huntington District established a Reservoir Sedimentation Investigative Program (RSIP). The program used traditional survey techniques based upon sediment ranges to develop sedimentation rates and trends. In 1997, the District implemented the use of total-bed-profile hydrographic surveys based upon global positioning systems (GPS) to determine these rates and trends. Output from the GPS surveys can be used in conjunction with geographic information systems (GIS) to generate lakebed profiles and drainage basin topographic/land use maps. In conjunction with the computed sediment rates and trends, these output results can be used to determine critical areas of sediment deposition in the lake that may adversely impact project purposes. Based upon this determination, future operation and maintenance decisions can be made.

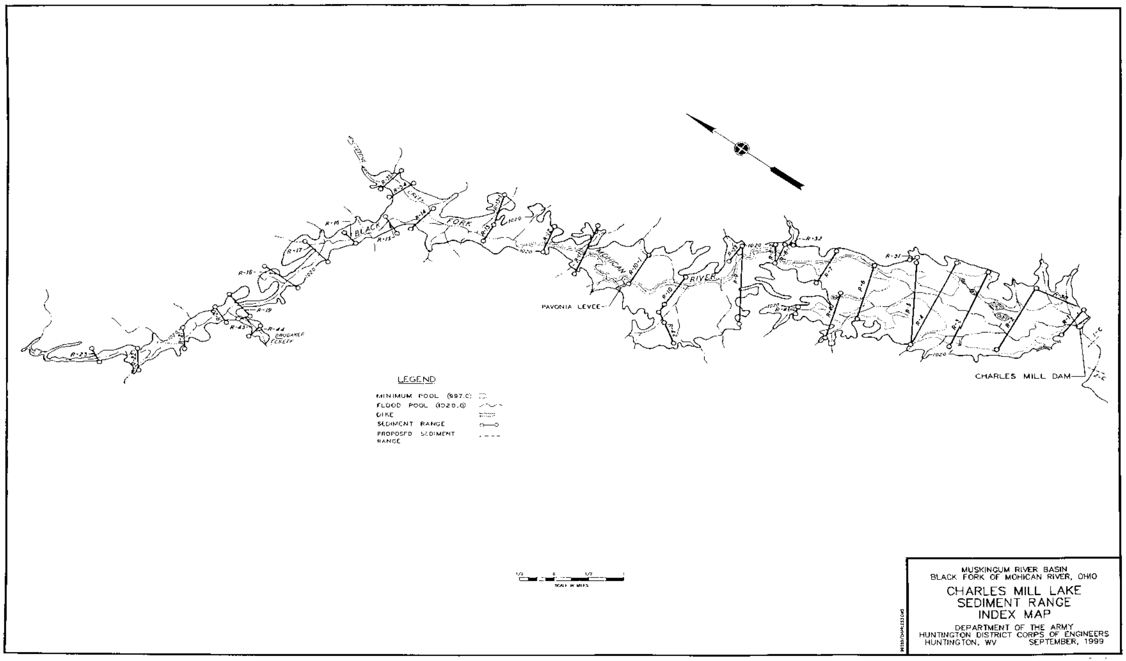
## INTRODUCTION

US Army Corps of Engineers Engineering Manual (EM) 1110-2-4000 outlines the basic objectives for a RSIP. These include: functional, operational and planning and design objectives. Although the District had been performing sediment surveys since the late 1940's, the District implemented a formal RSIP in 1972. The program was established to primarily meet the operational objective. As implied by the name, the purpose of this objective is to answer questions associated with the operation of the reservoirs. Such needs vary from project to project, but in general they include: (1) Criteria for the construction of boat docks, recreational facilities and other structures within the reservoir limits to include current knowledge on sedimentation. (2) If sediment yield to the project is large in proportion to storage capacities in multiple purpose reservoirs, the amount of sediment deposition will be needed for planning reallocation of storage and for revising reservoir regulation rules to assure optimum utilization of remaining reservoir storage space. (3) Actual depletion of storage capacity will be needed for forecasting future availability far enough in advance to permit planning and construction of replacement facilities. (4) For modifying regulating outlets and water supply intakes and for other facilities adversely affected by sediment accumulations. To date, the District has completed sediment survey reports on 25 of the 35 District flood control reservoirs. It should be noted that three of the 10 reservoirs for which no report has been prepared are dry reservoirs and one of the ten was only filled in 1992. The computed sedimentation rates for the 25 projects range from approximately 0.10 – 2.60 acre-feet/year.

## TRADITIONAL APPROACH TO RSIP

**Survey Procedure:** The traditional approach to RSIP has been the establishment of sediment survey ranges. Figure 1 provides an example of a sediment range layout for Charles Mill Lake located in the Muskingum River Basin in Ohio.

**Figure 1.**



The ranges are simply a fixed line across a reservoir along which elevations are measured. The traditional survey process involved sampling along the sediment ranges originating from permanent monuments. The survey boats were kept on line with the sediment range via land based survey crews and radio communication.

**Computational Procedure:** Based upon the surveyed elevations along the sediment range, the volume of the reservoir was calculated by use of the cross-sectional area method. This method involved averaging the end areas of successive ranges and multiplying by the distance between the ranges to obtain the intermediate volume. The total volume was computed by adding each intermediate volume for the entire reservoir length. The volume of sediment deposition was then calculated by subtracting the resurveyed capacity from the original lake capacity.

**Results from Traditional Approach:** Results from the traditional approach to RSIP consisted of tables of results with visualization of the results consisting of plots of historical surveys along the sediment ranges and historical plots of lakebed centerline profiles. Figure 2 provides a typical sediment range plot while Figure 3 provides a typical lakebed centerline plot. Provided in Table 1 are examples of historical sedimentation rates for two reservoirs in eastern Kentucky developed using the traditional method for a RSIP.

**Figure 2.**

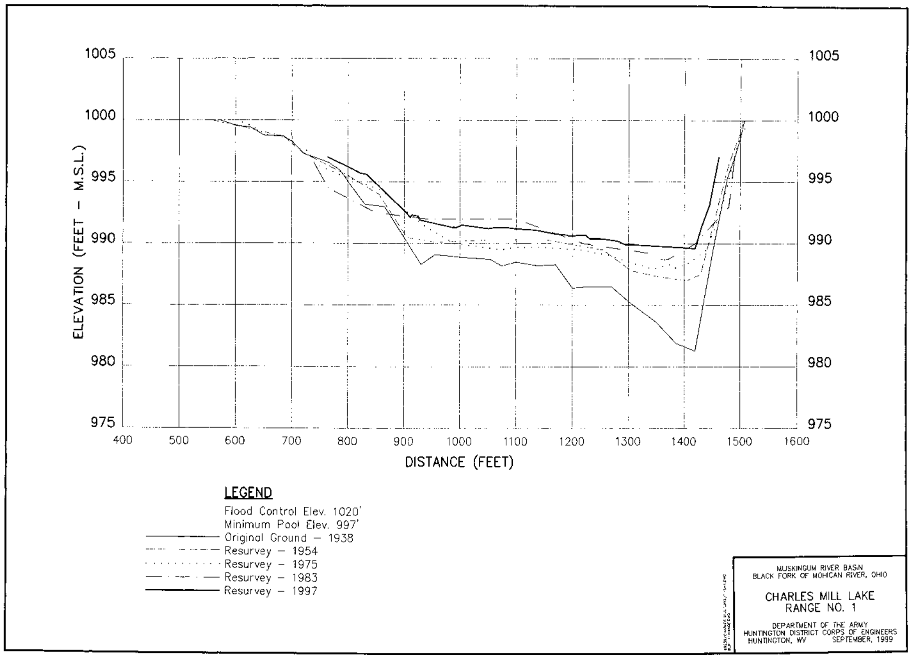


**Figure 3.**

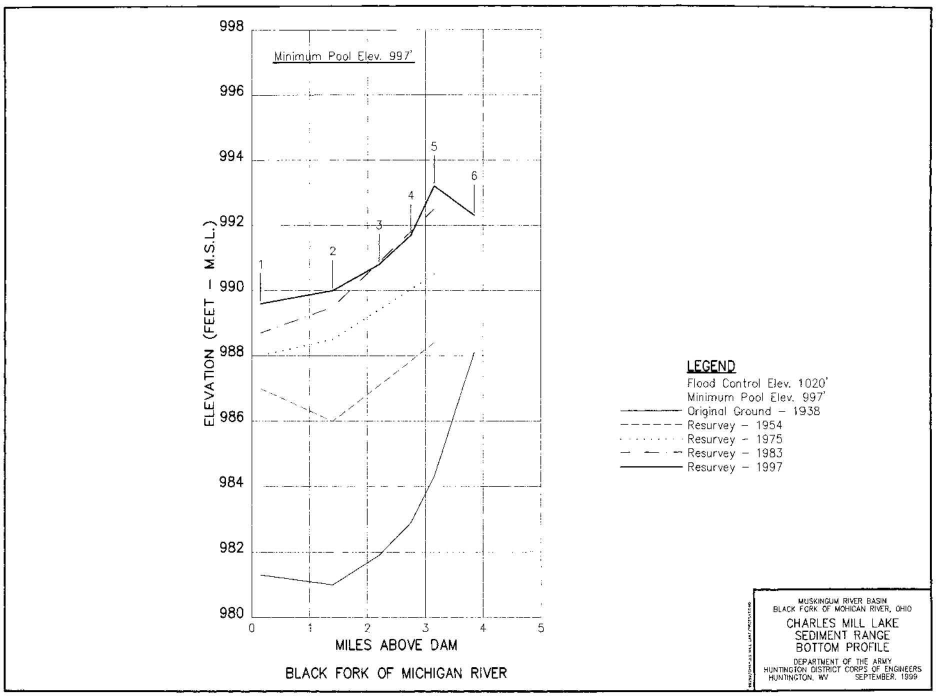


**Table 1.**

| LAKE | LAKE AREA INVESTIGATED | PERIOD | SEDIMENT RATE (AF/SQ.MI)YR | PERIOD | SEDIMENT RATE (AF/SQ.MI)YR |
|---|---|---|---|---|---|
| DEWEY | FLOOD CONTROL | 1953 - 1973 | 0.28 | 1953 - 1973 | 0.28 |
| | FLOOD CONTROL | 1973 -1975 | 0.75 | 1953 - 1975 | 0.32 |
| | FLOOD CONTROL | 1975 - 1978 | 0.82 | 1953 - 1978 | 0.37 |
| | FLOOD CONTROL | 1978 - 1984 | 0.53 | 1953 - 1984 | 0.40 |
| | SEASONAL | 1953 - 1973 | 0.23 | 1953 - 1973 | 0.23 |
| | SEASONAL | 1973 - 1975 | 0.38 | 1953 - 1975 | 0.24 |
| | SEASONAL | 1975 - 1978 | 0.63 | 1953 - 1978 | 0.28 |
| | SEASONAL | 1978 - 1984 | 0.27 | 1953 - 1984 | 0.28 |
| | SEASONAL | 1984 - 1994 | 0.74 | 1953 - 1994 | 0.36 |
| | SEASONAL | 1984 - 1997 | 0.40 | 1953 - 1997 | 0.32 |
| | | | | | |
| FISHTRAP | SEASONAL | 1968 - 1972 | 2.60 | 1968 - 1972 | 2.60 |
| | SEASONAL | 1972 - 1974 | 2.22 | 1968 - 1974 | 2.46 |
| | SEASONAL | 1974 - 1975 | 1.19 | 1968 - 1975 | 2.16 |
| | SEASONAL | 1975 - 1978 | 2.52 | 1968 - 1978 | 2.27 |
| | SEASONAL | 1978 - 1984 | 0.60 | 1968 - 1984 | 1.65 |
| | SEASONAL | 1984 - 1993 | 0.96 | 1968 - 1993 | 1.39 |
| | SEASONAL | 1993 - 1997 | 0.27 | 1968 - 1997 | 1.03 |

## CURRENT APPROACH USED IN RSIP

**Survey Procedure:** Due to the escalating costs of performing traditional sediment range surveys and improvements in the accuracy of GPS surveys, the District, in 1997, implemented the use of total-bed-profile hydrographic surveys based upon GPS. In addition to being less costly, the procedure is easier, less time consuming, and less personnel demanding. To perform the surveys, the District uses a Raytheon Fathometer in conjunction with a Trimble GPS system. HYPAC navigation software is used to keep the workboat on predetermined survey transects. Figures 4 and 5 provide photos of the equipment set-up aboard the District's workboat. While Figures 6 and 7 provide photos of the fathometer and GPS unit, respectively.

Figure 4.

Figure 5.

**Figure 6.**

**Figure 7.**

As shown in Table 2, the District has completed seven total bed surveys with five reports completed since 1997.

**Table 2.**

| LAKE | TOTAL BED SURVEY | |
|---|---|---|
| | | |
| | Field | Report |
| | | |
| Fishtrap | May-1997 | Sep-2000 |
| Dewey | Apr-1997 | Sep-2000 |
| Dillon | Sep-1997 | |
| Charles Mill | Sep-1997 | Sep-2000 |
| East Lynn | Apr-1997 | |
| R.D. Bailey | May-2000 | Sep-2000 |
| Bluestone | Jun-2000 | Sep-2000 |

<u>**Computational Procedure:**</u> Output from the GPS surveys can be used in conjunction with GIS products to determine sediment volume. Using ArcView and ARC/INFO, TIN files are developed for original conditions (prior to lake filling) and resurveyed conditions. To generate TIN files for the original conditions, topographic mapping of pre-reservoir conditions are digitized. For the resurveyed conditions, the x,y,z data from the GPS survey is converted to ground elevations by subtracting the depth component from the pool elevation of the lake at the time of the survey. Once the TIN files are developed, the VOLUME command found in

ARC/INFO is used to compute the volume for the original conditions and for the resurveyed conditions. The sediment volume is equal to the difference between these volumes. These results can be used to determine critical areas of sediment deposition in the lake that may adversely impact project purposes. Based upon this determination, future operation and maintenance decisions can be made.

**Results from Current Approach:** One of the most significant improvements by the use of the current approach to the RSIP involves the visualization of the results. Figures 8 – 11 provide examples of the visualization capabilities using the GIS products. Figure 8 shows an example of land-use determination using ArcView. Figures 9 and 10 provide examples of Shp files for pre-reservoir conditions and for the resurveyed condition with the survey transects shown, respectively. An example of visualization of deposition amounts is shown on Figure 11.

**Figure 8.**

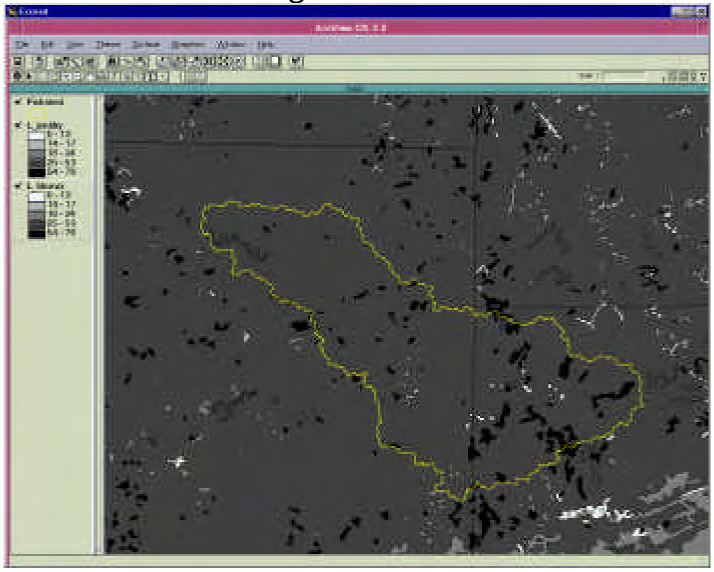


**Figure 9.**

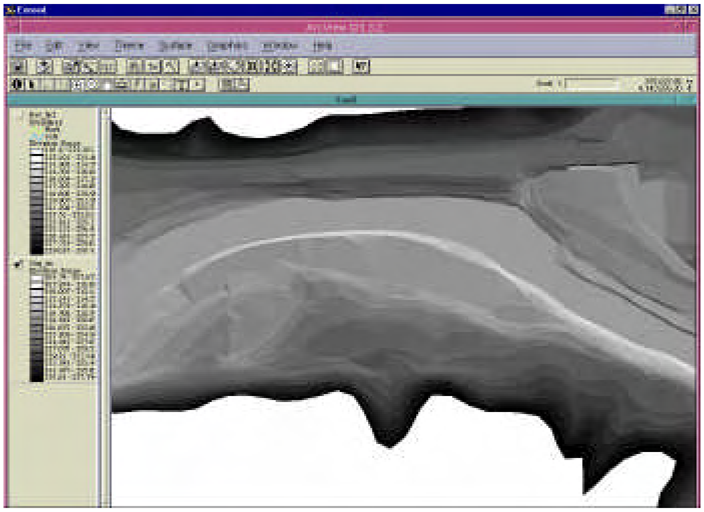


**Figure 10.**

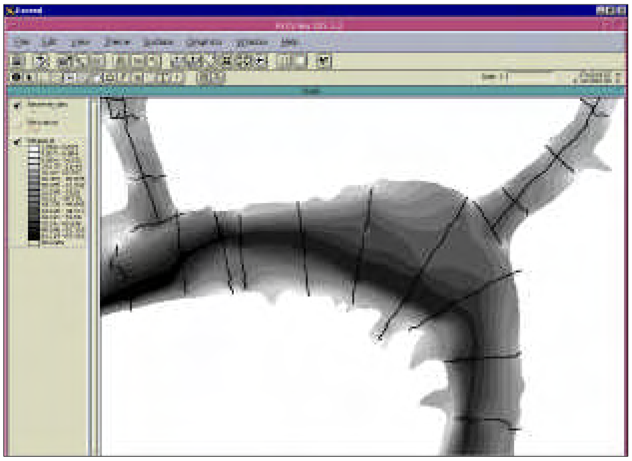
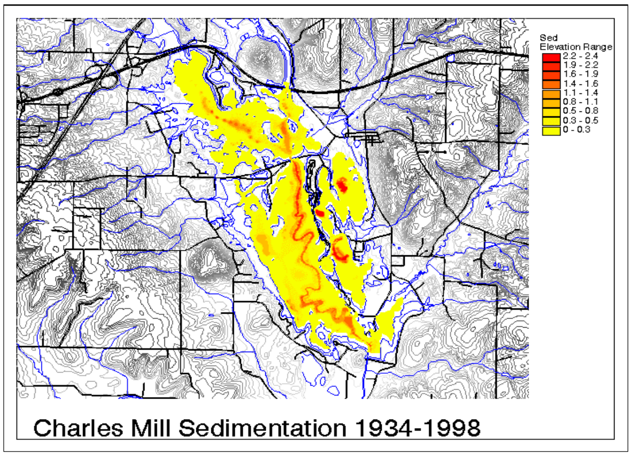


**Figure 11.**



## COMPARISON OF RESULTS USING TRADITIONAL AND CURRENT RSIP

One of the critical questions to the change in RSIP techniques was how would the results from the two techniques compare. Tables 3 and 4 provide comparisons of results from the use of end area computations and total-bed contour computations. Both computation procedures use the survey data obtained from the use of GPS. However, for the end area computations, transects corresponding with the location of the orginal sediment ranges were used. As shown in the two tables the results using the two computation procedures are very similar. These results add validity to the use of the new RSIP procedure.

**Table 3. – Fishtrap Lake, Kentucky**

| **Item** | **Total Bed Method** | **End Area Method** |
|---|---|---|
| | | |
| Original Lake Capacity | 37,950 ac-ft | 37,478 ac-ft |
| Resurveyed Lake Capacity | 26,759 ac-ft | 26,090 ac-ft |
| Total Sediment Volume | 11,192 ac-ft | 11,388 ac-ft |
| Rate of Sedimentation | 391 ac-ft/yr | 398 ac-ft/yr |

**Table 4. – Dewey Lake, Kentucky**

| **Item** | **Total Bed Method** | **End Area Method** |
|---|---|---|
| | | |
| Original Lake Capacity | 16,987 ac-ft | 17,233 ac-ft |
| Resurveyed Lake Capacity | 15,111 ac-ft | 14,423 ac-ft |
| Total Sediment Volume | 1,876 ac-ft | 2,810 ac-ft |
| Rate of Sedimentation | 42.4 ac-ft/yr | 63.5 ac-ft/yr |

## CONCLUSION

Due to rising cost of implementation of a traditional RSIP, the Huntington District has instituted a new procedure. This new procedure uses GPS for hydrographic survey and GIS to complete the analysis of the sediment survey and to develop the visualization of the results. When comparing cost, the traditional method cost approximately $40,000 for the survey and $20,000 to complete the report. Using the new procudure, the survey costs have been reduced to approximately $10,000. However, the report costs have increased to approximately $30,000 per report. Even with this increase in report costs, the total cost for the RSIP has been reduced by approximately 33% and as shown in Tables 3 and 4, the results are very comparable. One modification to the current RSIP will be made for the next survey. To-date, the surveys have been taken on preestablished transects. In future surveys, the path of the workboat will be more random. This will allow for a better development of the TIN files.

# RESIS-II: MAKING THE RESERVOIR SURVEY INFORMATION SYSTEM COMPLETE AND USER FRIENDLY

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## EXTENDED ABSTRACT

Here we report on work to update the Reservoir Information System (RESIS) database, referred to here as RESIS-II.

Several decades ago, the member agencies forming the Interagency Subcommittee on Sedimentation of the Interagency Advisory Committee on Water Data recognized the importance of maintaining a database of sediment deposition in U.S. reservoirs. The database consisted of data sheets that summarized reservoir sedimentation survey data and occasional summary reports. As such, it became the premiere database in the world for evaluating long-term sedimentation in reservoirs and long-term erosion in watersheds. Dendy et al. (1973) and Dendy and Bolton (1976) summarized the database through 1973. By relating reservoir properties to sedimentation rates, these papers have provided a guide for estimating reservoir sedimentation world wide. Renwick (1996) summarized the database though 1975, focusing on sediment yields as related to the properties of the contributing watersheds.

In 1996, Steffen (1996) introduced RESIS, a computer-based version of the database using INFORMIX software. Currently the database has 5,967 surveys for 1,819 reservoirs across the conterminous U.S.. Although digital, this version of the database was not available for desktop systems. It had not been error checked, and it was not linked to other databases such as the National Inventory of Dams (NID) or to a Geographic Information System (GIS). Linking to a GIS, in particular, would provide a powerful tool for assessing how watershed properties relate to reservoir sedimentation. Finally, RESIS did not have an easy procedure for adding new data, and few data have been added to RESIS since 1975. This is especially significant in light of substantial trends toward use of techniques involving less erosion in agriculture, forestry, and grazing, during the last 30 years. The impact of land-use and conservation-practice changes should be evaluated to fully assess the health of the nation's water supply system.

The Mississippi Basin Carbon Project, MBCP, chose to use the RESIS database as one means for evaluating sediment and carbon storage within the Mississippi River Basin. As part of this effort, RESIS was transferred to a desk-top computer environment using standard database programs (Paradox and Access). In addition to using the original version of RESIS data as the core of the new database, RESIS-II, links are being made to (1) the NID, (2) to scanned versions of the original primary data sheets, and (3) to a GIS polygon coverage of reservoir boundaries. This last feature will, in turn, allow unlimited linkage to all forms of mapped data. To assess quality of the data, a dynamic QA/QC parameter has been added to the database, whereby the accuracy of dam location and reservoir survey data are linked into a quality ranking. Finally, a front end is being designed that matches the format of the field data sheets so that additional data may be added.

A major impediment to completing RESIS-II has been the inaccuracy of the location of every dam in the database. Without an appropriate location, the watershed cannot be delimited in a GIS. Many dams are located in Township/Range/Section coordinates by specifying the nearest post office. Reservoirs were often named after the owners who have long since changed along with the name. After trying several methods for locating dams, we chose an inverse approach. We look for all points in the GIS that are near the location indicated and which have the drainage area and elevation specified in the database and which are on a stream channel. This may not exactly match the dam site because of the effects of the interaction of grid size in the digital elevation model with the algorithm for calculating contributing area. Presently, we have adequate locations for 1,327 reservoirs (Figure 1). Another 472 reservoirs have been located to within 20 km, and 20 reservoirs have no reliable coordinates.

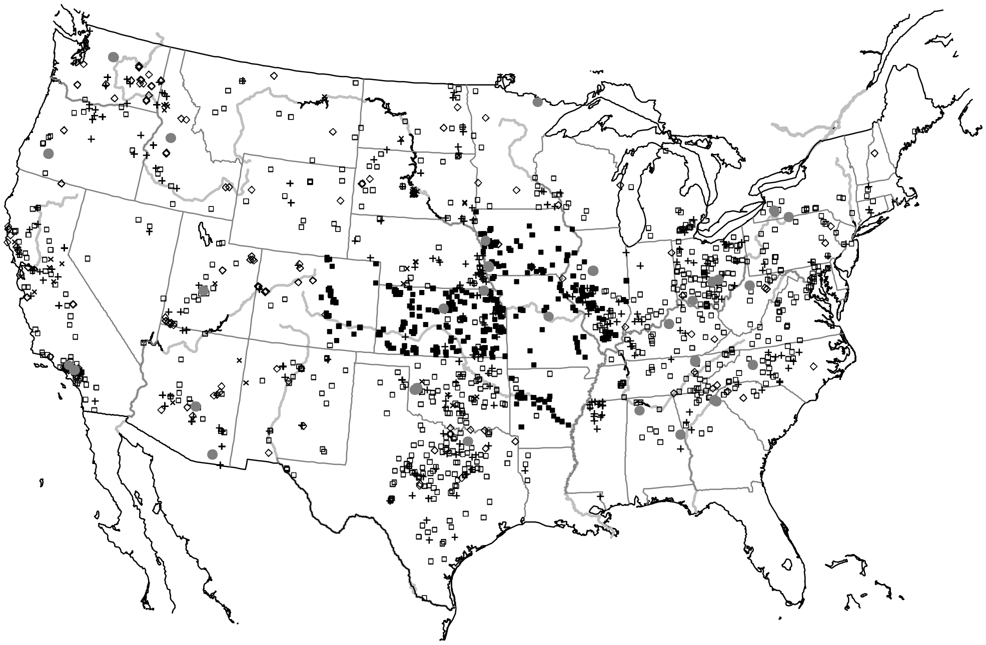

**Figure 1.** Map of the reservoirs from the RESIS-II database. Black symbols indicate location data quality: solid square - fully geolocated; open square - from the National inventory of Dams; open diamond - from RESIS; cross - township, section, range; plus - nearest post office. The grey circles represent the 50 reservoirs used to test the capabilities of watershed characterization using a GIS.

The MBCP plans to use RESIS-II to model carbon burial in reservoirs (Stallard, 1998, Sundquist, et al. 1998). Accordingly, the efficacy of the use of a GIS to study reservoir sedimentation was examined using a small subset of 50, well located reservoirs. GIS data selected for use in the MBCP (Sundquist, et al. 1998) were related to reservoir sedimentation. For each reservoir, area, relief, mean slope, mean topographic curvature, mean topographic index [ln(Area/tan(β))], mean rainfall, soil-organic-matter-content, fraction of agricultural land, RUSLE R factor [runoff factor], and RUSLE K factor [soil erodibility] were estimated and step-wise regressions were used to identify "controlling" factors influencing sedimentation rates. Of these, the K factor had the dominant influence.

Maintenance of a current and accurate reservoir sedimentation database is essential to many societal and managerial issues. Loss of reservoir storage affects water supplies in times of shortage and excess. Pressure is building to remove many dams. The quantity and quality of stored sediment can affect these decisions. RESIS-II, with its links to GIS, will provide a means of linking land-use history and associated chemical loadings to the sedimentation history of reservoirs. RESIS reservoirs can serve as metaphors for other reservoirs in a region. Reservoirs are also major carbon sinks. Accurate sedimentation models are needed to fully assess the importance of this carbon sink.

Remaining work on the database includes (1) completion of geolocation and watershed delimitation, (2) linkage of original data sheets to electronic records [all sheets have been scanned], and (3) completion of a suitable front end for data entry and data correction.

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# DIFFERENCES IN LAKE AND RESERVOIR SEDIMENTATION – IMPLICATIONS FOR SEDIMENT CORING STUDIES

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**Abstract:** Major differences between natural lakes and reservoirs that affect the sampling and interpretation of sediment cores for the reconstruction of water-quality trends include geometry, drainage area to surface area ratios, sedimentation rates, and sedimentation patterns. Reservoirs generally have larger drainage area to surface area ratios and higher sedimentation rates than lakes, and sedimentation in reservoirs is typically greatest in the pre-reservoir stream channel and varies longitudinally along the axis of the reservoir. The presence of a pre-reservoir boundary in cores can aid in sampling and provides a reliable date-depth marker in cores. These factors affect sampling-site selection and sub-sampling of cores from reservoirs.

Particle-associated contaminants in many reservoirs are dominantly from fluvial inputs and not atmospheric fallout on the water surface. Fluvial dominance means that concentrations of contaminants within a reservoir are generally independent of sedimentation rate and that contaminant mass accumulations correlate positively to sedimentation rates. The positive relation to sedimentation rates and the highly variable sedimentation patterns in reservoirs indicate that comparisons of contaminant mass accumulations among reservoirs based on cores should be approached with caution unless whole-lake sedimentation is accounted for. The relatively high sedimentation rates in reservoirs minimize diagenesis and improve temporal resolution in sediment cores. Fluvial dominance of contaminant inputs and minimal diagenesis suggest that reservoir cores are good indicators of stream-sediment quality in the influent streams over time.

## INTRODUCTION

The use of age-dated sediment cores to describe water-quality trends has a long history (Davis, 1990). Numerous studies describing trends in anthropogenic contaminants in sediment cores from natural lakes have appeared in the literature (LaFlamme and Hites, 1978; Heit and others, 1981; Eisenreich and others, 1989; Swain and others, 1992). Much less common are studies using sediment cores from manmade river impoundments, or reservoirs (Callender and Robbins, 1993; Van Metre and Callender, 1997). This paper explores some of the more important differences between sedimentation in natural lakes and reservoirs and discusses their implications for coring studies in reservoirs. The paper is based mostly on the results of a national study of trends in particle-associated contaminants in U.S. surface waters conducted by the U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Program (Callender and Van Metre, 1994). During 1992–99, 40 reservoirs, 9 lakes, and 1 estuary were sampled (fig. 1) to evaluate trends in metals (Callender and Van Metre, 1997; Callender and Rice, 2000), organochlorine compounds (Van Metre and others, 1997; Van Metre and others, 1998), and polycyclic aromatic hydrocarbons (PAHs) (Van Metre and

Figure 1. Reservoirs, lakes, and estuaries sampled during 1992–99 for the USGS National Water-Quality Assessment Program (multiple lakes sampled where noted.

others, 2000).

## RESERVOIR PALEOLIMNOLOGY

The major differences between natural lakes and reservoirs (Thornton, 1990) can significantly affect the collection and interpretation of cores from these two types of water bodies. Of particular importance are differences in the geometry, nature of influent streams, drainage area to surface area (da:sa) ratios, sedimentation rates, and sedimentation patterns. Reservoirs are usually elongated in shape and have from one to only a few dominant influent streams, whereas lakes are usually more rounded in shape and often have numerous lower-order influent streams. The drainage areas of reservoirs are much larger relative to their surface areas than are the drainage areas of natural lakes (Marzolf, 1990). Many lakes are located in areas of low relief and high precipitation (the upper midwest and Florida), whereas many reservoirs are located in areas of higher relief, lower precipitation, and with higher suspended-sediment concentrations in streams (Thornton, 1990). All of these factors contribute to relatively higher sedimentation rates in reservoirs than in lakes.

Eight reservoirs and three lakes sampled by the NAWQA program exhibit a wide range of da:sa ratios and sedimentation rates (table 1; Wilson and Van Metre, 1999; Van Metre and others, 2000). The reservoirs have da:sa ratios ranging from 15 to more than 5,000 and sedimentation rates at the coring locations ranging from 0.11 to 2.74 g/cm$^2$-yr compared with ranges of about 5 to 500 and 0.07 to 0.41 g/cm$^2$-yr, respectively, in the lakes. The correlation coefficient between da:sa ratio and sedimentation rate among these lakes and reservoirs is 0.9. The reservoirs with low sedimentation rates are located in areas of relatively low relief and high precipitation, such as New York, New Jersey, and Virginia. The reservoirs with the highest sedimentation rates are located in New Mexico and Texas. Not coincidentally, streams with much higher suspended-sediment concentrations are located in the southwestern rather than in the northeastern U.S. (Thornton, 1990).

Table 1. Characteristics of selected lakes and reservoirs and sediment cores.

| | Drainage area (km$^2$) | Surface area (km$^2$) | da:sa ratio | Time span represented by sediment core | Lacustrine sediment thickness (cm)[1] | Linear sedimentation rate (cm/yr) | Mass sedimentation rate (g/cm$^2$-yr) |
|---|---|---|---|---|---|---|---|
| LAKES | | | | | | | |
| Lake Ballinger, WA | 13.7 | 0.4 | 34 | 1947–98 | 23 | 0.45 | 0.11 |
| Lake Harriet, MN | 6.1 | 1.2 | 5.1 | ~1770–1997 | 84 | .37 | .07 |
| Palmer Lake, MN | 64.9 | .13 | 500 | 1949–97 | 38 | .78 | .41 |
| RESERVOIRS | | | | | | | |
| Lake Anne, VA | 2.3 | .13 | 18 | 1968–96 | 17 | .6 | .18 |
| Cochiti Lake, NM | 31,600 | 6 | 5,300 | 1975–96 | 138 | 6.6 | 2.74 |
| Lake Fairfax, VA | 8.4 | .11 | 76 | 1952–97 | 52 | 1.2 | .86 |
| Newbridge Pond, NY | 7.9 | .042 | 190 | 1952–97 | 54 | 1.2 | .32 |
| Orange Reservoir, NJ | 11.7 | .35 | 33 | 1949–97 | 32 | .67 | .24 |
| Lake Packanack, NJ | 4.8 | .33 | 15 | 1932–97 | 42 | .64 | .11 |
| Town Lake, TX | 4,041 | .73 | 5,500 | 1959–98 | 110 | 2.8 | 1.95 |
| White Rock Lake, TX | 264 | 4.4 | 60 | 1913–96 | 105 | 1.3 | 1.13 |

[1] For lakes, value is the length of the core.

These differences lead to several generalities in describing sediment deposition in reservoirs versus lakes. The dominance of one or two influent streams and elongated shape lead to longitudinal gradients in sedimentation rates and grain-size distributions in reservoirs. The presence of a pre-reservoir stream channel and, oftentimes, more pronounced lake-bottom topography in reservoirs leads to large variations in sedimentation rates with the greatest sedimentation typically in the pre-reservoir stream channel. For example, a sediment core collected at a water depth of 17.7 m in the pre-reservoir stream channel of Lake Livingston on the Trinity River in East Texas encountered 138 cm of lacustrine sediment above the pre-reservoir land surface, indicating an average sedimentation rate of about 6 cm/yr. In contrast, several cores collected away from the channel in 3 to 6 m deep water in the same part of the reservoir had lacustrine sediments of about 10 cm or less in thickness (Van Metre and Callender, 1996). Lake Livingston also exhibits longitudinal variation in sedimentation. The 138-cm core was collected from approximately the middle of the 40-km long reservoir. A core from about three-quarters of the way down the reservoir had 90 cm of lacustrine sediment, and a core from near the dam had 52 cm of sediment. These patterns are typical of many of the reservoirs sampled by the USGS: much greater sedimentation in the pre-reservoir channel and decreasing sediment thickness in the down-reservoir direction. Natural lakes, with generally smoother bottoms and more distributed sediment inputs, typically have more evenly distributed sedimentation.

**Sampling:** The coring tools used by the USGS NAWQA program include gravity and piston corers that can collect cylindrical 6-cm diameter cores from a few tens of cm to about 4 m in length and box corers that are 14-cm square and from 20 to 100 cm in length. The gravity and piston corers have the advantage of collecting longer cores but the disadvantages, relative to the box corers, of more disturbance in the core and a smaller volume of sediment for a given length of core.

During most of the studies conducted for the NAWQA program, the primary objective of reservoir paleolimnology was to describe trends in hydrophobic organic compounds and trace elements over a several-decade or more time span. Within-reservoir spatial variability in sediment chemistry, a factor in site selection, was not usually an objective; thus, only one location was sampled in many reservoirs and lakes. Site selection varied somewhat depending on the lake or reservoir size, sedimentation rate, and geometry. Selecting a sampling site in a typical reservoir is a balance between three competing objectives. These objectives, and a brief rationale for each, are:

1. Obtain as thick a sequence of lacustrine sediments as possible. Higher sedimentation rates and thicker sediments improve the temporal resolution of sampling and reduce the effects of post-depositional mixing and diagenesis on obscuring trends.

2. Penetrate to the pre-reservoir land surface to assure the longest temporal record possible and provide a reliable date marker at the bottom of the core.

3. Sample undisturbed, relatively homogeneous fine-grained sediments. To obtain a sample adequate to describe long-term trends, the sediments cored must not be disturbed by near-shore wave action, periodic exposure during low water periods, dredging, or episodic erosion by floods. The tendency of trace elements and organic carbon to positively correlate to finer grain-size particles (Horowitz and Elrick, 1987) results in higher concentrations and higher frequencies of detection in fine-grained sediments. The sorting action of a reservoir leads to generally very homogeneous, fine-grained sediments in the middle and lower parts of the reservoirs and improves the confidence in the interpretation of trends in a core by reducing “natural” variability among sub-samples of the core.

Sediments in reservoirs are deposited preferentially in the pre-reservoir stream channel. Deposits are generally thickest in the upper part of the reservoir where a delta forms. Sedimentation surveys in Cochiti Lake on the Rio Grande provide a good example. The lake was formed in 1975 and, like other reservoirs in the southwestern U.S., has very high sedimentation rates. By 1996, sediments in the pre-reservoir channel of the Rio Grande formed a very thick delta, as much as 20 m, resulting in a linear sedimentation rate of about 1 m/yr. There is a “delta front” with a relatively steep face about 8 km downstream from the original upper end of the lake. Downstream from the delta front, the sediments in the channel gradually thin to about 3 m near the dam. Several gravity cores were collected for the USGS studies at a site just off the main channel of the Rio Grande near the dam to obtain samples over the entire sequence of lacustrine sediments. The thickness of lacustrine sediments in the cores ranged from 120 to 156 cm (Wilson and Van Metre, 1999).

Where sedimentation rates are low and the thickness of lacustrine sediments is about 50 cm or less, box corers are preferred for sampling. The box cores are less disturbed than the gravity and piston cores because they have a larger cross-sectional area, are lowered gently into the bottom, and have jaws that close below the sample to hold it in place. They collect a much larger volume of sediment: a 1-cm slice from a box core is 196 $cm^3$ versus 31 $cm^3$ for the gravity and piston cores. This means sampling can be done on a small vertical interval, and sufficient material can be obtained to perform all the laboratory analytical tests on a single core. This improves temporal discretization and removes the uncertainty of correlating age dates or other information between cores if multiple gravity or piston cores are used to obtain enough material for sampling on the smaller interval.

In relatively low-sedimentation-rate reservoirs, typical depositional patterns require that samples be collected in the pre-reservoir channel and in the middle or upper part of the reservoir. In Tolt Reservoir, a forested reference site in the Cascade Mountains east of Seattle, Washington, for example, there was almost no lacustrine sediment at a site about one-third of the way up reservoir from the dam. The core obtained for chemical analysis was collected from the pre-reservoir channel about two-thirds of the way up reservoir from the dam and had 16 cm of lacustrine sediment.

**Age Dating:** One of the more distinctive differences between reservoirs and lakes is the pre-reservoir soil boundary underlying the lacustrine sediments in a reservoir. This boundary, in most reservoirs, provides a very reliable depth-date marker in cores: a time marker designating the beginning of accumulation of sediments in the reservoir that can be matched up with the date when the reservoir was filled. Furthermore, it can usually be easily distinguished in the field during sampling, providing very useful information to guide sampling site selection and sub-sampling of cores.

In addition to the pre-reservoir surface and the top of the core (matched with the sampling date), the most common approach for age dating recent (about 100 years or less) reservoir sediments is to measure $^{137}$Cs in the core samples. $^{137}$Cs is a radionuclide released to the global environment by atmospheric testing of nuclear weapons. $^{137}$Cs is useful in reservoir and lake cores primarily for identifying two dates: about 1952, when atmospheric testing reached detectable levels in global fallout, and 1963–64, when atmospheric testing and $^{137}$Cs levels peaked (Van Metre and others, 1997). In addition to these two age-depth markers, $^{137}$Cs can be useful for evaluating the relative amount of post-depositional mixing of sediments, the amount of sediment focusing at a coring site (Van Metre and others, 1997), and the rates of change in particle-associated contaminants in streams and lakes (Van Metre and others, 1998).

In some cases, other chemical signals in reservoir and lake cores can be used to determine age-depth relations or to verify age-depth relations determined from $^{137}$Cs and core lithology. These chemical signals include sharp peaks in lead in the mid-1970s (Callender and Van Metre, 1997; Van Metre and others, 2000), initial occurrence of organochlorine pesticides in the early 1940s, and peaks in DDT in the early 1960s (Van Metre and others, 2000).

**Interpretation of Chemical Concentration and Mass Accumulation:** The sedimentation patterns described above can have important implications on interpretations of sediment chemistry data from reservoir cores. Large da:sa ratios and high sedimentation rates, either on a whole reservoir/lake basis or at individual coring sites, can reduce the relative importance of atmospheric fallout signals on lake-sediment chemistry and increase the relative importance of fluvial input signals. Thus, the sediment chemistry of many reservoirs (Van Metre and others, 1997) and urban lakes (Van Metre and others, 2000) is dominated by fluvial inputs of contaminants. This fluvial dominance extends to some contaminants that have atmospheric pathways, including lead and PAHs, but, nevertheless, are primarily delivered to reservoirs and lakes attached to fluvial sediment particles. For example, PAH concentrations and accumulation rates in a core from Palmer Lake in Minneapolis, Minn., increased by a factor of 80 from the 1960s, when the watershed was mostly undeveloped, to 1997, when the watershed was about 50-percent urban (Van Metre and others, 2000). On the basis of the core data, the atmospheric deposition in greater Minneapolis had only a minimal effect on sediment quality prior to the onset of development of the watershed. The coincidence of increasing PAH trends and urbanization of the reservoir watershed is repeated in many urban reservoirs and lakes in the U.S. (Van Metre and others, 2000). These trends indicate that PAHs in these urban lakes and reservoirs are dominantly from fluvial inputs from the watersheds, and not from atmospheric fallout on the lake surface. A similar conclusion was reached for DDT and PCBs. Accumulation rates of DDT and PCBs in six reservoirs far exceeded estimated atmospheric fallout, leaving watershed sources and fluvial inputs as the only reasonable transport pathway (Van Metre and others, 1997).

When fluvial inputs of contaminants dominate sediment cores, chemical concentrations for comparable time intervals in cores with different sedimentation rates in the same lake are similar. The contaminants mostly enter the lake or reservoir attached to fluvial particles, are deposited, and then buried before significant enrichment from atmospheric fallout can occur. In lakes where this is the case, contaminant mass accumulation rates (MARs) correlate positively with sedimentation rates. This effect can be demonstrated using three cores collected in Lake Livingston on the Trinity River in East Texas (Van Metre and Callender, 1996). All three sites in the 40-km long reservoir were in the pre-reservoir channel. Lacustrine sediment thickness in three cores varied from 52 cm near the dam, to 90 cm about one-fourth of the way up the reservoir, to 138 cm halfway up the reservoir. Similar concentrations and temporal trends of DDE and lead occur in all three cores (Van Metre and Callender, 1996) and consequently contaminant MARs were approximately three times greater at the mid-lake site than at the near-dam site. The similarity of concentrations independent of sedimentation rates indicates sediments are not being significantly enriched by atmospheric fallout after deposition and that they, therefore, probably reflect input concentrations of fluvial sediments.

Because of general fluvial dominance and the large variability in sedimentation rates within any reservoir, comparison of contaminant MARs among reservoirs and lakes should be approached with caution. One approach that can allow comparison of MARs among reservoirs is to use sedimentation surveys and(or) numerous cores to estimate average sedimentation rates for the whole lake. These rates can then be used to calculate contaminant MARs by multiplying by concentrations in cores (Mau and Christensen, 2000). The main assumption is that core concentrations are representative of "average" concentrations for the lake. This assumption is probably reasonable for lakes/reservoirs dominated by fluvial inputs of contaminants or where multiple cores are analyzed for chemistry. The limitations of interpretations of either concentrations or contaminant MARs alone are illustrated using White Rock Lake (TX) and Lake Anne (VA).

The average total PAH concentration (excluding perylene) in four core samples deposited in the 1990s in White Rock Lake was 2,980 µg/kg compared with an average 1990s concentration of 20,000 µg/kg in Lake Anne. The watersheds of both lakes are mostly urbanized and, in the case of White Rock Lake, include major interstate highways and large commercial areas. Why then are PAH concentrations so much lower there than in Lake Anne? The answer lies in the comparison of concentrations to mass accumulations.

Multiplying PAH concentrations by sedimentation rates for each core yields a total PAH accumulation rate of 3.4 µg/cm$^2$-yr for White Rock Lake versus 3.6 µg/cm$^2$-yr for Lake Anne, indicating that while PAH concentrations in sediment were about seven times greater in the Lake Anne core, PAH MARs are about equal to those for White Rock Lake. This comparison can be taken one step further to account for the large variability in sedimentation rates within each lake. Using sedimentation surveys and sediment chemistry from the White Rock Lake core, the yield of PAH from the watershed that is being deposited in the lake in recent years is estimated as about 75 ng/cm$^2$-yr. No sedimentation surveys have been conducted on Lake Anne, however, the lake has a relatively flat bottom, probably leading to more uniform sedimentation than in some reservoirs. Five box cores collected in 1996 from near the dam to the upper end of the lake, at water depths from 2 to 8 m, had sediment thicknesses ranging from 14 to 20 cm. Average sedimentation rate in the lake was estimated using these cores. Multiplying this sedimentation rate by PAH concentrations in the core, then dividing by watershed area results in a PAH yield from the watershed of 25 ng/cm$^2$-yr, about one-third the estimated yield from White Rock Lake watershed. Obviously, there is a large amount of uncertainty in these estimates; however, it is clear that the much higher PAH concentrations in bottom sediments in Lake Anne do not mean that contaminant loading there is proportionally that much greater than in White Rock Lake. The higher sedimentation rate in White Rock Lake correlates to higher suspended-sediment concentrations in streams (Thornton, 1990) and is indicative of higher erosion rates and dilution of contaminated sediments washing off streets and rooftops by less-contaminated soils.

**Relations Between Reservoir Cores and Streams:** Relatively rapid sedimentation rates in reservoirs have been shown to contribute to minimal diagenesis (Callender, 2000). Minimal diagenesis and the fluvial dominance of contaminant sources to reservoir sediments indicate that chemical signatures of the fluvial sediments are relatively well preserved in the sediment cores. Reservoir cores should, therefore, be good indicators of stream-sediment quality over time. It is not being suggested that the concentrations of contaminants in influent streams can be reliably estimated using sediment cores, but rather that the accumulated lake sediment is indicative of sediment quality in the streams over time. In an attempt to better define the relation between reservoir sediments and stream sediments, large-volume suspended-sediment (LVSS) samples were collected from an urban stream and a rural stream in Austin, TX (Mahler and others, 2001). Both streams flow into Town Lake, formed by a dam on the Colorado River in Austin, although Barton Creek flows through urban areas near Austin, the watershed of the Barton Creek sampling site is rural. A sediment core from Town Lake showed large increasing trends in PAH, dramatic historical trends in

DDT (including a significant amount of parent DDT at the top of the core), and an increasing trend in chlordane concentrations to the top of the core (Van Metre and Mahler, 1999). The concentrations of these contaminants at the top of the core are compared to their occurrence in suspended-sediment samples from Shoal Creek, one of several urban tributaries to the lake, and samples from a reference site on Barton Creek (table 2). There is a strong relation between land use and contaminant occurrence in the suspended sediments, as indicated by the much greater concentrations in Shoal Creek compared to the rural Barton Creek. There is generally a good relation between the occurrence of anthropogenic contaminants in the urban stream (Shoal) and the top of the reservoir core, supporting the hypothesis that the chemistry of reservoir cores is indicative of influent stream quality.

Table 2. Comparison of LVSS chemistry and a sediment core in receiving water body.

(ND=non-detection, reporting levels vary)

| Chemical | Shoal Creek (urban site)[1] | | | | Barton Creek (reference site)[1] | | Town Lake Core[2] |
|---|---|---|---|---|---|---|---|
| | 3/18/99 | 4/26/99 | 10/30/99 | 3/17/00 | 5/26/99 | 6/9/00 | 1998 |
| Pesticides (µg/kg) | | | | | | | |
| Chlordane | 8.4 | 11 | 22 | 56 | ND | ND | 47 |
| p,p’-DDD | 2.6 | ND | ND | 1.3 | ND | ND | 8.2 |
| p,p’-DDE | 6.5 | 7.6 | 3.0 | 9.3 | ND | ND | 31 |
| p,p’-DDT | 4.2 | 5.2 | 2.4 | 19 | ND | ND | 2.4 |
| Dieldrin | 1.1 | 3.2 | 1.2 | 3.5 | ND | ND | <1 |
| PAHs (µg/kg) | | | | | | | |
| Total PAH | 21,200 | 15,200 | 9,820 | 19,200 | 725 | 96 | 11,400 |
| Dibenzo (a,h) anthracene | 195 | 115 | 86 | 187 | 12 | 2 | 150 |
| Benzo(a)-pyrene | 896 | 647 | 429 | 975 | 42 | 3 | 582 |
| Metals (µg/g) | | | | | | | |
| Copper | 25 | 29 | 25 | 30 | 21 | 13 | 33 |
| Lead | 41 | 47 | 40 | 38 | 39 | 16 | 54 |
| Zinc | 183 | 182 | 163 | 211 | 141 | 58 | 112 |

[1] Storm-event composite samples of suspended sediments.

[2] Top (0 to 5 cm interval) of sediment core from Town Lake (Van Metre and Mahler, 1999).

## SUMMARY

Differences in geometry, drainage area to surface area ratios, sedimentation rates, and sedimentation patterns between reservoirs and lakes affect the sampling and interpretation of sediment cores for the reconstruction of water-quality trends. Reservoirs typically have much larger da:sa ratios than lakes, which correlate positively to sedimentation rates. Although reservoirs tend to have much larger sedimentation rates than lakes, rates vary greatly across the U.S. in relation to variability in stream suspended-sediment concentrations. Reservoirs in southwestern parts of the U.S. have the largest sedimentation rates whereas reservoirs in the northeastern U.S. have low rates approaching those of some natural lakes. Sedimentation in reservoirs is typically greatest in the pre-reservoir stream channel and varies longitudinally along the axis of the reservoir. The large range in sedimentation rates and the amount of variability within reservoirs necessitate the use of several different coring tools and sampling strategies, depending on the sedimentation rate and geometry of the reservoir.

Age-dating sediment cores from reservoirs benefits from the presence of a recognizable pre-reservoir soil boundary in cores that can be matched with the date the reservoir filled. The pre-reservoir boundary can also be useful during sampling to help select sampling sites and design sub-sampling of the core. Additional age-depth information can be obtained using $^{137}$Cs and, in some cases, first occurrence and peak concentrations of total DDT and peak concentrations of lead.

In most reservoirs and many lakes, particularly in urban areas, the majority of contaminants in bottom sediments are transported to the reservoir or lake attached to particles in the influent streams and are not delivered by direct atmospheric fallout on the water surface. This is true even for contaminants with atmospheric pathways, including lead and PAHs, for which short-range atmospheric transport and fallout on soils and impervious surfaces can be intermediate transport steps. Large da:sa ratios and high sedimentation rates enhance the importance of fluvial transport of contaminants from the watershed and reduce the importance of atmospheric fallout on the lake. Because of the highly variable sedimentation patterns in reservoirs and the fluvial dominance of contaminant inputs, concentrations of contaminants in a reservoir are generally independent of sedimentation rates and contaminant MARs correlate positively to sedimentation rates. Thus, comparisons of contaminant MARs among reservoirs based on cores should be approached with caution unless whole-lake sedimentation is accounted for. The relatively high sedimentation rates in reservoirs minimize diagenesis and improve temporal resolution in sediment cores. Fluvial dominance of contaminant inputs and minimal diagenesis mean that reservoir cores should be good indicators of stream-sediment quality over time.

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# MESA VERDE PREHISTORIC RESERVOIR SEDIMENTATION

**By: Kenneth R. Wright, P.E.[1], Ernest L. Pemberton, P.E.[2], and Jack E. Smith, PhD[3]**

**Abstract**: In 1997 the authors excavated a prehistoric Mesa Verde water reservoir built and operated by Early Americans. Morefield Reservoir, located in Morefield Canyon of Mesa Verde National Park and known as 5MV1931, evolved over time from an excavated pond into an off-stream impoundment. Sediment accumulation caused the reservoir to grow into a 200-foot-diameter mound rising 16 feet above the valley floor with an elevated inlet canal. The excavation provided the opportunity to study the sediment depositional characteristics, including sedimentation rates. Analysis was made of the berm-building techniques used and problems encountered by the Early Americans, including frequent sediment removal efforts to maintain capacity of the water storage reservoir over a 350-year period.

## INTRODUCTION

In 1995, the authors selected for paleohydrological research the Morefield Canyon mound, long an enigma at Mesa Verde National Park. Working under a U.S. Department of Interior archeological permit, the authors conducted engineering and scientific studies in Morefield Canyon to determine the reason for, and function of, the mound. The mound and adjacent long berm sit on the canyon floor in a manner inconsistent with what one would expect an ancient reservoir to look. Prior to 1997, the scientific community still judged the Morefield mound to be a ceremonial mound, an erosional remnant of a Pleistocene valley terrace, or a reservoir. The May 1997 field effort included a 125-foot-long excavation across the mound to a depth of 16 feet. The research effort proved that the site was a domestic water supply reservoir likely dating from about A.D. 750 to 1100. The berm extending northward was the route of an ancient feeder canal to the reservoir. As a result of the paleohydrology study, the uncertainty related to the Morefield Reservoir was put to rest.

## SITE LOCATION

Site 5MV1931 of Mesa Verde National Park is in Morefield Canyon in the SW¼ of Section 33, Township 35 North, Range 14 West of the New Mexico Meridian. It is approximately 12.8 miles southeast of Cortez, Colorado in Montezuma County. Morefield Canyon is closed to the public to preserve its extensive, abundant and valuable ruins for future study when funds are available to permit a thorough scientific evaluation of the canyon. The canyon held a large prehistoric population. The watershed contains 4.2 square miles. The drainage basin ranges from 7,200 feet to 8,300 feet in elevation, with a mean elevation of 7,800 feet. The current land use is characterized as un-grazed rangeland.

## TOPOGRAPHY AND GEOLOGIC FRAMEWORK

Morefield Canyon is a broad valley with the side ridges rising 400 to 600 feet on each side of the nearly flat bottom that ranges from 600 feet to 1,100 feet wide. At the 5MV1931 archaeological site, the valley bottom is approximately 800 feet wide. The Morefield channel gradient slopes to the south at approximately 135 feet per mile for a slope of .025 ft/ft. Approximately 10,000 feet north of the site, a decrease in gradient coincides with the change in bedrock from Mancos shale to the Point Lookout sandstone.

The Mesa Verde plateau is formed by the sandstones of the Cretaceous Age Mesaverde Formation that are more erosion resistant than the underlying Mancos. The top of the plateau is essentially a dip slope lying on the Cliff House Sandstone of the Mesaverde group. Morefield Canyon has cut through the Cliff House Sandstone and is

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floored in the sands and shales of the Menefee Formation. No bedrock outcrops were observed along the valley bottom. No data has been found to establish the thickness of the deposits in Morefield Canyon, but the alluvium is estimated to be about 30 feet thick.

Figure 1. View looking north up channel of Morefield Canyon. Note the wide, flat bottom of the canyon. The mound of Site 5MV1931 is in the lower left center of the photograph.

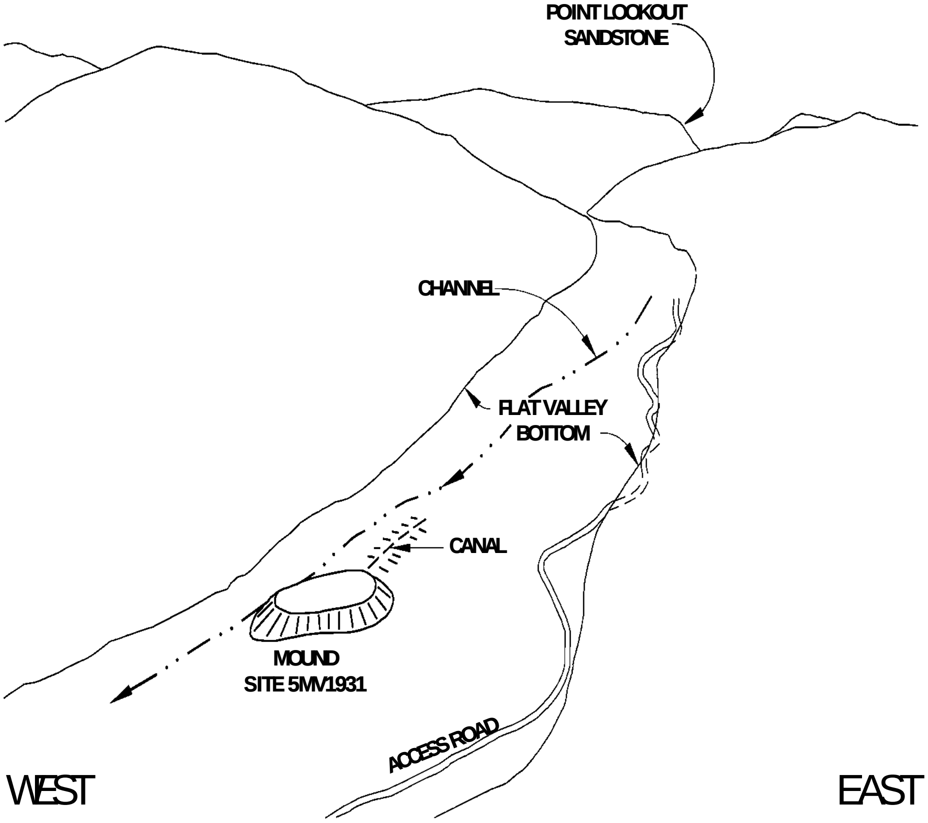

Figure 2. Overlay sketch of Figure 1 showing the valley bottom, Site 5MV1931, channel, and access road.

## PREHISTORIC PRECIPITATION

Dendroclimatic reconstructions for the Mesa Verde area were studied to estimate average annual precipitation during the ca. A.D. 750 to 1100 period of prehistoric operation of Morefield Reservoir and to compare the prehistoric precipitation with modern records. Dr. Jeffrey Dean of the University of Arizona's Laboratory of Tree-Ring Research in Tucson, Arizona, provided the dendroclimatic reconstruction data for the Mesa Verde area from A.D. 481 through 1988 that were evaluated. The long-term average annual precipitation for the period of record was estimated to be 18.1 inches. This agrees with the 74 years of modern record from the weather station at nearby Chapin Mesa. The average annual precipitation from A.D. 750 through 1100 was 18.0 inches. For this reason, precipitation records from modern times were considered suitable for use in analyses of the ancient period.

## PREHISTORIC RUNOFF CHARACTERISTICS

Fires and human activities can significantly increase the runoff potential of a watershed and, when a forested watershed is converted to an agricultural watershed, runoff increases. The Wright Water Engineers, Inc. (WWE) pollen studies of the site showed extensive cultivation of maize (corn) during the period of reservoir use of 1,000 years ago. Archaeological evidence indicates that up to 500 people lived in Morefield Canyon. Farming was practiced, and there was doubtless removal of trees and brush for cooking, construction, and heat. Rough estimates suggest it is likely that at least 125 acres were farmed (one acre for every four people). In addition, people may have denuded a portion of the watershed by gathering firewood. Forest fires occurred in the canyon, as evidenced by layers of charcoal found in the reservoir excavation.

A study of land use/type suggests that a rainfall of 0.5 inch would produce a runoff of 0.033 inch from the 125 acres of farmland. The volume of runoff from this would be 0.34 acre-feet, adequate water to fill the reservoir at the site. The estimated runoff does not consider the area that would have been denuded for fuel or by forest fires. If these denuded areas were upstream of Site 5MV1931, then additional runoff would have been generated that could have been stored. For instance, it was estimated that the 1996 Chapin #5 Fire in Mesa Verde National Park temporarily changed runoff characteristics so as to increase the peak runoff potential some 500 to 600 percent because of loss of forest floor cover and hydrophobic soil conditions resulting from the fire. The Buffalo Creek (tributary of South Platte River in Colorado) fire of 1996 resulted in 12 100-year floods in the first month following the fire. Forest fires cause a significant increase in runoff and sediment yield characteristics.

The Chapin Mesa rainfall records were evaluated to determine the frequency of rainfall events of 0.5 inch or greater. In the 48 years of record analyzed, there were approximately 200 days of recorded precipitation greater than 0.5 inch per day during the summer months. Under the prehistoric hydrologic conditions (farming, fires, and human activity), such events would have produced runoff. This suggests that direct runoff water would have occurred and would have been available for capture and storage about four to five times each summer. The water diversion canal route, defined in the field using instrument surveys, would have been able to intercept the canyon flow and deliver the water to the reservoir for storage.

**Paleoflood Hydrology**: WWE's team made Paleoflood estimates at 12 sites along Morefield Canyon in 1997 from Morefield campground near the head of the canyon to Site 5MV1931. Maximum paleoflood discharges range from about 250 to 350 cubic feet per second (cfs) near Site 5MV1931. The paleoflood evidence is at least 100 years old and likely reflects the largest flooding in several hundred years. One of the largest flash-flood-producing rainstorms during the past century in southwestern Colorado occurred at Mesa Verde National Park. On August 3, 1924, 3.50 inches of rain fell in one to two hours at the U.S. Weather Bureau gage located at Mesa Verde National Park. The estimated paleoflood discharge for nearby Spruce Canyon is about 1,000 cfs, and the drainage area is about 2 square miles.

## ARTIFACTS

Fragments of pottery vessels (potsherds) were found throughout the excavation. Thirty-one potsherds were found in situ in the profile exposed in the south wall of the trench. The excavated pottery places the site within the late Pueblo I, Pueblo II period of occupation of the canyon. A few potsherds indicate a trace of the early Pueblo III. This suggests an absolute time range of around AD 750 to 1100. The excavated pottery was analyzed as to probable vessel type. Most fragments came from jars presumed to have functioned for carrying and storing water; these account for 76 percent of the recovered potsherds. Bowls account for another 21 percent, although in some instances their identification was somewhat borderline. The remaining 3 percent were either too fragmentary, too eroded, or both, to be identified as falling into either of these or any other functional category. This potsherd distribution is similar to that found by Breternitz (1999) in the Mummy Lake excavation conducted in 1969.

While pottery makes up the bulk of artifactual evidence of human use of the site, a few non-pottery items also indicate that use. A broken deer antler (carbon dated at A.D. 860) found deep within the clay layers may have been part of a digging implement; it occurred in isolation; no other bone or antler fragments were found with it. A small roughly-shaped disk of tabular sandstone was probably a lid for one of the above-mentioned pottery jars, and another roughly rectangular piece of tabular sandstone appears to have been intentionally shaped but of an unknown use.

## INTAKE CANAL

The Morefield Reservoir evolved into an off-stream reservoir during its early life after the original excavated pond filled with sediment and was mucked out to form perimeter berms. An off-stream reservoir requires an intake canal for water delivery. The existing route of such an intake canal represents the final canal alignment at the time the reservoir was abandoned. Field instrument route surveys were conducted for mapping purposes. An inspection of the area in the vicinity of the final canal heading and the drainage channel revealed no compelling evidence of a diversion structure.

In situ aligned stones and extrapolation defined the canal route. The canal was 1,425 feet long with an average slope of 1.0 percent—the slope ranging between 0.5 and 2.0 percent, not unlike modern farm irrigation systems in southwestern Colorado. Almost all of the observed stones along the right-of-way of the canal were likely used for erosion control and were rectangular shaped. Most were from the Menefee sandstone. Some of the stones served to protect the canal bank from stream erosion. Excavations of the canal cross section were conducted in 1967. These excavations indicated a bottom width of 3 feet, 2:1 side slopes and a maximum depth of about 1 foot. With these data and by use of Manning's Equation the computed bank full canal capacity under subcritical flow conditions was 19 cfs at a velocity of 3.8 feet per second (fps). The roughness coefficient was estimated at 0.03, with the canal having an average slope of 0.01 ft/ft. The canal and the reservoir were integrated into a single operating structure for diversion, transport, and storage of water.

## SEDIMENT DEPOSITION

The 1997 excavation of the Morefield Reservoir mound penetrated to the original ground surface on the east and west portions of the trench. In the trench's midsection the original ground surface was reached by auger at about 5 feet below the trench bottom. The auger at this deeper elevation penetrated the original pond bottom dug by the Early Americans for groundwater and surface water collection prior to the reservoir building.

**Profile of 1997 Trench Cut**: Figure 3 identifies the long horizontal layers of alluvial sediments exposed throughout the trench walls, along with gently upward sloping layers at the edges where the reservoir embankment existed. At one location, evidence of embankment slope failure was evident. A long buried antler found near Station 54 at elevation 7,212.3 feet was carbon dated. The distinct layers, while initially considered to be fine sand, were found to be mostly sandy clay or sandy silt. Approximately 14 thin continuous layers of charcoal deposits were found, likely representing fluvial transported charcoal from forest fires.

Analyses of the trench walls show that:

A. The 1997 trench face contained approximately 1,900 square feet of surface area, of which 65 percent was a densely compacted clay matrix. The tightness of the clay would have obviated any measurable reservoir storage seepage losses. The clay deposits would have been deposited in the reservoir during small rates of water diversion from the thalweg of Morefield Canyon and from wind-blown sediment.

B. Over the life of the reservoir, there were about 21 instances of measurable sand to sandy clay depositional occurrences that would have represented larger (and sometimes uncontrolled) diversions to the reservoir during canyon flooding periods. This would represent an average of one sediment-carrying flood each 17 years, when the inlet canal likely would have been overtopped and damaged or perhaps washed out in one or more places. The material in the sand layers is 30 percent clay, 55 percent silt and 15 percent sand. One sample not included in the average was first classified with 60 percent sand-sized material, which was visually identified as predominantly charcoal particles rather than sediment.

C. Fill sediments consist of "couplets" with a lower layer of very fine sand (locally silt) and a thicker upper layer of dense clay. Generally, the lower layer is ripple-bedded and has a smooth lower contact, although some beds have undulating lower contacts that fill irregularities in underlying clay beds. In a few places, the sandy layers contain thin interbeds of clay and the clay layers include fine laminations of sand. In cross section, the couplets have concave shapes that rise toward the edges of the fill. Toward these edges, the sandy layers thin, become silty, and may become discontinuous or pinch out.

D. Near the middle of the trench, the lower part of the fill contains a disconformity with several feet of relief. Slump blocks overlying this disconformity probably moved toward a void created by removal of sediment from the lower middle area. Because the lowest part of the detachment surface is tangential to lower, undisturbed couplets, the void was probably created by manual excavation.

E. Some six reservoir-forming berm structures were exposed in the 1997 reservoir trench. The overall distribution of berm and fill sediments suggests that the width of the water surface varied with time, as the reservoir rose progressively upward. At both ends of the trench, very weakly bedded clayey material overlaps the berm sediments and is overlain by well-bedded fill sediments. Some parts of this clayey material contain thin or discontinuous beds of silt or fine sand. This unit may consist of peripheral fill sediments in which bedding was mostly destroyed during maintenance work on the berm. Overlapping, well-bedded fill sediments are consistent with this interpretation (Figure 3).

F. Potsherds were found throughout the trench wall, but they were more common in the berm material, or in fill sediments near the berm, than near the middle of the fill. All of the sherds in the trench were found in the clay matrix, with none in the sandy silt or sand deposits.

G. A detailed comparison was made between WWE's 1997 excavation and the University of Colorado's 1967 excavation. The latter excavation was typically 8 feet deep; however, 3 test pits carried the field observations an additional 2 to 5 feet below the trench bottom. Correlation between the 1967 and 1997 excavations was good.

H. The volume of storage would have varied considerably over the years; however, an approximate storage estimate would place the volume of maximum active storage at about 120,000 gallons. The storage volume at other times is estimated to have ranged down to about 40,000 gallons.

**Sediment Volume Computations**: The sediment gradation and estimated transport velocities associated with peak runoff from estimated ancient thunderstorm events are compatible with an inlet canal capacity of about 19 cfs. Two selected sediment transport formulas (Laursen and Yang) showed for the 19 cfs canal discharge an average concentration of 14,000 mg/L and an instantaneous transport rate of about 700 tons per day. It is concluded that the sandy layers represent erosion at the higher elevations of the drainage area. The heavy clay material represents materials eroded from the channel banks in the upstream valley alluvium representing previously deposited materials from the Mancos shale. The clay was judged to have been deposited during the dominant low-flow conditions. Of the total sediment deposited over the life of the reservoir, it was estimated that on the average about 1230 $ft^3$ were diverted and deposited per year. About 270,000 $ft^3$ of the mound are clay, while 160,000 $ft^3$ are sandy silt representing high-flow periods. The reservoir rose in elevation, because of sediment accumulation, about 1.6 inches per year. However, due to cleaning efforts (dredging) the overall net rise averaged only 0.7 inches per year until in A.D. 1100 the reservoir fill was about 21 feet above the original pond bottom.

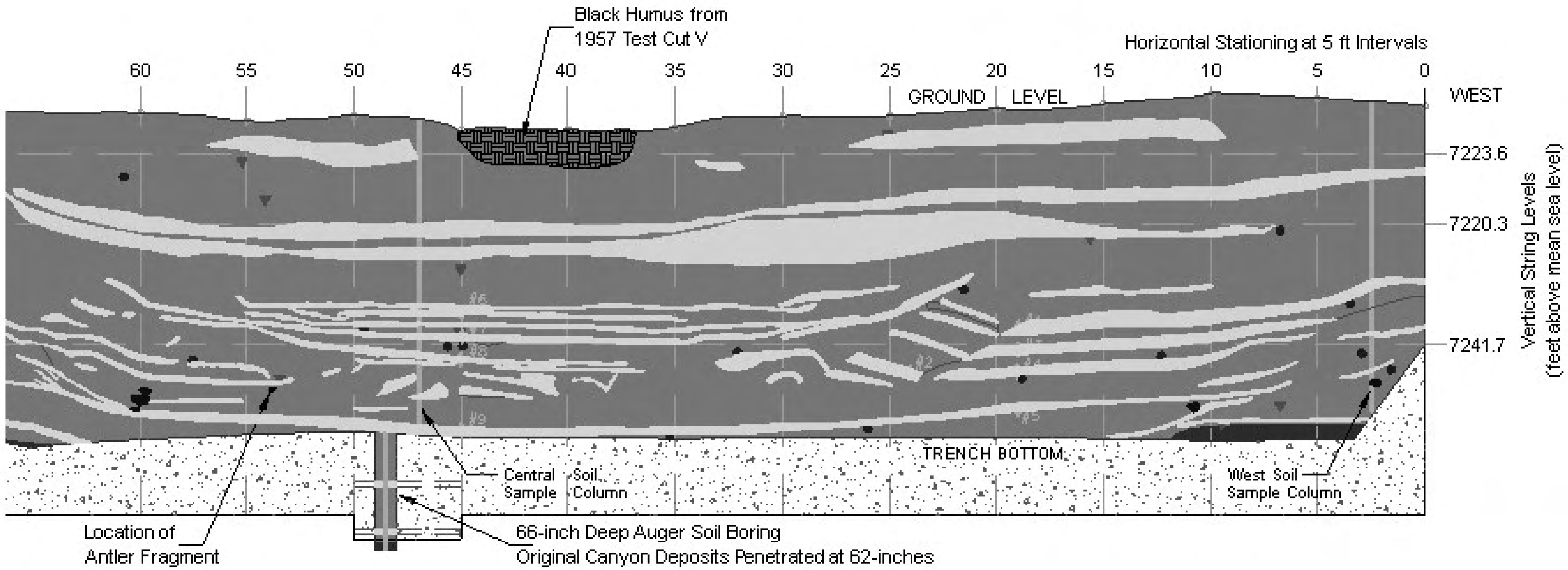

Figure 3. Profile of sediment deposits for middle portion of Morefield Reservoir from Excavation of May 1997.

Figure 4. View looking westerly of Site 5MV1931 showing the May 1997 trench excavation.

**Sediment Yield**: The total sediment deposited in the reservoir of 430,000 $ft^3$ provides data for computing the sediment yield for the 4.2-square-mile drainage basin. Morefield Canyon is considered an ephemeral channel, and the area would be considered to be a low mountain valley. The computed annual sediment yield for deposited sediment in Morefield Reservoir is 0.0067 acre-feet/square mile. A portion of the total sediment transported by the channel would, during extreme flood flow conditions, have bypassed a diversion structure and likely overflowed the canal and reservoir. This would support an annual sediment yield of 0.01 acre-feet per square mile as a long-time average sediment yield for areas similar to Morefield Canyon.

Figure 5. Example of sandy layer with charcoal layers and overlying thick dense clay deposits near Station 50.

## CONCLUSIONS

The work of paleohydrologists is important to the field of anthropology to aid in defining and interpreting evidence at archeological sites that are water-based or that have a water-related component. By analyzing ancient water management one can learn about the organizational and engineering skills of ancient people. One can also learn about climate impacts of many years ago and how such impacts might have affected the Early Americans.

In modern engineering studies, long-term reservoir sedimentation studies are typically not available. At the Morefield Reservoir site of Mesa Verde National Park the human impact of 350 years of modest sediment deposition rates was laid out like an open book; complete with pollen for analysis of agriculture, potsherds from daily life, carbon for C-14 dating, remains of berms and even evidence of an ancient berm failure. The canal remains provided evidence for determining sediment transport and open-channel hydraulic analyses. It was determined that the prehistoric inhabitants of Mesa Verde National Park had technical capabilities far beyond those for which they are usually given credit.

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# RESERVOIR SEDIMENTATION STUDIES TO DETERMINE VARIABILITY OF PHOSPHORUS DEPOSITION IN SELECTED KANSAS WATERSHEDS

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**Abstract:** *Phosphorus is an important nutrient because it is the principal limiting factor for primary biotic production in most freshwater environments. It also is an important water-quality constituent because excessive phosphorus concentrations in reservoirs can cause algal growth that may result in taste-and-odor problems in water supplies (eutrophication). In Kansas, reservoirs are the primary source of drinking water for many municipalities and rural water districts, and taste-and-odor problems could be a major concern.*

*Phosphorus in Kansas reservoirs primarily is of nonpoint-source origin and may be related to fertilizer application and livestock production in contributing watersheds. Because phosphorus is transported primarily in the particulate phase, analysis of fluvially transported sediment that has accumulated in Kansas reservoirs can provide information on historical phosphorus concentrations and yields that may cause accelerated eutrophication.*

*For the purpose of comparing phosphorus transport throughout Kansas, four reservoirs in watersheds with different topography, soils, underlying geology, land use, and climate were selected for analysis of reservoir bottom sediment. Bottom-sediment cores were collected from Webster Reservoir in north-central Kansas, Cheney Reservoir in south- central Kansas, and Tuttle Creek and Hillsdale Lakes in northeastern Kansas. The cores were analyzed for total phosphorus, bulk density, and selected constituents and properties. The chemical data were combined with reservoir bathymetry, which showed changes in reservoir sediment volume, to estimate mean annual sediment and phosphorus yields for each of the four reservoir watersheds.*

*Estimated mean annual sediment yields varied considerably among the four reservoir watersheds and ranged from 0.03 acre-foot per square mile per year in the Webster Reservoir watershed to 0.97 acre-foot per square mile per year in the Hillsdale Lake watershed. Estimated phosphorus yields ranged from 0.04 pound per acre per year in the Webster Reservoir watershed to 1.7 pounds per acre per year in the Hillsdale Lake watershed.*

*Reservoir sediment studies in Kansas have been useful in reconstructing historical trends in water quality that can be used as a measure of the effectiveness of best-management practices implemented throughout the watersheds. With the addition of bathymetric surveys and the inclusion of additional reservoirs, sediment studies also can be used to establish baselines for estimating historical loading of phosphorus and other constituents in future water-quality assessments throughout Kansas.*

## INTRODUCTION

Phosphorus is an essential element for plant growth, and its addition to cropland has become important in the maintenance of profitable agricultural production in the United States. However, excessive phosphorus inputs from municipal, industrial, and residential sources as well as from agriculture can have detrimental effects on adjacent or downgradient aquatic systems by increasing the biological productivity of surface water. The resultant eutrophication may cause taste-and-odor problems for water suppliers, degrade habitat for aquatic life, and discourage recreational use of the affected water body.

Remedial efforts during the past several years have been focused on reducing water contaminants from nonpoint sources because it is believed that point sources, for the most part, have been identified and controlled where it is cost effective to do so. Nonpoint sources of water contamination, such as from agricultural application of phosphorus, are difficult to identify, and remediation efforts are difficult and expensive to implement. It also can be many years before any improvements are seen in water quality once remediation efforts begin.

Phosphorus, along with many other constituents, adsorbs to fine-grained sediment particles, primarily silt and clay, and also is associated with fine organic material. In stream channels and reservoirs, these particles can be transported great distances, finally settling into the quiet, deeper areas of reservoirs where they accumulate in sediment. Because reservoir sediment acts as an integrator of activities within the watershed (Mau and Christensen, 2000), sampling the reservoir bottom sediment can be very informative in determining trends in phosphorus use throughout the watershed.

The U.S. Geological Survey (USGS), in cooperation with various local, State, and Federal government agencies, began investigating Kansas reservoir bottom sediment in 1995. The studies were multifaceted, looking at sediment deposition along with selected chemical constituents in sediment cores from reservoirs located in various geologic, topographic, and climatic landscape regions throughout Kansas. The results of four reservoir sedimentation studies that examined the variability of phosphorus deposition for the Webster Reservoir, Cheney Reservoir, Tuttle Creek Lake, and Hillsdale Lake watersheds (fig. 1) are presented in this paper. The purpose of this paper is to: (1) describe phosphorus yields since reservoir impoundment, and (2) discuss probable causes for differences in phosphorus yields among the reservoirs and their respective watersheds. The four reservoirs described were sampled during the period October 1, 1995, through September 30, 1999.

**Setting:** The Webster Reservoir watershed is located in north-central Kansas and has a contributing-drainage area of about 1,150 square miles (table 1). Land use primarily is agricultural, with about 57 percent used for cropland and 37 percent used for pastureland (Bureau of Reclamation, 1984, p. 9). Topography within the watershed is flat to gently rolling, with narrow, shallow valleys and low relief. The soils consist of sand, clay, loess, or silt.

The Cheney Reservoir watershed, located in south-central Kansas, is approximately 933 square miles. Land use primarily is agricultural, with about 52 percent of the watershed in cropland and the balance consisting of pastureland, forest cover, and small urban areas. Topography within the watershed generally is flat to gently sloping hills. The soils are classified as clayey loam in the uplands to sand or sandy loam in the low-lying areas.

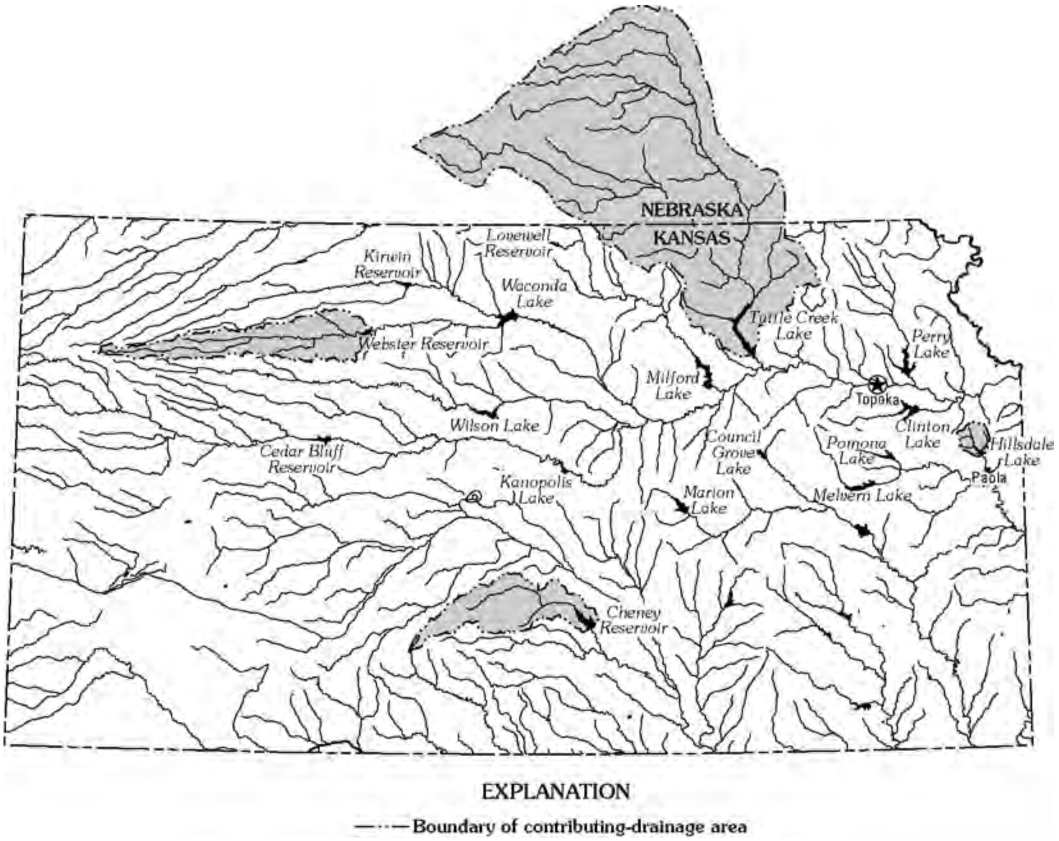

**Figure 1.** Location of four reservoir watersheds in Kansas.

Tuttle Creek Lake has the largest watershed and surface area of the four reservoirs, with a contributing-drainage area of about 9,600 square miles (table 1) in southeastern Nebraska and northeastern Kansas. About 72 percent of the watershed is cropland, and nearly 16 percent is pastureland. The topography is reflected in generally smooth plains consisting of sand, gravel, silt, and clay in the Nebraska section and areas of greater local relief underlain by shale, sandstone, limestone, and fluvial and eolian deposits in the Kansas section of the watershed (Pope, 1995, p. 4).

The smallest of the four reservoir watersheds described in this paper, the Hillsdale Lake watershed, has a contributing-drainage area of about 144 square miles and is located in northeastern Kansas. Croplands constitute about 35 percent of the land use, and the balance consists mostly of pastureland and forest cover. The watershed consists of gently rolling uplands, with hilly areas along the streams, and is underlain by shale and limestone (O'Connor, 1971).

Precipitation varies considerably among the four reservoirs studied. Long-term mean annual precipitation is about 24 inches at Webster Reservoir compared to about 27 inches at Cheney Reservoir. The long-term mean annual precipitation at Tuttle Creek Lake is about 32 inches and about 41 inches at Hillsdale Lake (measured 5 miles south at Paola, Kansas). Long-term means were based on a period of record from 1961-90 (National Oceanic and Atmospheric Administration, 1998). Consideration should be given to the fact that precipitation varies throughout each watershed. In general, precipitation increases west to east in Kansas and Nebraska; therefore, the precipitation at Webster Reservoir and Tuttle Creek Lake is likely to be greater than in their respective watersheds.

**Methods:** The methods used to estimate total phosphorus deposition since reservoir impoundment included both bathymetric surveying (mapping of the reservoir bottom) and reservoir bottom-sediment coring. Bathymetric surveys have been done infrequently at the four reservoirs making it infeasible to calculate an accurate annual volume and rate of phosphorus deposition. Therefore, a mean annual phosphorus yield was estimated by dividing the total accumulated sediment volume by watershed drainage area and by the time period since reservoir impoundment.

Bathymetric surveys were done at each reservoir along existing range lines established by either the U.S. Army Corps of Engineers or the U.S. Department of Interior's Bureau of Reclamation (BOR). Global-positioning-system (GPS) technology was used to record the geographic location of the boat on the reservoir, and a fathometer system was used to determine the depth to the reservoir bed. The data were digitally recorded and used to compare the original pre-reservoir, range-line topographic data to the most recent bathymetric data.

Dry-mass estimates of sediment deposition into the reservoirs required determining reservoir bottom-sediment bulk density. This was done by collecting reservoir bottom-sediment cores using a gravity corer (fig. 2). The gravity corer was fitted with cylindrical, transparent plastic liners with a 2.63-inch inside diameter that collected and stored the sediment-core sample. Sediment-core samples were collected from several locations in each reservoir to obtain representative samples. The core samples were processed at the USGS laboratory in Lawrence, Kansas, and analyzed for percentage of sand and fines (particles less than 0.062 millimeter in diameter; silt and clay), bulk density, and percentage of moisture, according to methods presented in Guy (1969). Sediment samples from three of the reservoirs also were submitted to the USGS National Water-Quality Laboratory in Denver, Colorado, for analysis of total phosphorus and other chemical constituents. Sediment samples from Webster Reservoir were analyzed for total phosphorus and other chemical constituents by the BOR laboratory in Bismarck, North Dakota, using both U.S. Environmental Protection Agency (1997) and USGS methods (Fishman and Friedman, 1989).

**Table 1.** Comparison of reservoir and watershed characteristics for Webster Reservoir, Cheney Reservoir, Tuttle Creek Lake, and Hillsdale Lake, Kansas

| | | | | Land use[1] | | |
|---|---|---|---|---|---|---|
| **Reservoir or lake** | **Date of impoundment** | **Contributing-drainage area (square miles)** | **Original conservation pool storage (acre-feet)** | **Percentage of basin in pastureland** | **Percentage of basin in cropland** | **Long-term mean annual precipitation[2] (inches)** |
| Webster | 1956 | 1,150 | 72,000 | 37 | 57 | 24 |
| Cheney | 1965 | 933 | 152,000 | <48 | 52 | 27 |
| Tuttle Creek | 1962 | 9,600 | 425,000 | 16 | 72 | 32 |
| Hillsdale | 1981 | 144 | 68,000 | 50 | 35 | 41 |

[1] Land-use percentages from Nebraska Resources Commission (1983), Bureau of Reclamation (1984), Kansas Applied Remote Sensing Program (1993), Kansas Department of Agriculture and U.S. Department of Agriculture (1997), and Putnam (1997).

[2] Long-term mean annual precipitation is based on 1961-90 data from the National Oceanic and Atmospheric Administration (1998).

## VARIABILITY OF PHOSPHORUS DEPOSITION

Estimated mean annual phosphorus yields to the reservoir watersheds varied from 0.04 pound per acre per year for the Webster Reservoir watershed to 1.7 pounds per acre per year for the Hillsdale Lake watershed (table 2). The relation between phosphorus concentration and percentage of fines in the sediment has been documented. At Cheney Reservoir, for example, a correlation coefficient, r, of 0.96 was determined for the relation between concentrations of phosphorus in sediment and percentage of fines in sediment (Pope, 1998). On a per-square-mile-of-watershed basis, the largest mean annual phosphorus yield was estimated for the Hillsdale Lake watershed where the largest estimated mean annual sediment yield occurred. The Hillsdale Lake watershed also receives the most annual precipitation and, in conjunction with the relatively hilly topography and substantial percentage of cropland, may be prone to more erosion losses per square mile than the other reservoir watersheds in this study. The Webster Reservoir watershed, in comparison, experiences significantly less precipitation, a mean annual total of 24 inches, and has a more gently sloping topography. There also are more than 800 small farm ponds in the Webster Reservoir watershed that serve as sediment and water traps, reducing streamflow and suspended sediment transport to the reservoir (Bureau of Reclamation, 1984, p. 37).

**Figure 2.** Bottom-sediment cores were collected with a gravity corer mounted on a pontoon boat. The corer is lowered to a designated distance above the sediment and allowed to free fall to penetrate through the entire thickness of reservoir bottom sediment.

Historical trends of chemical constituents in reservoir bottom sediment over time can be an important measure of the effectiveness of best-management practices (BMP's) as well as the accumulation effect of phosphorus. However, reservoir-bottom-sediment layers can undergo mixing during storms or periods of flooding, or phosphorus may be converted from the sediment phase to the dissolved phase. Mixing and conversion can create difficulties in the analysis of trends.

Substantial conversion of phosphorus in sediment to dissolved phosphorus can occur at the sediment/water interface (Lung and Larson, 1995). In Kansas reservoirs, burial of sediment is relatively rapid, which may restrict the effect of the conversion process in altering the vertical distribution of phosphorus. However, as previously stated, the conversion of phosphorus from the sediment to the dissolved phase may affect the interpretation of shallow sediment layers.

To determine whether bottom sediment had been disturbed physically, selected sediment cores were analyzed for cesium-137. Cesium-137, a by-product of thermonuclear-weapons testing of the 1950's and early 1960's, is widely dispersed by atmospheric deposition and is sorbed to soil particles (primarily clay). Detectable cesium-137 concentrations in sediment began about 1952 and peaked about 1964, followed by a steady decline in concentrations (Holmes, 1998).

**Table 2.** Estimated total sediment deposition and sediment and phosphorus yields to Webster Reservoir, Cheney Reservoir, Tuttle Creek Lake, and Hillsdale Lake, Kansas

| Reservoir or lake | Total sediment deposition (acre-feet) | Mean annual sediment yield (acre-feet per square mile of watershed per year) | Percentage of sediment deposition, in-channel | Mean annual phosphorus yield to reservoir (pounds per acre per year) |
|---|---|---|---|---|
| Webster | 1,330 | 0.03 | 81 | 0.04 |
| Cheney | 7,800 | .25 | 10 | .53 |
| Tuttle Creek | 114,000 | .31 | 34 | .41 |
| Hillsdale | 2,100 | .97 | 56 | 1.7 |

Because of its wide dispersal, cesium-137 can be used as a method to age-date sediment layers (McHenry and Ritchie, 1981; Ritchie and McHenry, 1990; Callender, 1993). Three of the four reservoirs in this study—Webster, Cheney, and Tuttle Creek—were analyzed for cesium-137 by sectioning selected sediment cores. Webster Reservoir and Tuttle Creek Lake were built prior to 1964, and the cesium-137 peak concentrations are evident in the sediment profile from Tuttle Creek Lake (fig. 3). Cheney Reservoir was built after the cesium-137 peak concentration; therefore, only the tail (decreasing cesium-137 concentration) following the peak is visible in the reservoir bottom sediment from Cheney.

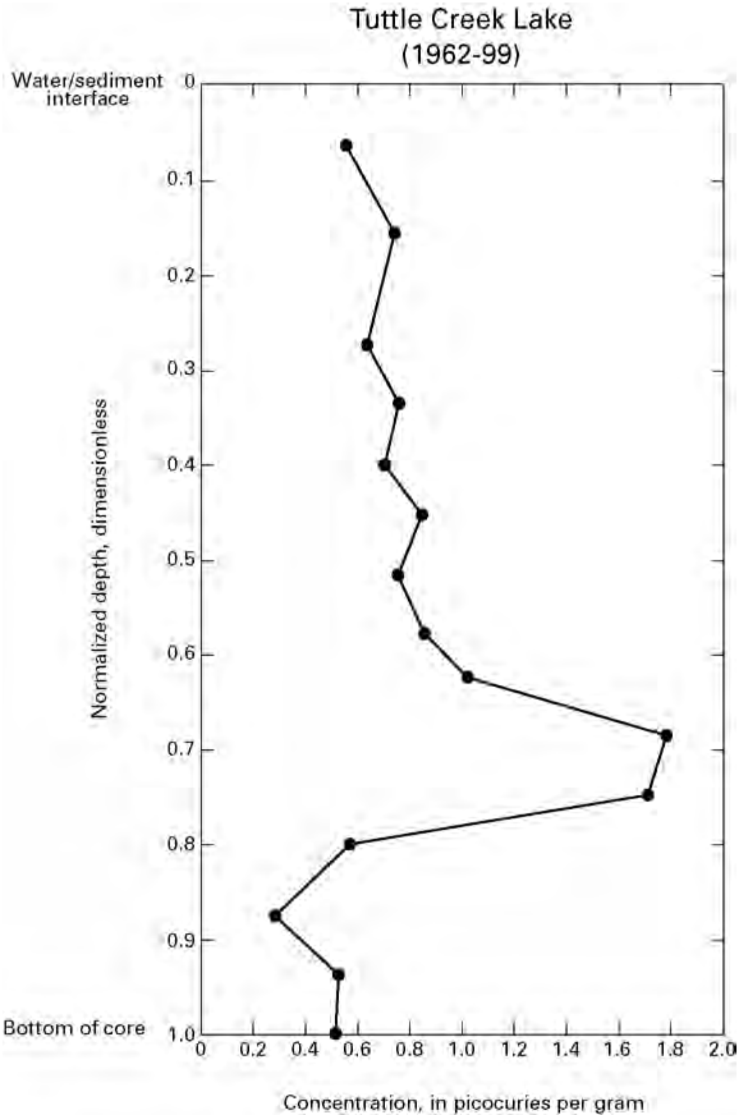

**Figure 3.** Concentrations of cesium-137 in sediment profile from Tuttle Creek Lake.

The sharp peak and relatively uniform decrease of cesium-137 concentrations in the sediment (fig. 3) suggest that the sediment was deposited in the reservoirs and not resuspended or mixed annually. Therefore, evaluation of trends in phosphorus deposition over time can be done with some confidence. Although cesium-137 concentration analysis was not done on the reservoir bottom sediment at Hillsdale Lake, total phosphorus concentrations did not show any trend with depth. Total phosphorus concentrations in selected bottom-sediment cores from Webster Reservoir and Tuttle Creek Lake also did not show any trends with depth. However, the evidence from Cheney Reservoir indicates that total phosphorus concentrations in the more recent sediment are larger than in the deeper, older sediment (fig. 4). The correlation coefficient, r, between total phosphorus concentrations and depth within the sediment cores from Cheney Reservoir ranged from 0.71 to 0.95, indicating a significant relation between the two variables (Pope, 1998). This implies that phosphorus use in the Cheney Reservoir watershed has increased in the past 33 years, probably as a result of increased agricultural activities.

Both Spearman's rho and Kendall's tau correlation analyses were done on the total phosphorus concentrations in Webster Reservoir to evaluate whether a statistical relation existed between sediment depth within the core and total phosphorus concentration (Christensen, 1999). Both analyses are nonparametric procedures that are based on ranks, but Spearman's rho gives more weight to differences between data values ranked farther apart; Kendall's tau is resistant to the effects of extreme values. Results from the two tests indicated that there was no discernible trend for total phosphorus concentrations with depth in the reservoir bottom sediment from Webster Reservoir (Christensen, 1999). Similarly, at Hillsdale Lake, no apparent trend was observed between total phosphorus concentration and depth in the reservoir bottom sediment (Juracek, 1997), and preliminary results from Tuttle Creek Lake indicate that no trend exists (D.P. Mau, USGS, unpublished data on file at the U.S. Geological Survey office in Lawrence, Kansas).

The adsorption of phosphorus to silt and clay particles and the association of phosphorus with fine organic material suggest that phosphorus can be transported farther into the reservoir and deposited in the deeper, less turbulent water, typically near the dam. Larger concentrations of phosphorus, therefore, might be expected in the reservoir bottom sediment near the dam, especially in the in-channel locations which are typically the deepest areas within the reservoir. However, an analysis of bottom-sediment cores from in-channel sites upstream and downstream in the reservoirs provided ambiguous results. There were no in-channel trends in phosphorus concentrations within the reservoirs identified at either Webster or Hillsdale (Christensen, 1999; Juracek, 1997). However, trends were apparent at Cheney Reservoir and Tuttle Creek Lake (Pope, 1998; D.P. Mau, unpublished data on file at the U.S. Geological Survey office in Lawrence, Kansas).

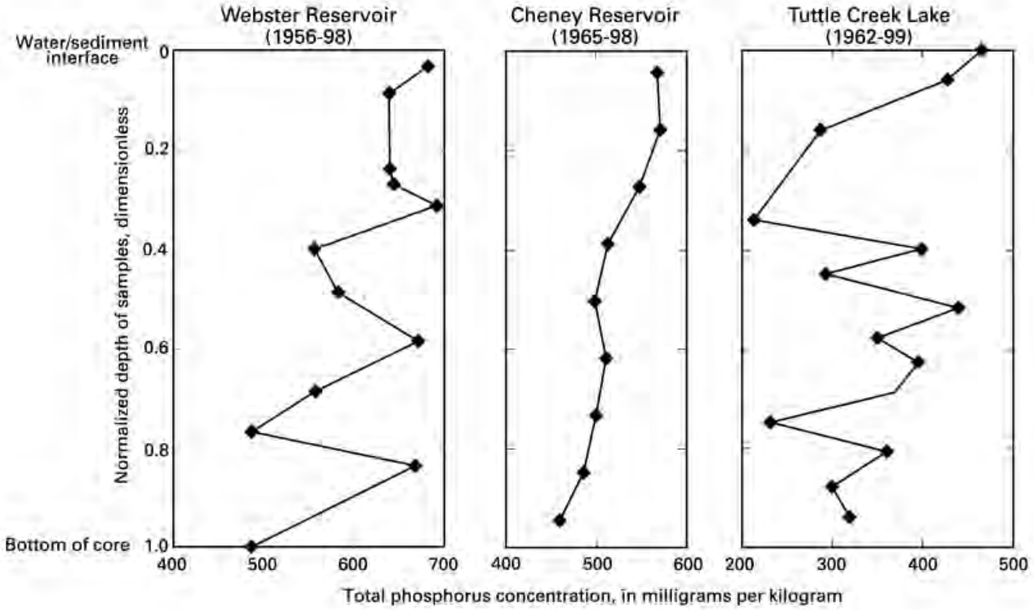

**Figure 4.** Concentrations of total phosphorus in sediment profiles from Webster Reservoir, Cheney Reservoir, and Tuttle Creek Lake, Kansas.

The extremely low sediment yield for Webster Reservoir, possibly a result of sediment retention from more than 800 small farm ponds scattered throughout the watershed, in addition to low precipitation, might explain the small phosphorus yield. Hillsdale Lake, in comparison, had the largest phosphorus yield on a per square mile basis. Precipitation in the Hillsdale Lake watershed is the highest among the watersheds of the four reservoirs studied and, along with the substantial relief in topography, suggests an increased transport of sediment and total phosphorus into the reservoir. The lack of any trend in total phosphorus upstream to downstream, or in-channel versus out-of-channel, in Hillsdale Lake is surprising but may be related to the fact that the reservoir is relatively new (completed in 1981) and trends may not have developed yet.

Trends in depositional patterns of total phosphorus upstream to downstream are evident, however, within Cheney Reservoir and to a lesser extent within Tuttle Creek Lake (Pope, 1998; D.P. Mau, USGS, unpublished data on file at the U.S. Geological Survey office in Lawrence, Kansas). Percentage of fines in sediment from Cheney Reservoir was highest near the dam and progressively decreased farther upstream. Phosphorus concentrations showed a similar trend, probably because of the adsorption to fine-grained sediment and association with fine organic material. Tuttle Creek Lake data showed increases in mean phosphorus concentrations upstream to downstream, but concentrations decreased near the dam. The reason for this is unknown but may be related to the hydrodynamics and subsequent turbulence created by water releases from the dam. A low-energy environment, therefore, may not be available near the dam for the smaller particles to be deposited in the bed sediment near the dam.

## SUMMARY AND CONCLUSIONS

Bathymetric surveying and sediment coring were used in this study to examine four reservoirs in watersheds with different topography, soils, underlying geology, land use, and climate. The reservoirs are integrators of watershed activities, and therefore, trends in reservoir bottom sediment may be indicative of trends in the watershed. Estimated sediment and phosphorus yields varied considerably among the watersheds.

Mean annual sediment yields ranged from 0.03 acre-foot per square mile per year in the Webster Reservoir watershed to 0.97 acre-foot per square mile per year in the Hillsdale Lake watershed. Estimated phosphorus yields ranged from 0.04 pound per acre per year in the Webster Reservoir watershed to 1.7 pounds per acre per year in the Hillsdale Lake watershed. The largest phosphorus yield was estimated for the Hillsdale Lake watershed, where the largest annual sediment yield occurred. The size of sediment particles also had a strong relation to phosphorus concentrations as documented by the results from Cheney Reservoir. This indicates that the amount and size of sediment particles can be an important factor for phosphorus yield in Kansas reservoirs.

Also important are topography and precipitation in the watersheds. The hilly topography and higher precipitation in the Hillsdale Lake watershed likely caused more erosion and runoff of sediment and increased phosphorus yield to the reservoir. Precipitation is important because watersheds in Kansas that have more precipitation also have a larger sediment yield (Mau and Christensen, 2000).

Finally, land use can be an important factor in the variability of sediment and phosphorus yields. Phosphorus in Kansas reservoirs is mainly of nonpoint-source origin and may be related to the application of fertilizers or the production of livestock. BMP's may decrease the input of phosphorus to reservoirs from these nonpoint sources, and reservoir sediment studies may provide an important indication of BMP effectiveness.

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# RESERVOIR SEDIMENTATION DURING HIGHWAY CONSTRUCTION, OAHU, HAWAII, 1983-98

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**Abstract**: Sedimentation surveys were done from 1983 to 1998 at Waimaluhia Reservoir to calculate the rate of sediment accumulation during H-3 Highway construction upstream. Rates of storage-capacity loss ranged from 1.2 acre-ft/year between 1983 and 1988 to 4.8 acre-ft/year between 1988 and 1992. The average rate of storage loss between 1983 and 1998 was equal to the design rate of 2.0 acre-ft/year. The average bulk density of deposited sediments was 25 pounds per cubic foot. On the basis of the bulk density of deposited sediments, loss of storage capacity, and measured suspended-sediment loads downstream of the reservoir, it was calculated that a total of 24,470 tons of sediment was delivered to the reservoir from 1983 to 1998, of which 67 percent or 16,500 tons was trapped in the reservoir. Average sediment yield for the Waimaluhia Reservoir watershed during this period was 510 tons/mi$^2$/year. A trap efficiency of 60 percent, bulk density of 65 pounds per cubic foot, and sediment yield of 1,500 tons/mi$^2$/year were used to compute the reservoir design loss rate of 2.0 acre-ft/year. These design values were based on short-term (1967-69) sediment data. The sediment yield used in the reservoir design was about three times greater than measured sediment yields indicating the magnitude of differences that can result when using short-term sediment records for reservoir design purposes.

## INTRODUCTION

Waimaluhia Reservoir is located on the eastern, or windward, side of the island of Oahu (fig. 1). The flood-control reservoir was designed to maintain a permanent pool surface-water elevation of 160 ft above mean sea level and lose 2 acre-ft of storage capacity per year due to sediment deposition (U.S. Army Corps of Engineers, 1981). A trap efficiency of 60 percent, bulk density of 65 pounds per cubic foot, and sediment yield of 1,500 tons/mi$^2$/year were used to compute the design loss rate of 2.0 acre-ft/year on the basis of short-term sediment data collected from 1967-69 (Jones and others, 1971; U.S. Army Corps of Engineers, 1981). The H-3 Highway was constructed in phases upstream of the reservoir between 1983 and 1998. Because the highway construction involved substantial disturbance of the land surface, concern was raised over possible erosion from the construction areas and subsequent accelerated loss of reservoir storage capacity. Because of this concern, the U.S. Geological Survey, in cooperation with the Hawaii State Department of Transportation and the Federal Highways Administration, conducted a series of sedimentation surveys in Waimaluhia Reservoir from 1983 to 1998.

Elevations within the 3.20 mi$^2$ drainage basin of the Waimaluhia Reservoir range from about 2,750 ft at the crest of the Koolau Range, to about 150 ft near the reservoir dam site. Median annual rainfall near the study area ranges from about 59 in. near the coast to about 100 in. near the Koolau crest (State of Hawaii, 1982). Annual rainfall at four rain gages, two National Weather Service (Luluku and Pali Golf) and two U.S. Geological Survey (located at stations 16265600 and 16270900) (fig. 1), operated in the study area ranged from 40 to 130 in. with an

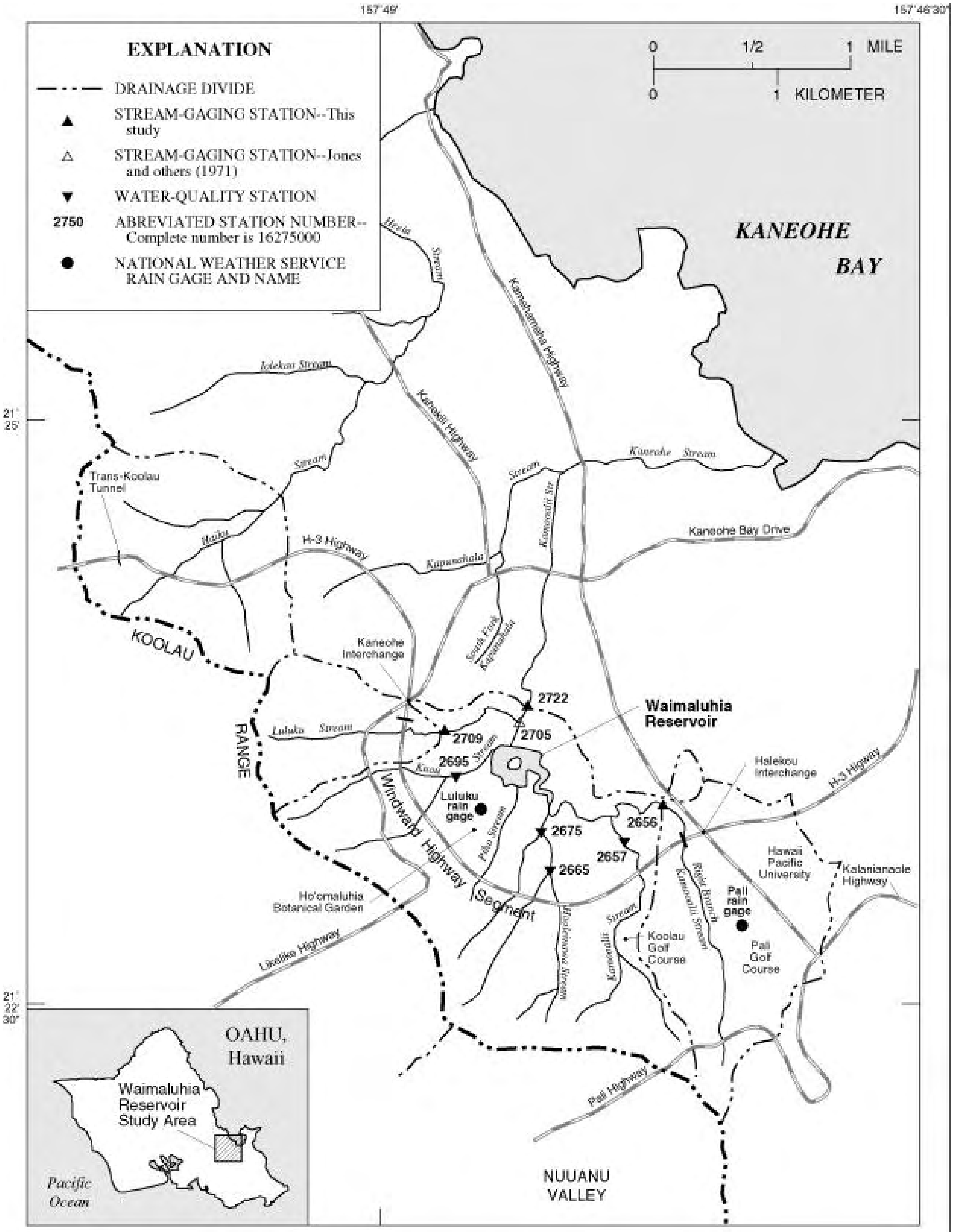

**Figure 1.** Waimaluhia Reservoir study area and hydrologic stations, Oahu, Hawaii.

average at all four gages of about 73 in. during the 1983-98 study period. Streamflow and suspended-sediment data were collected downstream of the reservoir at station 16272200 (fig. 1) with a drainage area of 3.81 $mi^2$. Because the dam was constructed upstream of the confluence of Luluku and Kamooalii Streams, streamflow at station 16272200 includes water released from Waimaluhia Reservoir and perennial streamflow from Luluku Stream, measured at station 16270900, that does not flow through the reservoir. The streamflow and suspended-sediment load discharged from the reservoir can be computed by subtracting the values at station 16270900 from station 16272200.

Highway construction within the basin began with the construction of the Halekou Interchange upstream of station 16265600 between 1983-88. Numerous court injunctions temporarily stopped the construction at various times. Construction of the Windward highway segment, which affects most of the basin, began in the summer of 1989 and was completed in the summer of 1992. One of the two golf courses, the Koolau, (fig. 1) also was built between 1989 and 1991.

## METHODS

Sediment accumulation in Waimaluhia Reservoir was monitored by bathymetric surveys of monumented cross sections. Cross-sectional surveys were made in 1983, 1988, 1990-95, and 1998. During each survey, a tagline made of buoyant non-stretching material was attached to the two monuments defining the end points of each cross section. Because of wave action and wind deflection, positional coordinates determined from tagline readings are considered accurate to the nearest foot. The depths from the water surface to the bottom of the reservoir were determined to a precision of 0.01 ft with an accuracy of 0.05 ft, because of the effects of wave action. Depths were measured with a sounding weight fabricated with an 8 in. diameter perforated base designed to prevent the sounding weight from sinking into soft bed sediments. A modified surveying rod was used to measure water depths where vegetation growth near the shoreline interfered with use of the sounding weight. The modification involved the addition of an 8 in. diameter perforated wood base designed to prevent the surveying rod from sinking into soft sediments. Both the sounding weight and the surveying rod were fabricated or modified such that all readings were direct. Samples for bulk density were collected from the reservoir bottom using a clam-shell sampler at six locations in 1993.

The design shoreline altitude of 160 ft was used for creating the bathymetric contour maps and as a reference datum in the reservoir volume calculations. The bed-elevation data points were plotted on a map of the reservoir and bathymetric contour lines at a 2 ft interval were drawn by hand for each survey. The contour lines were then digitized and entered into a GIS program. Figure 2 is the 1998 bathymetric map and is shown as an example of site bathymetry. Reservoir volumes were computed from the digitized contours by the GIS program using a triangulated irregular network (TIN) algorithm.

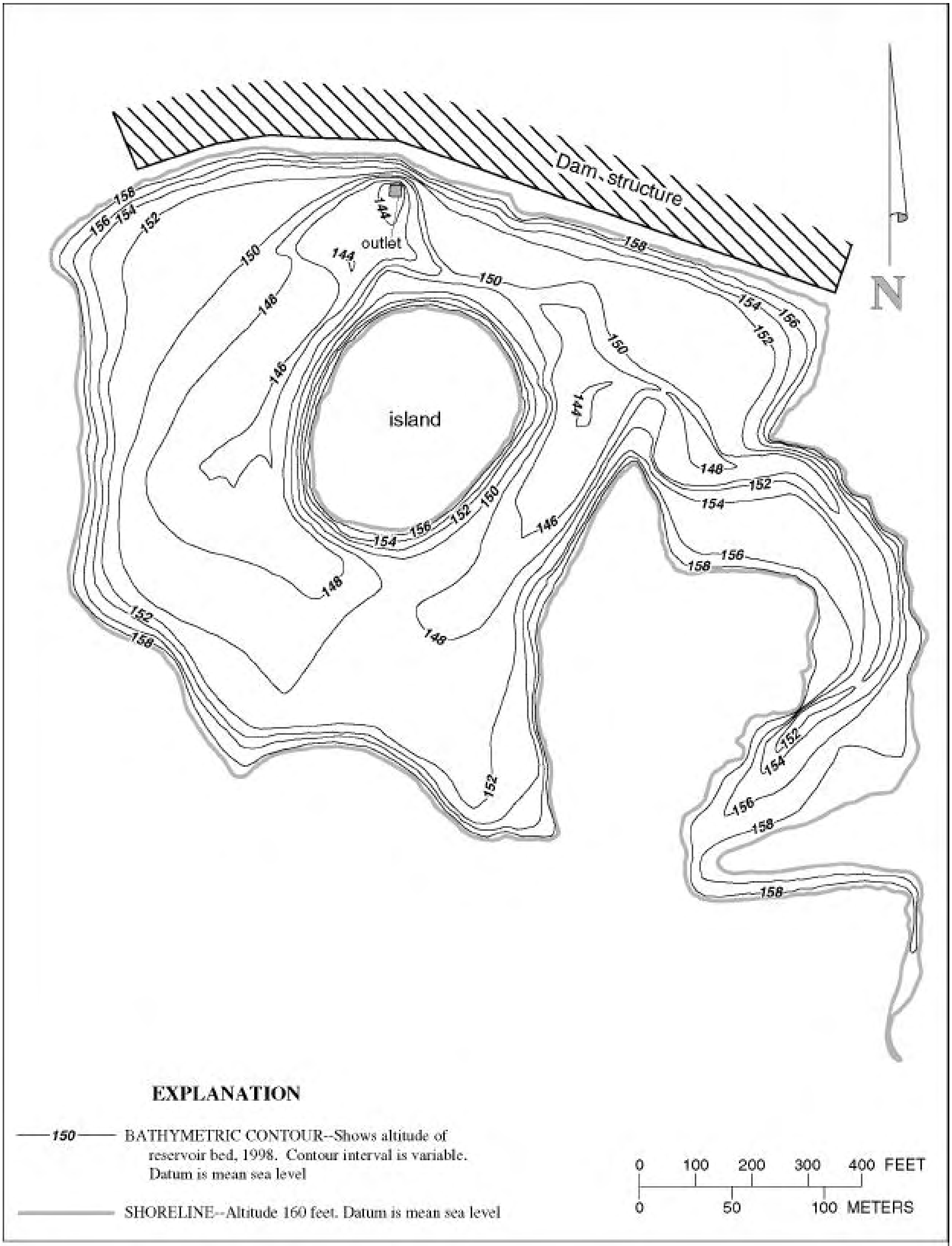

**Figure 2.** Bathymetry of the Waimaluhia Reservoir, 1998, Oahu, Hawaii.

## SEDIMENTATION

Rates of sediment accumulation in Waimaluhia Reservoir were determined by computing the changes in storage volume between surveys. Computed surface area and storage volume for each survey are shown in table 1. The total loss of storage volume during the construction period (1983-98, 15 years) was 30.3 acre-ft which gives an average loss rate of 2.0 acre-ft/year. During 1983-88, when construction of the Halekou Interchange took place (fig. 1) total storage loss was 5.9 acre-ft or an average of 1.2 acre-ft/year. The period of major construction activity in the watershed was the Windward highway construction which took place between 1989 and 1992. No sedimentation survey was done in 1989, so storage loss for this period was computed from the 1988 survey data which was done after the Halekou Interchange construction was completed. The total storage loss from 1988 to 1992 was 19.0 acre-ft which is equivalent to an average rate of 4.8 acre-ft/year. The total storage loss from 1992 to 1998 after all intensive construction work was completed was 5.4 acre-ft for a loss rate of 0.9 acre-ft/year. For the entire period of intensive construction work from 1983 to 1992, the total loss was 24.9 acre-ft, equivalent to a loss rate of 2.8 acre-ft/year.

**Table 1.** Computed area, volume, average bed altitude, and change in volume for Waimaluhia Reservoir, Oahu, Hawaii, 1983–98, based on bathymetric maps

[Area, volume, and calculated bed-altitude values are relative to 160.0 feet mean sea level pool elevation; bed altitude calculated by dividing volume by area, and subtracting that value from 160.0 feet; change in volume calculated by subtracting volume for previous survey's volume]

| Date of survey | Surface area (acre) | Storage volume (acre-feet) | Average bed altitude (feet) | Change in volume (acre-feet) |
|---|---|---|---|---|
| September 1983 | 26.8 | 239.6 | 151.1 | |
| November 1988 | 26.7 | 233.7 | 151.3 | -5.9 |
| August 1990 | 26.5 | 223.1 | 151.6 | -10.6 |
| September 1991 | 26.3 | 218.6 | 151.7 | -4.5 |
| September 1992 | 26.3 | 214.7 | 151.8 | -3.9 |
| August 1993 | 26.4 | 215.8 | 151.8 | +1.1 |
| July 1994 | 26.3 | 213.9 | 151.9 | -1.9 |
| September 1995 | 26.4 | 212.3 | 152.0 | -1.6 |
| July 1998 | 26.2 | 209.3 | 152.0 | -3.0 |

The trap efficiency of Waimaluhia Reservoir and the sediment yield of the surrounding drainage basin were determined from the bulk density, storage capacity, and suspended-sediment data. The average of all six bulk density samples of reservoir bottom sediments was 0.40 g/cm$^3$ or 25 pounds/ft$^3$. This value is quite low when compared to the average values of 40 to 65 pounds/ft$^3$ for submerged clay-silt mixture sediments (Geiger, 1963; Lara and Pemberton, 1963) and from suspended sediments (57 pounds/ft$^3$) sampled by Jones and others (1971). However, the 25 pounds/ft$^3$ value is not unusual when compared to the range of specific weights, 20 to 120 pounds/ft$^3$, determined for permanent pool reservoirs throughout the United States (Lara and Pemberton, 1963). Multiplying the total amount of sediment deposited in the reservoir, 30.3 acre-ft, by the average bulk density, 25 pounds/ft$^3$, gives the net amount of sediment trapped in the reservoir from 1983 to 1998, which is 16,500 tons. For a similar period from 1985 to 1997, for which complete years of data are available at stations 16270900 and 16272200, the suspended-sediment load that flowed through the reservoir was 7,700 tons. The total amount of sediment delivered to the reservoir can be estimated as the sum of the 16,500 tons deposited and the 7,700 tons discharged, or 24,200 tons. This number divided by the reservoir's drainage area of 3.20 mi$^2$

and the time of 15 years gives a sediment yield of 504 tons/mi$^2$/year. Adjusting the sediment load data to account for water years 1983-84 and 1998 by estimating through a comparison of sediment loads at stations 16270900 and 16272200 and partial years of record for 1984 and 1998 at station 16270900 only increased the load to 7,970 tons and sediment yield to 510 tons/mi$^2$/year. This value is about three times smaller then the sediment yield of 1,500 tons/mi$^2$/year used in the design of the reservoir. The trapping efficiency of the reservoir was computed by using the total suspended sediment load flowing through the reservoir (7,970 tons) and dividing by the total sediment yield or the sum of the total amount of sediment deposited (trapped) in the reservoir (16,500 tons) plus the amount flowed through (7,970 tons). Thus, the trapping efficiency is [1 - (7,970/24,470)] x 100 percent or 67 percent. This value compares favorably with an estimate of trap efficiency using the capacity/inflow (C/I) ratio relationship described by Brune (1953). A C/I ratio of 0.03 was computed for Waimaluhia Reservoir on the basis of the average of the 1983 and 1998 storage capacities and streamflow data at station 16272200. From figure 6 in Brune (1953) the trap efficiency is 70 percent with a possible range of 60 to 80 percent. Both the computed value and the value taken from Brune (1953) are slightly higher than the 60 percent trap efficiency design value.

## SUMMARY

The rate of sediment accumulation for the entire period of construction from 1983 to 1998 was 2.0 acre-ft/year, which was equal to the design loss rate. During the period of intensive construction activities, 1983-92, the loss rate was higher at 2.8 acre-ft/year. The highest loss rate of 4.8 acre-ft/year occurred during the period of greatest land disturbance during 1988-92. A trap efficiency of 60 percent, bulk density of 65 pounds per cubic foot, and sediment yield of 1,500 tons/mi$^2$/year were used to compute the design loss rate of 2.0 acre-ft/year on the basis of short-term sediment data collected from 1967-69 (Jones and others, 1971; U.S. Army Corps of Engineers, 1981). A trap efficiency of 67 percent, bulk density of 25 pounds per cubic foot, and a yield of 510 tons/mi$^2$/year were computed from data collected in this study. The differences in these two sets of values indicate that short-term sediment records used to predict reservoir sedimentation can result in large discrepancies.

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# SEDIMENT DEPOSITION RATES AND CARBON CONTENT IN THE SOILS OF AN AGRICULTURAL RIPARIAN ECOSYSTEM

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**Abstract** Research over the past 20 years has shown that riparian ecosystems capture sediments, carbon, and nutrients in the overland flow from upland watersheds. The purpose of this study was to determine the sediment deposition rates and carbon content of the soils/sediments in a riparian wetland ecosystem adjacent to a small first-order stream that drains an agricultural/forest area. The soils of the riparian area consist of histosols buried by recent sediments. Sediment deposition rates were determined using the $^{137}$Cesium technique to determine the 1954 and 1964 deposition layers. Profiles of deposited sediments in the riparian area and soils of the upland agricultural area were collected in 5 cm increments and the concentration of $^{137}$Cs in each increment was used to determine the sediment layer deposited in 1954 and 1964. Sediment deposition rates for the 1964 to 2000-period ranged from 0.14 to 0.69 cm yr$^{-1}$ with an average of 0.39 ∀ 0.20 cm yr$^{-1}$ while deposition rates for the period from 1954 to 1964 ranged from 0.50 to 2.00 cm yr$^{-1}$ with an average of 1.30 ∀ 0.44 cm yr$^{-1}$. Changes in rates of deposition between the two periods probably reflect changes in land use and agricultural practices in the watershed. $^{137}$Cs in the upland agricultural soils was uniformly distributed in the tilled layer. Carbon content of the riparian profiles in the 0-5 cm layer ranged from 2.4 to 14.4 % with an average of 8.0 ∀ 4.1 %. Carbon content of the 0-5 cm layer of the upland soils ranged from 0.8 to 3.0 % with an average of 1.7 ∀ 0.6 %. The riparian sediments (0-15 cm) have a fivefold increase in carbon as compared to the tilled layer (0-15 cm) of the upland soils indicating that large amounts of carbon have been captured within this zone of sediment deposition in the riparian zone. The recent riparian sediments (0-5 cm layer-8.0 % C) are enriched in carbon as compared with the older riparian sediments (30-35 cm layer - 3.4 % C). Rates of carbon buildup are higher than those that occurred in the premodern sediment of the wetland. These data suggest that carbon content in this riparian ecosystem is associated with increased sediment deposition rates.

## INTRODUCTION

A defining feature of landscapes in the Coastal Plain Province of the Eastern United States is the presence of areas of forest especially narrow strips or bands of forest and other vegetation along streams and waterways in areas that are too wet or too steep for agricultural use. These riparian ecosystems are recognized for having many valuable functions such as sediment trapping, nutrient removal, ground water recharge, flood reduction, and carbon storage. Research over the past 20 years has indicated that riparian ecosystems are effective buffers for reducing soil and nutrient movement from upland agricultural areas to streams in the Atlantic Coastal Plain. (i.e., Sheridan et al. 1999; Gilliam 1994; Cooper et al. 1987; Lowrance et al. 1986). Eroding soils transported to the riparian zone are deposited before they can enter the stream to be transported out of the watershed (Sheridan et al. 1982).

Wetlands, including riparian wetlands, form one of the largest carbon pools in the terrestrial biosphere (Armentano and Menges 1986; Moore and Bellamy 1974). Riparian wetlands usually receive material fluxes from the upland watershed and are considered sinks for sediment, carbon, and nutrients (Craft and Casey 2000). However, there are wide variations in the fluxes of sediment and carbon into riparian wetland depending on land use and management in the watershed as well as environmental factors.

The purpose of this study was to determine the rates of sediment deposition using the $^{137}$Cesium ($^{137}$Cs) technique in a riparian ecosystem adjacent to a small first-order stream that drains an agricultural/forested watershed in a Northern Coastal Plain area of Maryland. These sediment deposition rates will be used along with carbon content data to calculate sediment and carbon deposition rates.

## STUDY AREA

The study area is located on the Northern Coastal Plain physiographic province at the USDA-ARS Beltsville Agricultural Research Center in Beltsville, Maryland. The riparian ecosystem borders a first-order stream that drains an agricultural and forested watershed (Fig. 1). The watershed is approximately 40 m above sea level. The forest in the riparian zone is a mature bottomland forest typical of riparian wetland areas in the Coastal Plain of Maryland west of the Chesapeake Bay. Coastal Plain sediments of gravel, sand, silt and clay underlie the area. The soils of the riparian area are histosols

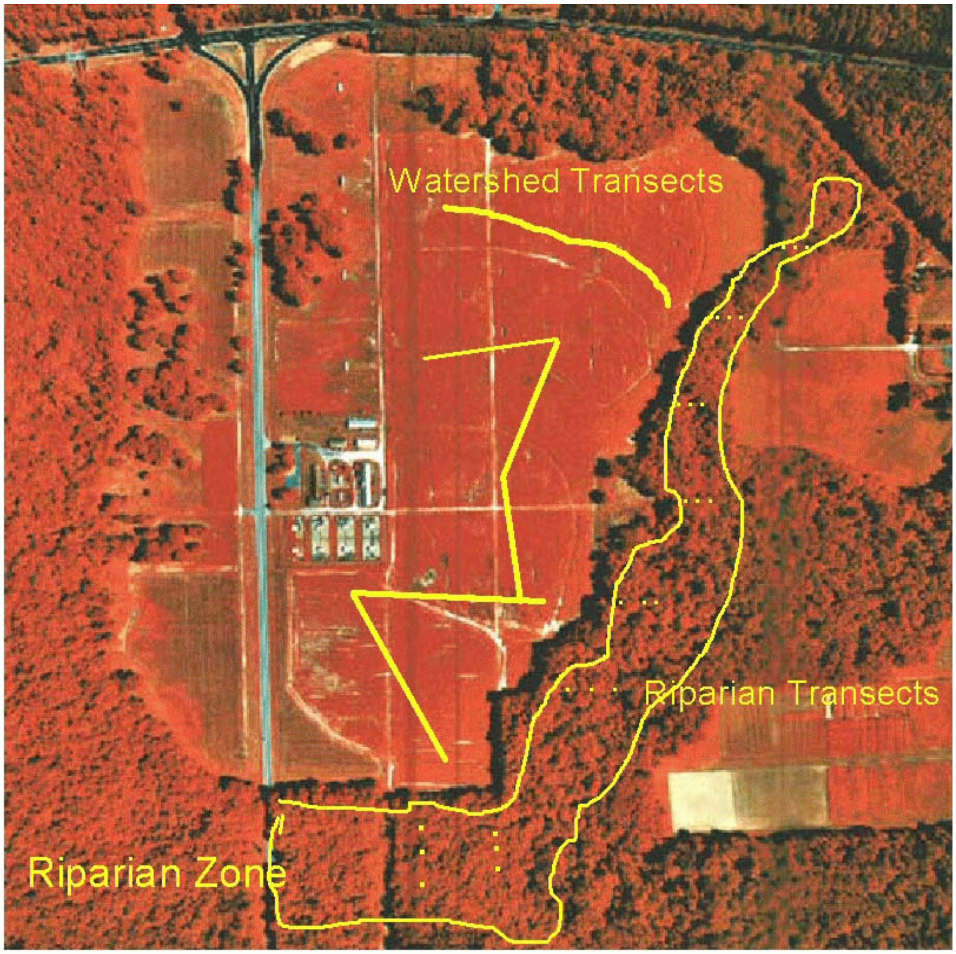

**Figure 1. Aerial photograph of study area showing the riparian and upland watershed sampling transect.**

(organic soil) which have been buried by 20 to 50 cm of recent sediments. The soils in the upland watershed are Hapludults, Paleudults, and Fragiudults consisting of four soil major series; Downer-Muirkirk-Matawan sandy loam, Bourne fine sandy loam; Matawan-Hammonton loamy sand, and Downer-Ingleside loamy sand. A clay layer at varying depth that acts as an aquiclude underlies the watershed.

Part of the watershed is the primary site for an USDA-ARS research program (OPE$^3$ - Optimizing Production Inputs for Economic and Environmental Enhancement) to compare the effects of different management treatments (conventional farming, precision farming, and animal waste treatments) on agricultural production systems (Dulaney et al. 1998). Four watersheds have been established for monitoring the effects of the different production systems. The OPE$^3$ watersheds have been well characterized for the chemical and physical properties of the soils as well as other physical properties of the watershed. Runoff and nutrient movement from the watershed is monitored.

The Chesapeake Bay influences the climate of the area. Based on climatological data collected at the Baltimore-Washington International Airport (1871-1999), which is approximately 30 km north of the study area, average annual temperature is approximately 13°C with monthly averages ranging from -4°C in February to 27°C in July. Average annual rainfall is 1035 mm with a range from 547 to 1584 mm for the 1871-1999 period.

## METHODS AND MATERIALS

Samples of the upland watershed and riparian zone were collected by pressing a 15-cm plastic corer into the soils or sediment to a depth of 30-40 cm. Samples were extruded from the corer and divided into 5 cm increments. Sample in the riparian zone were collected along eight transects (Fig. 1) with three profiles on each transect. Profiles were collected from the edge of the riparian zone to the stream channel. Soil samples on the upland watershed were collected along transects from the upper part of each of the four OPE$^3$ watersheds to the lower edge of the watershed.

Soil and sediment samples were dried at 90°C for 48 hours and weighed. The samples were passed through a 2-mm screen. A 1-liter Marinelli Beaker was filled with approximately 1000 g of the sieved soil and sealed for gamma ray analyses. Gamma-ray analyses were made with a Canberra[1] Genie-2000 Spectroscopy System. This is a Windows-based software/hardware package that receives input into two 8192 channel systems from two solid state crystals. One crystal is a Canberra Lithium-drifted Germanium crystal (GeLi - 15% efficiency) and the other is a Canberra high purity coaxial Germanium crystal (HpC - 30% efficiency). The system is calibrated and efficiency determined using an Analytic[1] mixed radionuclide standard (10 nuclides) whose calibration can be traced to U.S. National Institute of Standards and Technology. $^{137}$Cs is detected at 662 Kev and count time for each sample provides a measurement precision of ∀ 4 to 6 % on most samples. Estimates of radionuclide concentration of the samples are made using Canberra Genie-2000 software. $^{137}$Cs concentration is expressed in becquerel per gram (Bq g$^{-1}$).

Using $^{137}$Cs to estimate sediment deposition rates is based on measurements of $^{137}$Cs concentrations in depositional profiles (Ritchie and McHenry 1990). Two dates (1954 and 1964) can usually be determined. First global deposition of $^{137}$Cs occurred in 1954 and maximum deposition occurred in 1964. Soil erosion rates are estimated by comparing $^{137}$Cs concentration at a sample point with local fallout input of $^{137}$Cs as measured at the reference site where no loss of $^{137}$Cs has occurred (Ritchie and McHenry 1990). Sample sites with $^{137}$Cs concentrations less than the reference sites are eroding and sampling sites with higher concentrations are sites of deposition. Actual estimates of soil erosion and redeposition rates based on $^{137}$Cs concentrations are made using the models and software developed by Walling and He (1999).

Soil carbon analyses were performed by dry combustion using a Leco CNS 2000 elemental analyzer. Carbon concentration is expressed in percent (%).

## RESULTS AND DISCUSSION

The distribution of $^{137}$Cs in the upland soil was uniform in the plow layer (Fig. 2). This is typical of agricultural soils where tillage operations uniformly mix $^{137}$Cs in the upper part of the profile. In undisturbed soil profiles $^{137}$Cs

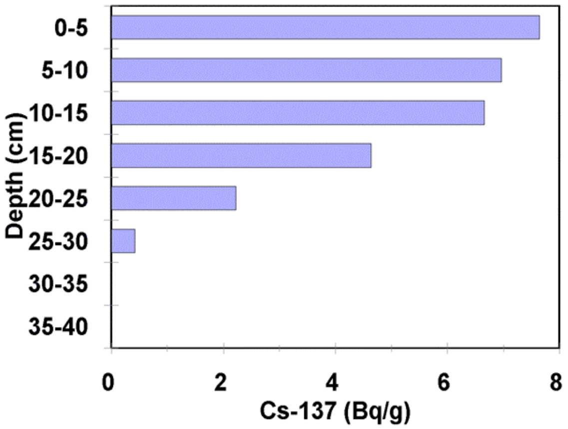

**Figure 2. Average depth distribution of $^{137}$Cs in upland soil profiles (Average of 17 profiles).**

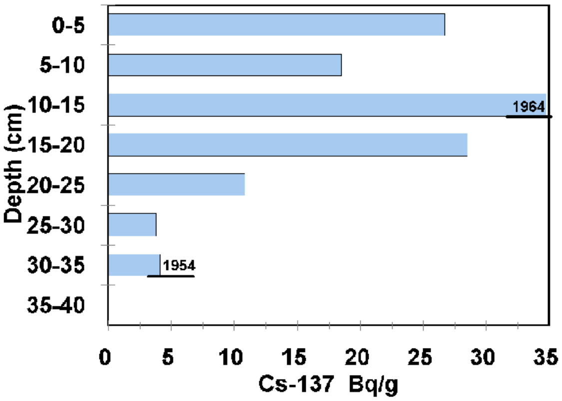

**Figure 3. Depth distribution of $^{137}$Cs in riparian profile A. Marks show 1954 and 1964 layers.**

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[1] Trade names are included for the benefit of the reader and do not imply an endorsement of or a preference for the product listed by the U. S. Department of Agriculture.

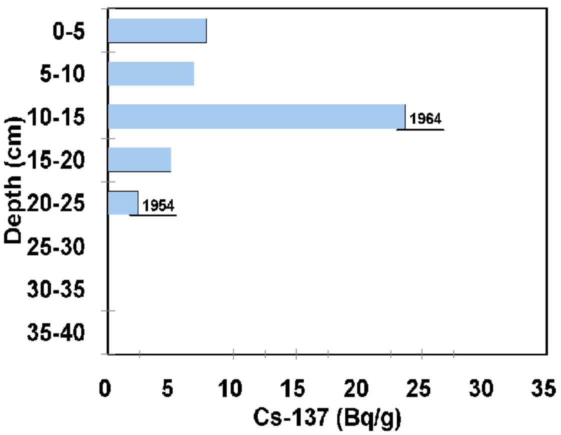

**Figure 4. Depth distribution of $^{137}$Cs in a riparian profile B. Marks show 1954 and 1964 layers.**

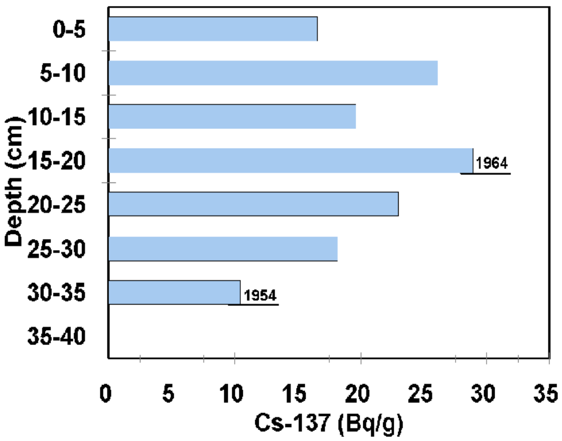

**Figure 5. Depth distribution of $^{137}$Cs in a riparian profile C. Marks show 1954 and 1964 layers.**

concentration shows an exponential decrease with depth with most of the $^{137}$Cs in the surface layer (Ritchie and McHenry 1990). Depth distribution of $^{137}$Cs in the soil profiles from the riparian zone varied (Figs. 3-5). Depth to the maximum $^{137}$Cs concentration ranged from the 0-5 cm layer to the 20-25 cm layer in different profiles. Average depth to the maximum $^{137}$Cs concentration was 12.5 ∀ 7.2 cm for 12 profiles. Assuming that the maximum concentration of $^{137}$Cs in the profiles occurred in 1964, the year of maximum fallout of $^{137}$Cs from the atmosphere, then deposition rates from 1964 to 2000 ranged from 0.14 to 0.69 cm yr$^{-1}$ with an average of 0.39 ∀ 0.20 cm yr$^{-1}$ for these 12 profiles. Depth to the 1954 sediment layer beyond which there is no detectable $^{137}$Cs ranged from the 10-15 cm layer to greater that 40 cm. Sampling depth in 5 of the 12 profiles did not go deep enough to reach a layer with no $^{137}$Cs concentration. Calculating deposition rates for the 1954 to 1964 period based on difference between the maximum depth of detectable $^{137}$Cs and the depth of the maximum concentration of $^{137}$Cs show a range of 0.5 to 2.0 cm yr$^{-1}$ with an average of 1.3 ∀ 0.4 cm yr$^{-1}$. However, this average rate should be higher since the total depth of $^{137}$Cs containing layers was not reached in 5 of the profiles. The difference in deposition rates between the 1954-1964 period and the 1964-2000 period could be due to changing management practices in the watershed that reduced the amount of soil loss in the watershed or a reduced efficiency of the riparian zone to capture the soils moving through the area.

These sediment deposition rates would indicate that the riparian zone is capturing and storing eroded soils entering the area. A wide range of sediment deposition rates has been published for riparian areas and floodplains (i.e., Ritchie et al. 1975; Cooper et al. 1987; Lowrance et al. 1988; Walling and Bradley 1989). The sediment deposition rates calculated for our study area are in the mid range of those published.

Carbon in the upland agricultural soil was uniformly distributed in the tilled layer (0-15 cm) with decreases in the layer below 15 cm (Fig. 6). Carbon concentration in these soils ranged from 0.65 to 2.96 % with an average of 1.56 ∀ 0.51 % in the 0-15 cm layer while soils below the tilled layer (15-30 cm) ranged from 0.17 to 1.57 % with an average of 0.57 ∀ 0.37 %. Total carbon in the upper 15 cm of the profile was 2.96 kg m$^{-2}$ with a total of 4.19 kg m$^{-2}$ in the upper 30 cm of the upland soils.

Carbon content of the riparian profiles was 2 to 6 times higher than the upland soil in the recent deposits (Fig. 7). Carbon content of the 0-5 cm layer in the riparian zone ranged from 2.4 to 14.4 % with an averaged 8.0 ∀ 4.1 % and was significantly higher than the other layers. This is an almost five-fold increase over the average carbon content (1.7∀ 0.6 %) in the surface soils (0-5 cm) of the upland area. Carbon in the 0-15 cm layer ranged from 0.85 to 14.4 % with an average of 5.55 ∀ 3.18 % for six profiles while carbon below 15 cm ranged from 0.75 to 14.25 % with an average of 3.18 ∀ 4.59 %. Carbon content in the 35-40 cm layer was similar to the carbon content of the upland soil. Total carbon in the upper 15 cm of the riparian profile was 7.49 kg m$^{-2}$ with 13.51 kg m$^{-2}$ in the upper 30 cm of the riparian profiles. This is an increase of total carbon by a factor of 2.5 and 3.2 for the upper 15 cm and upper 30 cm of the riparian profiles, respectively, when compared to the upland soil profiles. These data suggest that in addition to the carbon that is being captured from the overland flow in the riparian zone, primary production in the riparian zone is contributing to the buildup of carbon in the riparian profiles.

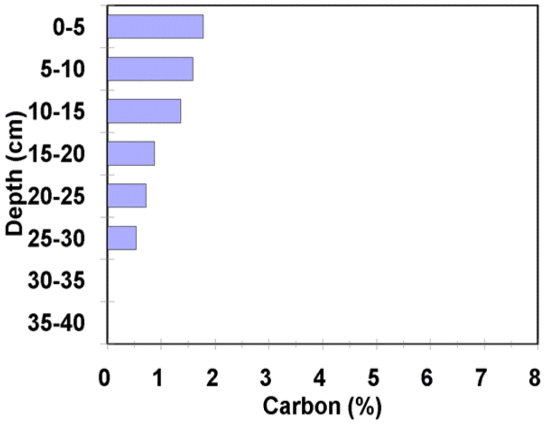

**Figure 6. Depth distribution of carbon in upland soil profiles (Average of 23 profiles).**

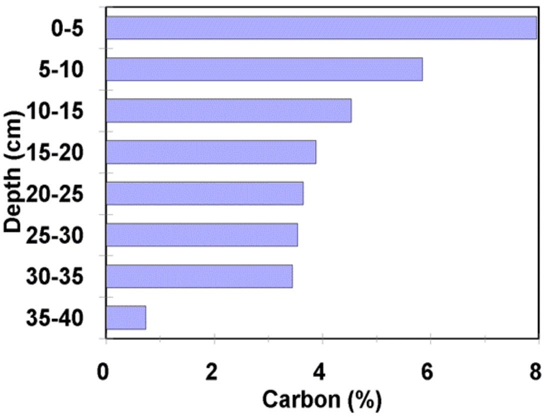

**Figure 7. Depth distribution of carbon in riparian soil profiles (Average of 6 profiles).**

## SUMMARY

The riparian area in this study is acting as a filter removing eroded soils from the overland flow before it reaches the stream. Sediment deposition rates measured using $^{137}$Cs for the 1964 to 2000 period ranged from 0.14 to 0.69 cm yr$^{-1}$ with an average of 0.39 ∀ 0.20 cm yr$^{-1}$ while deposition rates for the period from 1954 to 1964 ranged from 0.50 to 2.00 cm yr$^{-1}$ with an average of 1.30 ∀ 0.44 cm yr$^{-1}$. Studies are underway to estimate the erosion rates in the watershed. Combining these two data sets (erosion rates in the watershed and sediment deposition rates in the riparian zone) will permit estimates of the efficiency of the riparian zone for capturing eroded material from the overland flow.

Carbon content of the upland soils and the riparian sediments indicates that riparian buffer systems can be an important component of the overall watershed carbon budget. Our estimate of carbon storage in the riparian wetland is 5-8 times that in agricultural soils in the watershed in the upper 30 cm of the profile. Other studies (Ritchie and McCarty 2000) would indicate that there may be as much as 10-15 times more carbon in the total profile (0 - 200 cm) of the riparian zone. In terms of the total amount of carbon stored within soil resources of this watershed, the wetland may constitute a major portion of the soil carbon budget. This study supports the concept that riparian wetlands are sinks for carbon and may be significant sites for carbon sequestration.

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# COLLECTING SEDIMENT YIELD DATA FROM SEDIMENT DEPOSITS IN SMALL PONDS: POSSIBILITIES AND LIMITATIONS

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**Abstract:** Assessment of sediment transport to river channels is one of the major issues in watershed management studies. At present much is known about the rates and controlling factors of soil erosion by water, the primary source of sediment in river channels. Data on annual sediment loads in larger river basins are also available. The linkage between soil erosion processes on hillslopes and levels of suspended sediment in larger river channels, however, remains poorly understood, partly because no data are available for the intermediate scale. This paper discusses the possibilities and the limitations that sediment deposits in small ponds have to assess the sediment yield from these smaller watersheds (< 100 km²).

## INTRODUCTION

Probably one of the most important environmental problems associated with soil erosion by water is the high level of suspended sediment in river channels. Sediment deposition within riverbeds or reservoirs causes problems for navigation, water supply or energy production. Furthermore, sediment loads disturb aquatic environments, especially if many pollutants, e.g. phosphates, nitrates or heavy metals, are associated to sediment particles. A prediction of annual sediment delivery values to river channels is therefore highly needed. This can be done by lumped regression models using watershed characteristics (e.g. Bazoffi et al., 1996; Onstad, 1984; Flaxman, 1972) or spatially distributed models (e.g. LISEM, De Roo, 1996; SEDEM, Van Rompaey et al., submitted). The construction of these lumped models and the validation of spatially distributed soil erosion and sediment delivery models, however, requires a dataset on measured sediment yield values.

In the past, much research has focussed on the rates and controlling factors of soil erosion by water on rather small spatial scales varying from plot box studies in the laboratory over small field erosion plots to field parcels and very small watersheds of a few ha. On the other hand, sediment yield data from several large river basins (> 1000 km²) are available. Little information exists, however, for small watersheds (1-100 km²) that act as a very important link between the sediment sources in the landscape and the larger river channels. In this paper we will discuss a methodology to provide data on sediment yield for these small watersheds through the use of pond sediments. Throughout the world, several million of ponds are constructed for irrigation purposes, water supply or flood control. In many of these ponds, sediment deposition can be observed.

## ASSESSING SEDIMENT YIELD USING SEDIMENT DEPOSITS IN PONDS

**Methodology:** Sediment deposits in small ponds, lakes or reservoirs can be used to assess the sediment yield from the corresponding watershed with eq. (1):

$$SY = 100 \frac{SV * dBD}{TE} \tag{1}$$

with SY sediment yield (t $yr^{-1}$), SV the measured sediment deposition rate in volumetric units ($m^3$ $yr^{-1}$), dBD the dry bulk density of the sediment deposits (t $m^{-3}$) and TE the sediment trap efficiency of the pond (%).

**Possibilities:** The use of sediment deposits as presented by eq. (1) provides a cheap alternative to measure sediment yield compared to standard procedures like (1) sediment rating curves or (2) a suspended sampling program (measuring both discharge and sediment concentration). No expensive monitoring equipment has to be installed, neither are frequent field visits and maintenance operations required. At regular time intervals, e.g. once every year, the sediment level in the pond is measured with total station. Comparing two successive pond surveys gives the sediment deposition volume for the considered period. Since this method uses existing infrastructure and requires a minimum of time, many ponds can be surveyed annually over relatively large areas, providing information on the spatial variation in sediment yield.

Analysis of sediment cores taken from the ponds makes it possible to identify multiple depositional events. If eq. (1) is used for each event, a probability distribution of event sediment yields can be made (e.g. Laronne, 1990), which is similar to probability distributions of rainfall or runoff. In this way, ponds provide as much information on sediment delivery to river channels as continuous measurements of suspended sediment concentrations do.

## LIMITATIONS OF THIS METHODOLOGY

As is often the case with measuring techniques, the proposed methodology has some important limitations, which can be related to the estimation of each parameter needed to apply eq. (1). For each pond for which sediment deposition rates are known (i.e. SV), representative values for dBD and TE are needed. The accuracy on the calculated sediment yield value will therefore not only depend on the accuracy of the calculation of SV, but also on that of dBD and TE. The error on the calculated SY, E(SY), can be assessed by:

$$E(SY) = \sqrt{\sum_{i=1}^{3} \left( \frac{dx_i}{dSY} \right)^2 E(x_i)^2} \tag{2}$$

where $x_i$ represents SV, dBD and TE, and $E(x_i)$ equals the associated error on each of these parameters. Each of these possible errors will be discussed.

**Sediment deposition volumes:** The sediment level in the pond needs to be surveyed at regular time periods. This can be done with standard equipment (total station). By comparing two successive surveys with appropriate software (e.g. Surfer®, Golden Software Inc.), the recently deposited sediment volume can be calculated. The accuracy on SV will depend on both the accuracy of the survey and that of the volume computation. During survey, it is important that well-fixed checkpoints are used, which are not subject to even minor vertical or lateral

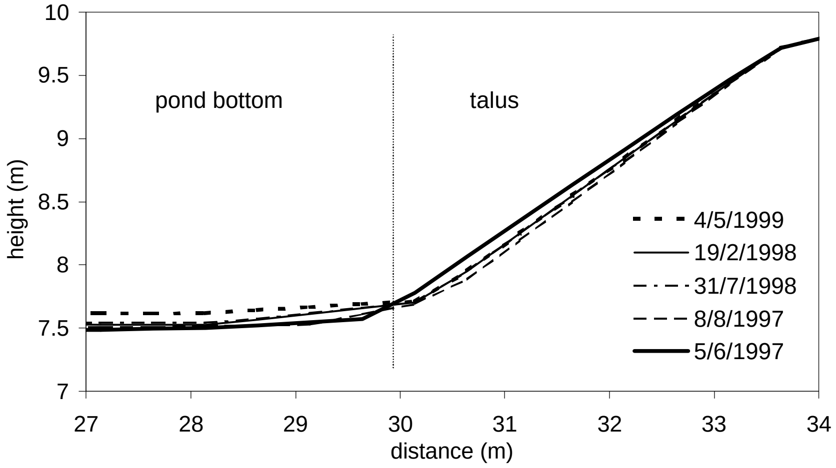

Fig. 1: Interpolated cross-sections for five successive surveys in a small pond.

displacements between two successive surveys. Measuring accuracy will nearly always be larger than equipment accuracy (the latter often less than 1 mm), certainly if the survey is conducted in rather difficult circumstances. A value of ± 5 mm is a fairly acceptable survey error. Total error on SV will be dependent on the rate of sedimentation and the pond area. High deposition volumes in a small pond (i.e. with high vertical accretion rates) will be determined with higher accuracy than low deposition volumes in a large pond (i.e. with low vertical accretion rates). Other important errors in volume computation can be related to the inadequate representation of marked topographical points in the survey (e.g. edges). This is illustrated for five successive surveys in a small pond (Fig. 1). The exact transition from the pond bottom to the talus was not surveyed at the same position during each survey. This will lead to changes in computed volume in the talus area, which are not caused by sediment deposition, and will introduce errors in SV. Table 1 compares the calculated values of SV for two situations: 1) all surveyed points are used, including those on the talus; 2) only those points in the pond bottom, where deposition takes place, are included.

Table 1: Computed values of SV for four periods in a 2000 m² pond as a function of survey procedure.

| period | volume 1° | volume 2* |
|---|---|---|
| June 1997-August 1997 | -12 | 15 |
| August 1997-February 1998 | 31 | 15 |
| Februari 1998-July 1998 | 16 | 0 |
| July 1998-May 1998 | 100 | 67 |
| June 1997-May 1998 | 135 | 97 |

° all survey points used, incl. talus (m³)
* only with survey points on the pond bottom (m³)
note: a survey error of 5 mm corresponds with 4 m³

**Dry sediment bulk density:** Sediment yield data are normally expressed in mass units (t $yr^{-1}$) so measured sediment volumes need to be converted to sediment masses using a representative value of the dry sediment bulk density (dBD, t $m^{-3}$). Data from several large US reservoirs showed that dBD is controlled by sediment texture, hydrologic condition (aerated-submerged) and the thickness of sediment deposits (e.g. Morris and Fan, 1998). Several empirical equations and overview tables have been established in the past using these data and are nowadays widely used (e.g. Lane and Koelzer, 1943; Miller, 1953; Koelzer & Lara, 1958; Lara and Pemberton, 1963; Komura, 1963; USDA, 1983).

The use of these techniques for sediment deposits in small ponds, however, may yield significant errors as is illustrated for flood retention ponds in central Belgium (Verstraeten and Poesen, in press). The dBD of the deposits within each of the 13 studied ponds vary both in space as with

Table 2 Dry sediment bulk density (dBD) of sediment deposits in 13 flood retention ponds in central Belgium.

| pond | overall texture | prevailing hydrologic condition* | number of samples | dBD (t m$^{-3}$) of all samples min. - max. | mean dBD (t m$^{-3}$) | CV (%) (95%)° |
|---|---|---|---|---|---|---|
| Sterrebeek | silt loam | E, Se | 10 | 1.158 - 1.343 | 1.265 | 10 |
| Ciplet | silt loam | E, Se | 30 | 1.187 - 1.430 | 1.320 | 19 |
| Hannut | silt loam | E | 11 | 1.152 - 1.472 | 1.350 | 14 |
| Ville-en-Hesbaye | silt loam | S, Eld | 5 | 0.888 - 1.171 | 1.002 | 23 |
| Holsbeek | loamy sand | S, Eld | 12 | 1.003 - 1.443 | 1.185 | 21 |
| Hammeveld | silt loam | E, Se | 40 | 1.140 - 1.580 | 1.340 | 19 |
| Mullem | sand | S | 11 | 0.738 - 1.304 | 1.035 | 31 |
| Munkbosbeek | sand | E, G | 10 | 0.946 - 1.325 | 1.112 | 10 |
| Broenbeek | sand | S | 3 | 0.860 - 0.956 | 0.776 | 10 |
| St.-Jansbeek | sand | S | 8 | 0.313 - 1.403 | 0.955 | 80 |
| Steenbeek | sand | S | 3 | 1.007 - 1.140 | 1.096 | 14 |
| Nerm | silt loam | E, Se | 15 | 0.871 - 1.536 | 1.313 | 25 |
| Hoegaarden | silt loam | E, Se | 8 | 1.239 - 1.321 | 1.27 | 7 |

*E: normally empty; Se: submerged for several weeks after a runoff event; S: normally submerged; Eld: empty after a long dry period; G: high groundwater level, sediments mostly saturated.

° CV (%) (95 %): coefficient of variation at two standard deviations, i.e. 2 times the standard deviation divided by the mean.

time. Mean dBD for each pond varies from 0.78 t m$^{-3}$ to 1.35 t m$^{-3}$ (Table 2). Sediments that are mostly aerated have higher values of dBD while this is lower for submerged sediments. This observation is in agreement with the data from large reservoirs. This is not the case, however, if sediment texture is considered: coarser sediments have lower observed values of dBD than finer sediments. Since most submerged ponds are characterised by coarse sediments and the dry ponds by finer sediments, it might be concluded that for the studied ponds, the hydrologic condition is more important in controlling dBD than sediment texture does. As most empirical equations from large reservoirs give more importance to sediment texture, it was not surprising that their predictions for the studied ponds were not satisfactory (Fig. 2). The fact that the hydrologic condition of the ponds were in most cases not static but rather dynamic (changing from dry to submerged and back to dry in short time spans) also contributed to errors in predicted dBD. Errors on the mean predicted dBD varies from 1% to 72% with mean values in the order of 20%. It should be

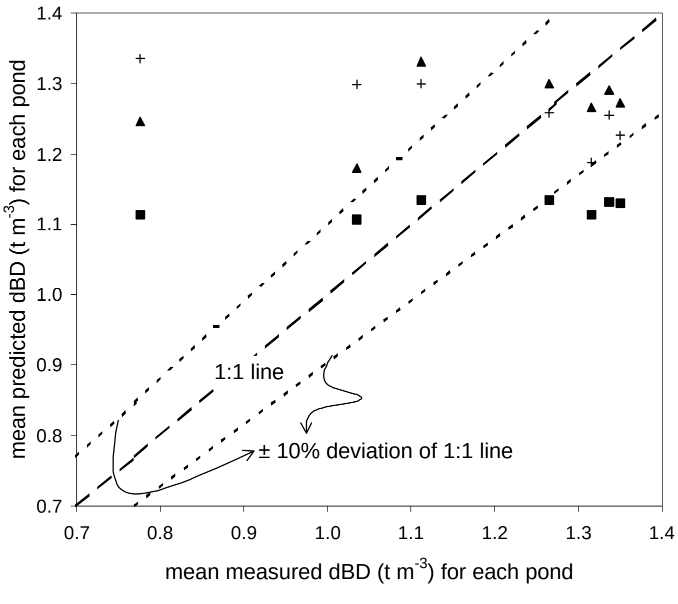

Fig. 2: Predicted versus measured mean dBD for seven ponds. (+) Komura (1963); (%) Miller (1953) with values of Lane and Koelzer (1943); (!) Miler (1953) with values of Lara and Pemberton (1963).

noted that one method might yield good predictions for one pond but bad predictions for other ponds and vice versa.

This illustrates that the use of simple empirical equations outside the area where they were constructed for (i.e. large reservoirs with rather static conditions) can lead to substantial errors. Frequent and dense sampling of pond sediments is therefore needed to reduce the risk of large errors in dBD.

**Sediment trap efficiency:** The proportion of the inflowing sediment that is deposited in a pond is called the sediment trap efficiency (TE). Verstraeten and Poesen (2000) gave an overview of the various methods that can be used to predict TE. Many empirical relations have been drawn in the past, mostly for normally ponded reservoirs, based on easy calculated parameters like a capacity/inflow ratio (e.g. Brune, 1953; Brown, 1943; Churchill, 1948; Heinemann, 1981). These models, however, are not suitable for smaller ponds with highly variable hydrologic conditions, certainly if they are not normally ponded. Furthermore, the empirical methods are valid for mid-term to longer term predictions of TE, while this methodology needs values for TE for each period for which SV is measured. Year to year variations in rainfall and runoff may cause varying values of annual TE. For a small flood retention pond in central Belgium (2000 m³), annual TE as calculated with several of these empirical equations ranges from 9% to 94%, depending on the assumptions that have to be made. It is clear that this is not a valid basis to calculate sediment yield values.

On the other hand, many theoretical models have been constructed based on the principles of sedimentation physics in water (e.g. DEPOSITS, Ward et al, 1977; CSTRS, Wilson and Barfield, 1984; BASIN, Wilson and Barfield, 1985). These models, however, produce TE values for single events, whilst using eq. (1), a mean TE value for the period over which SV is deposited is needed. Verstraeten and Poesen (2000) concluded that the lack of theoretically based models that predict the mid-term TE for small ponds with varying geometric and hydraulic characteristics makes a correct interpretation of sediment records in small ponds difficult. Recently, a first approach to solve this problem is made by the development of STEP (Sediment Trap Efficiency model for small Ponds; Verstraeten and Poesen, submitted a) that simulates the TE of a pond for a continuous record of flow events. Fig. 3 shows the results of simulations with STEP for a small flood retention pond in central Belgium (2000m³) for a 30-year period. Large variations in annual TE are simulated (58% to 100%) with a weighed average of 68% (weighed for the annual deposited sediment volume).

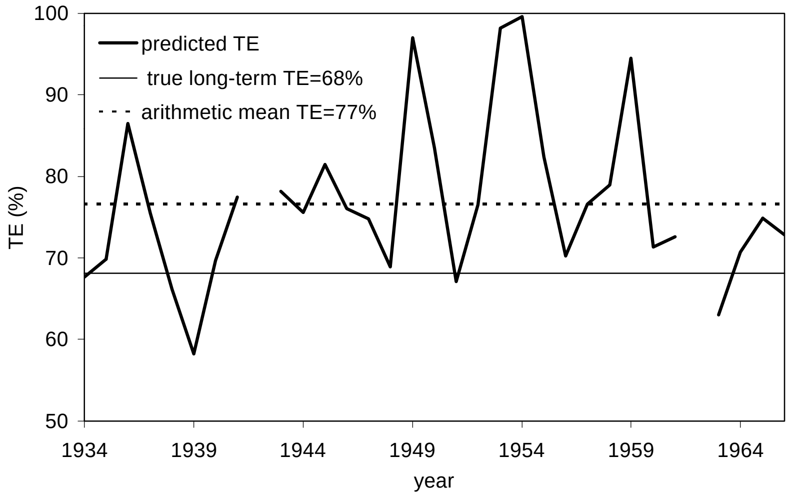

Fig. 3: Annual variations in simulated TE for a 2000 m³ pond.

**Total errors on sediment yield:** Using eq. (2) the error on computed SY (eq. (1)) can be estimated. If SV, dBD and TE can be estimated with an accuracy of 20%, which are realistic error values, total errors on SY for 21 small ponds surveyed in central Belgium can be estimated at 38%-201%, with a median error of 43%. These errors can be reduced if dBD is measured by dense sampling, and when surveying is done carefully. For a 29 ha area with a 2000 $m^3$ pond, the calculated SY totals 107 t $yr^{-1}$ if TE and dBD are calculated with empirical equations and with incorrect survey procedures (see Table 1). If, however, measured dBD is used, good survey points and observed values of TE (only available for this particular pond), SY equals 148 t $yr^{-1}$, which is 38% higher than the first, rough estimate.

## IMPLICATIONS AND CONCLUSIONS

It can be questioned whether these mean errors on computed sediment yield of 40% to 50% are acceptable. These errors should therefore be compared to errors associated with other methods to quantify SY. The use of sediment rating curves, which are based on a limited number of samples, can also result in significant errors on computed sediment load (Walling and Webb, 1981; Walling, 1994; Robertson and Roerish, 1999). Frequently, sediment load is underestimated with sediment rating curves, often up to 60%-80% (Walling and Webb, 1981). If the sediment load is measured together with runoff discharge, the accuracy will depend on the sampling regime and sampling frequency (e.g. Robertson and Roerish, 1999). Steegen et al. (2000) found that the widely used technique of time-spaced sampling underestimates sediment yield with 20% to 35% compared to flow-proportional sampling (storm chasing). In addition, the operation of sampling suspended sediment in river channels will also generate errors. Steegen and Govers (in press) showed that errors up to 25% are made if the sample is taken near the bottom of the flow, due to the existence of a concentration gradient in the flow.

Overall, mean errors associated with eq. (1) are not too high compared to those of other methods, certainly not if attention is paid to survey accuracy and dBD assessment which would reduce the errors to 20%-30%. It can therefore be concluded that the methodology described in this paper is a valuable tool for studying spatial variations in sediment yield from various watersheds over relatively large areas (e.g. Verstraeten and Poesen, submitted b). This makes it possible to construct lumped regression models to predict sediment yield for other watersheds. Furthermore, these collected data can be used for calibrating and/or validating spatially distributed sediment yield models (e.g. Van Rompaey et al., submitted). This is mostly not done since adequate data are lacking.

On the other hand, the construction of even sediment yield probability distributions by identifying individual sediment layers in cores will probably not be realistic. The mean sediment thickness of these events is often that low (e.g. only ± 2 cm in the ponds studied by Laronne, 1990, with many much smaller) that errors in SV will be relatively large. Furthermore, each event will be characterised by varying values of TE, certainly for small ponds where the storage capacity compared to runoff volumes is much lower than it is for large reservoirs. Given the high difficulty involved in estimating annual TE, it will be even more difficult in relating each sedimentary event to a particular value of TE.

It should be stressed that, whatever the methodology used, each value of sediment yield that is computed should be associated with an error. This is mostly lacking in soil erosion and sediment yield studies.

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# CHARACTERIZING THE SEDIMENT IMPOUNDED BY USDA-NRCS FLOOD CONTROL DAMS, OKLAHOMA

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## INTRODUCTION

Since 1948, the USDA-Natural Resources Conservation Service (NRCS) has constructed over 10,450 flood control dams in 47 states under the Flood Control Act of 1944 (PL-534), the Pilot Watershed Program (1953-54), the Watershed Protection and Flood Prevention Act of 1954 (PL-566), and the Resource Conservation and Development Program (Caldwell, 1999). The primary purposes for these structures were to prevent flooding and to protect watersheds. Other dams were built or have evolved into structures for water management, municipal and industrial water supply, recreation, and the improvement of fish and wildlife, water quality, and water conservation. More than $14 billion (1997 dollars) of federal and local funds have been invested in these projects. They provide nearly $1 billion in benefits annually.

Flood control dams typically consist of an earthen embankment 6 to 20-m high with a principal spillway made of concrete pipe 0.3 to 1.8-m wide (Caldwell, 1999). Because the dams were built on small streams in the upper reaches of watersheds, upstream drainage areas range from 1.6 to 16 $km^2$. The majority of these dams were planned and designed for a 50-year service life. The inlet pipe of the principal spillway is placed at an elevation that would provide water retention for the design storm and storage for sediment accumulation. Each reservoir also has an emergency or auxiliary spillway for safe conveyance of water around the embankment when runoff rates exceed storage capacity.

At present, more than half of the dams constructed are older than 34 years and more than 1,800 will reach their 50-year design life within the next 10 years (Caldwell, 2000). A rapid survey conducted in April 1999 revealed more than 2,200 dams in need of immediate rehabilitation at an estimated cost of more than $540 million. The primary issues of dam rehabilitation are: replacement of deteriorating components, change in hazard classification, reservoir sedimentation, failure to meet dam safety regulations, failure to meet resource needs of the watershed, inadequate land and water rights, inadequate community benefits, and the potential transfer of responsibility. Common approaches to address rehabilitation typically involve dredging the reservoir to remove accumulated sediment, raising the dam to increase storage capacity, and removing or decommissioning the dam.

Rehabilitation of aging watershed flood control dams is critical to Oklahoma. Since 1948 more than 2,100 watershed flood control dams have been constructed including 1,140 in the Washita River Basin, which was one of the original eleven watershed projects authorized by PL-534. Many of these dams are in critical need of rehabilitation (Caldwell, 2000).

Before any rehabilitation strategy can be designed or implemented, the sediment impounded by these dams must be assessed in terms of the structure’ s efficiency in regulating floodwaters, the potential hazard the sediment may pose if reintroduced into the environment, and the future projection of sediment delivery to the reservoirs in light of changing land-use, hydrology, and rates of erosion. To this end, a demonstration project was designed to evaluate technologies, methodologies, and protocols for the cost-effective characterization of impounded sediment. This project had four primary objectives.

1. Define a chronology of land-use and hydrology within the particular watershed. This would identify the potential agrochemicals or other contaminants within the sediment and provide information on rates and patterns of deposition.
2. Use high-resolution geophysical techniques to map the subsurface sediment stratigraphy. Such equipment is capable of detecting non-intrusively decimeter-scale reflectors (seismic horizons) several meters below the bottom of the lake.
3. Use vibracoring equipment to obtain continuous, undisturbed sediment cores through the entire post-construction deposit. Once extracted and opened, each core would be logged and sediment samples secured.

4. Use analytical and sedimentological techniques to determine the quality, mineralogy, and physical characteristics of the sediment including heavy metal and agrochemical concentrations and the amounts of radioactive isotopes for dating purposes.

Two USDA-NRCS flood control dams were chosen for examination. Sugar Creek #12 is located near Hinton, OK and dam construction was completed in 1964. The structure has an upstream drainage area of 817 ha (2,016 acres). Historic land-use includes cultivated fields of cotton and peanuts and drilling operations for oil and gas production. Sergeant Major #4 is located in Cheyenne, OK and dam construction was completed in 1955. This structure has an upstream drainage area of 1,513 ha (3,735 acres). Historic land-use is primarily rangeland with several oil and gas drilling sites located within its drainage area. Sergeant Major #4 has become the sole municipal water supply for the town of Cheyenne (population 1000).

For each lake, chronologies of land-use and hydrology are being constructed, the seismic data were collected and are being processed, undisturbed cores of the deposited sediment have been secured, and the chemical composition of the sediment is being determined. Preliminary results from the seismic surveys and the chemical (heavy metal and agrochemical) composition of select sediment samples were discussed in Bennett and Cooper (2000). Here, we present results of the vibracoring activities at each of the reservoirs and discuss the stratigraphic and sedimentological characteristics of these cores with special reference to designing and implementing dam rehabilitation strategies.

## VIBRACORING EQUIPMENT AND PROCEDURE

Vibracoring is a common approach for obtaining undisturbed cores of unconsolidated sediment in saturated or nearly saturated conditions (Lanesky et al., 1979; Smith, 1984). Vibracoring works on the principle of transferring a high-frequency vibration to a thin-walled core pipe held in a vertical position on the sediment bed. The vibrating pipe causes the liquefaction or fluidization of sediment only at the core-sediment interface, thereby allowing the pipe to penetrate the sediment with little resistance and without disrupting sediment stratification.

A commercially available vibracoring system is used in this study. This system uses a 1-HP motor that drives a pair of weights (masses) eccentrically mounted on two shafts and housed within a water-tight aluminum chamber. When in operation, the masses rotate in opposite directions causing the chamber to vibrate at frequencies ranging from 6000 to 8000 RPM depending upon the sediment substrate. The chamber (driver) is connected to the top of an aluminum irrigation pipe 1.5-mm thick, 76-mm wide, and over 3-m long and cabled to a 4.2-m high aluminum tripod fitted with a battery-operated winch. Since the driver is sealed, the entire system can be immersed into water. A simple check valve placed into the flange connecting the core pipe to the driver induces internal suction during core extraction. The tripod is mounted to a raft that can be easily carried and constructed on-site, towed with a small boat, and anchored into position.

Once the core has been driven into the sediment, the vibrating motion is stopped and the winch lifts the core to the water surface. When successful, the core typically has a hard sediment bottom that acts as a seal. If excessive sand or gravel is present at the bottom of the core, the entire contents of the pipe are lost during lifting. The position of the raft is recorded with a hand-held GPS receiver whose data are differentially corrected using available base station information. The core is transferred to the boat and transported to shore. Each core is opened on-site by cutting the aluminum pipe length-wise on both sides with a circular saw, and the top half of the pipe is carefully lifted from the sediment. The core is photographed and logged and sediment samples secured for laboratory analysis.

## RESULTS AND DISCUSSION

Continuous, undisturbed cores were obtained at Sugar Creek #12 (10 in total) and Sergeant Major #4 (4 in total) and their positions are shown in Figure 1. These cores ranged in length from 1.3 to 3.1 m and were extracted from water depths ranging from about 2 m at Sugar Creek #12 and up to 12 m in Sergeant Major #4. Select examples are shown in Figures 2 and 3. The positions for these cores were chosen to coincide precisely with the seismic profiles collected previously (Bennett and Cooper, 2000). Equipment failure prohibited the collection of additional cores at Sergeant Major #4.

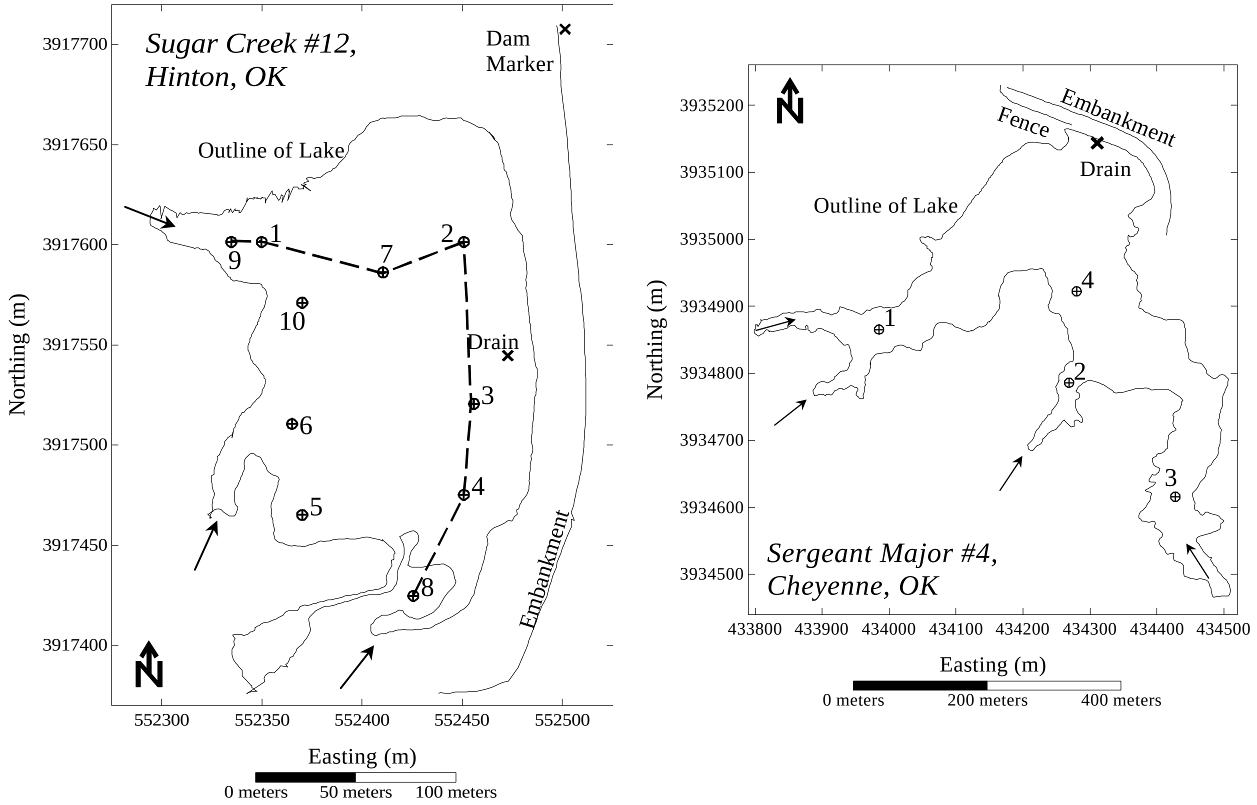

**Figure 1: Base maps of Sugar Creek #12 (on left) and Sergeant Major #4 (on right) constructed using a hand-held GPS receiver with differential corrections applied. Shown are the outline of the lake (taken in October 1999), the centerline of the earthen embankment, the primary spillway (drain), other pertinent benchmarks, the location of all sediment cores (numbered), and the main tributaries entering the reservoir (arrows). For Sugar Creek #12, the dashed lines show the positions of the stratigraphic cross-sections depicted in Figures 4 and 5. All positions are in UTM coordinates.**

**Radioactive Cesium Analysis and Determination of Rates of Sedimentation:** Select cores were analyzed for radioactive Cesium ($^{137}$Cs; 30-year half-life) for the purpose of dating sediment horizons. Since $^{137}$Cs is produced during nuclear fission, its presence in the environment is due to nuclear testing or releases from nuclear reactors (Ritchie and McHenry, 1990). First global deposition of $^{137}$Cs occurred in 1954 and maximum deposition occurred in 1964 in the Northern Hemisphere, related to above ground nuclear testing, and in 1980 (Europe) due to the Chernobyl nuclear accident. Since $^{137}$Cs is strongly adsorbed on clay and organic particles and is essentially non-exchangeable, its concentration can be used as a unique tracer for erosion and sedimentation. Rates of sediment accumulation can be calculated by knowing the depth of these different $^{137}$Cs horizons.

The following cores were chosen for $^{137}$Cs analysis: 4, 7, and 9 from Sugar Creek #12, and 1 and 4 from Sergeant Major #4. Sediment samples were obtained inclusively at increments of 0.15 m at Sugar Creek #12 and 0.1 m at Sergeant Major #4 and encompassed the entire core length. All samples were dried in a greenhouse, crushed, and passed through a 2-mm sieve. A 1-L beaker was filled with sediment, sealed, and a gamma ray spectrometer was used to measure $^{137}$Cs emissions for a period of 30,000 seconds, providing measurement precision of ±4 to 6% (Ritchie and Rasmussen, 2000).

The concentration of $^{137}$Cs (becquerels per gram; Bq/g) as a function of core depth is shown in Figure 2 for Sugar Creek #12 and Figure 3 for Sergeant Major #4. For Sugar Creek #12, a peak in the $^{137}$Cs emissions occurs at a subsurface depth of 1.98 m (lower bound of histogram bar) for Core 4 and 1.83 m for Core 7. This peak coincides with the 1964 peak in $^{137}$Cs fallout. A similar peak was observed at 1.07 m for Core 9 (not shown here). Using this 1964 datum, sedimentation rates from 1964 to the present are 55.0, 50.8, and 29.6 mm/yr or 0.067, 0.062, and 0.036

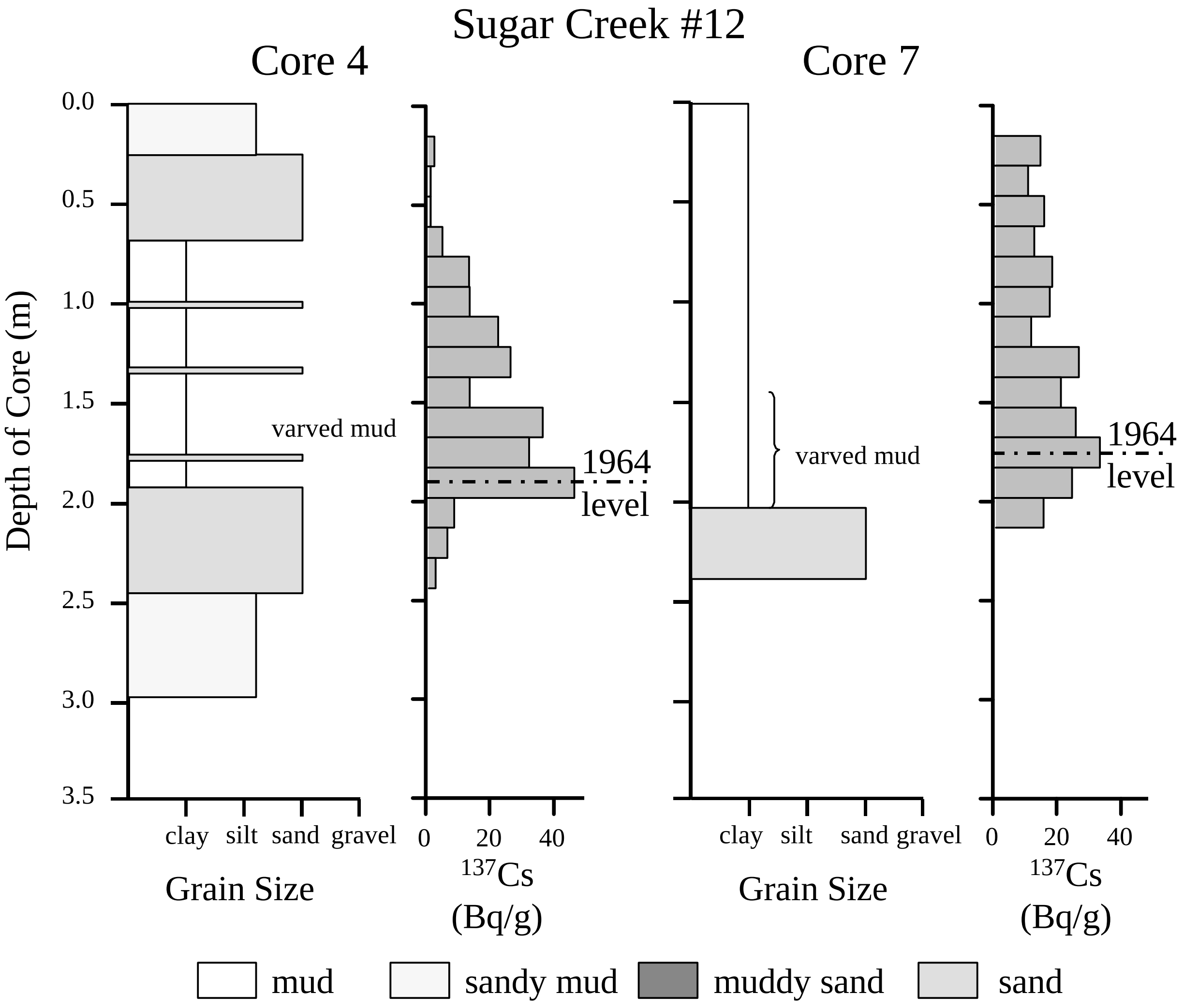

**Figure 2: Stratigraphic logs and distributions of $^{137}$Cs for Cores 4 and 7 obtained at Sugar Creek #12. For the stratigraphic logs, grain size and lithologic descriptions are based on observational criteria. The peaks in the distributions of $^{137}$Cs coincide with the 1964 datum, and some samples near the top and bottom of each core had zero emissions.**

mm/ha-yr (using drainage basin area) based on Core 4, 7, and 9, respectively. The sand deposited below these stratigraphic levels (Figure 2) is interpreted as parent (pre-construction) material.

Similar peaks in the distribution of $^{137}$Cs and the demarcation of the 1964 datum are observed in the cores taken at Sergeant Major #4 (Figure 3): at 0.91 m for both Core 1 and 4. From 1964 to the present, a sedimentation rate of 25.4 mm/yr or 0.017 mm/ha-yr is deduced from these cores. Since the dam was constructed in 1955, the sand and gravel located stratigraphically below the mud layers (Figure 3) are interpreted as parent (pre-construction) material. Therefore during the period from 1955 to 1964, sedimentation rates are 28.2 and 18.3 mm/yr or 0.019 and 0.012 mm/ha-yr based on Core 1 and 4, respectively. This proposal is substantiated by the presence of alternating layers (laminae) of black and brown mud interpreted as varves, which represent seasonal variations in water stratification due to temperature and its effect on silt and clay deposition (Leeder, 1982).

In a number of samples near both the top and bottom of the cores, no $^{137}$Cs was detected (Figures 2 and 3). This lack of $^{137}$Cs emission is attributed to the presence of sediment that has not been exposed to the atmosphere since 1954.

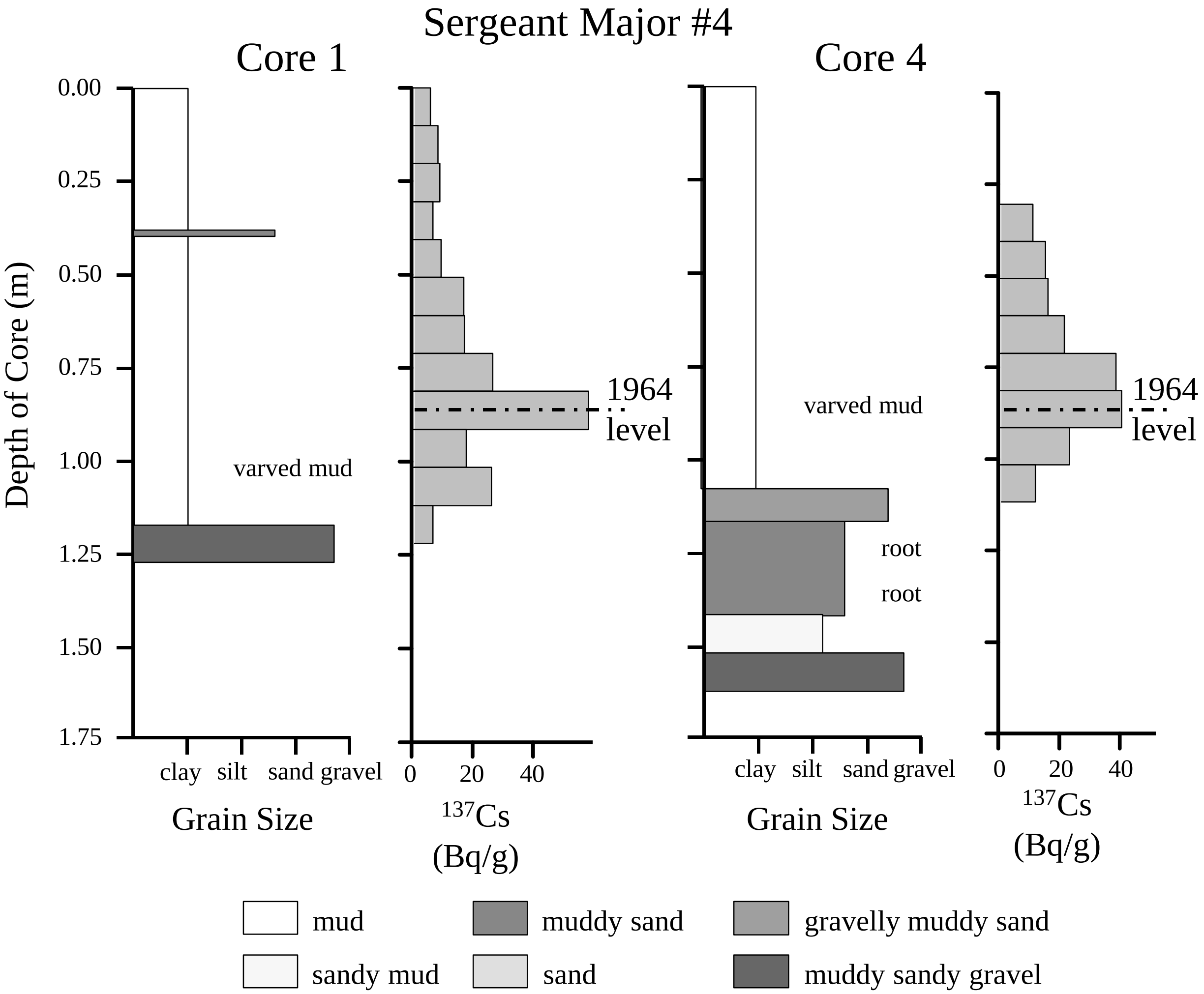

**Figure 3: Stratigraphic logs and distributions of $^{137}$Cs for Cores 1 and 4 obtained at Sergeant Major #4. For the stratigraphic logs, grain size and lithologic descriptions are based on observational criteria. The peaks in the distributions of $^{137}$Cs coincide with the 1964 datum, and some samples near the top and bottom of each core had zero emissions.**

**Physical and Stratigraphic Characteristics of Sediment Impounded at Sugar Creek #12:** The physical and stratigraphic characteristics of the sediment deposited at Sugar Creek #12 were assessed using several methods. From each core, 2 to 5 sediment samples were processed for grain size, color, and magnetic susceptibility. For each sample, approximately 10 g of sediment was dispersed overnight (using sodium hexametaphosphate). Total percent clay (<0.002 mm) by mass was determined by siphoning off 5-mL of the dispersed sediment and using the pipette method (Method 3A1, Soil Survey Staff, 1992). Total percent sand by mass was determined by wet sieving the remaining sample through a 0.053-mm sieve and weighing the dried sediment retained. Total percent silt by mass was calculated by subtracting the masses of sand and clay from the original sample mass. Quantitative color was determined using a chroma meter that employs a self-contained pulsed xenon arc lamp as a light source (see Lindo et al., 1998). Saturated sediment colors using the Munsell system of hue, value, and chroma are reported here (Munsell Color Company, 1994). In addition, dried and crushed sediment samples were packed into 20-mL glass vials and the magnetic susceptibility of the sample was measured using a specialized meter (values presented here are in SI units; $10^{-8}$ $m^3$/kg; see Lindbo et al., 1997). The magnetic susceptibility of each glass vial was determined prior to use.

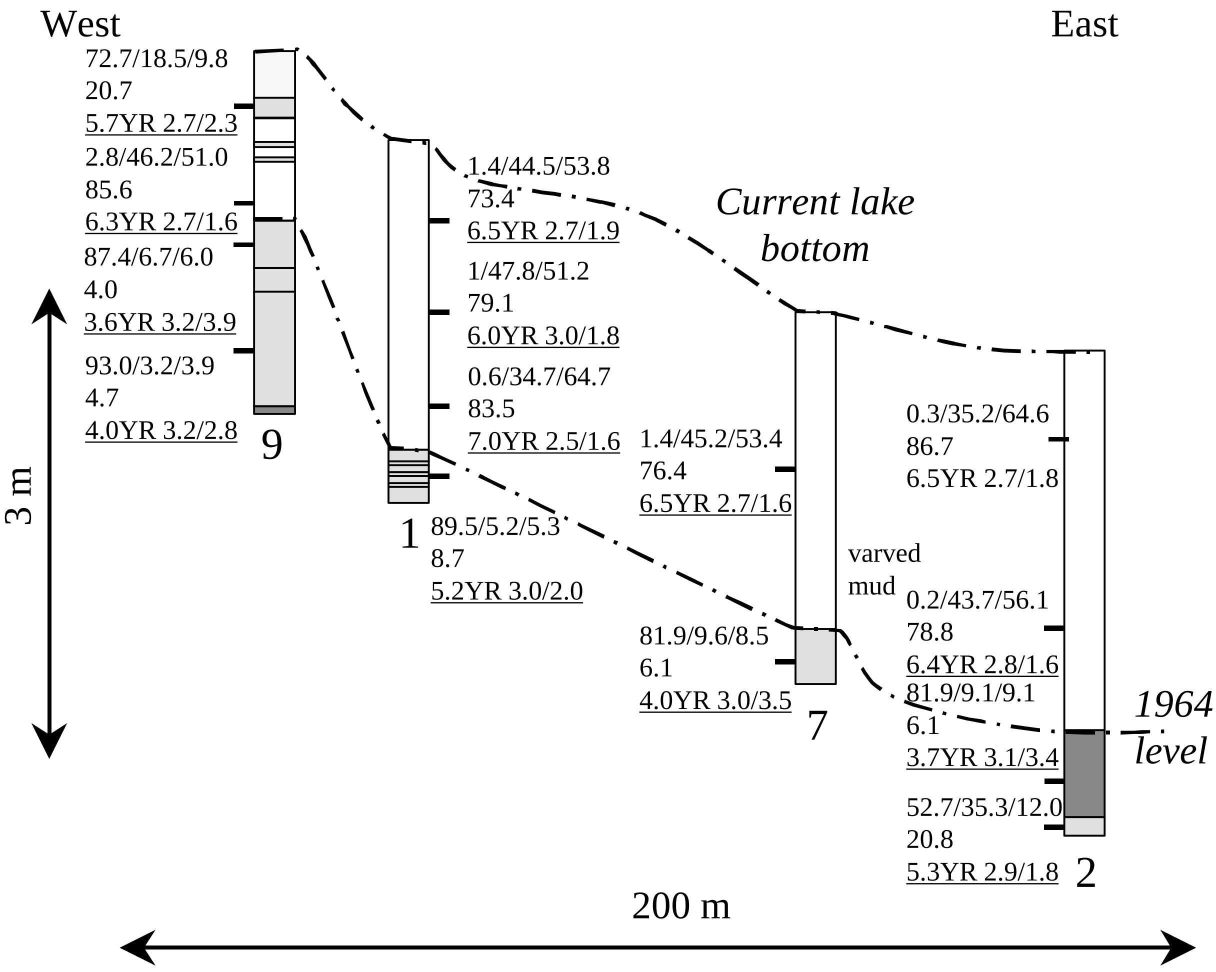

**Figure 4: A west to east representation of the subsurface stratigraphy obtained at Sugar Creek #12 for Cores 9, 1, 7, and 2, placed relative to the current lake bottom and distance across the reservoir (note vertical exaggeration). Lines show the current lake bottom and the 1964 datum. The location of the sediment samples examined are shown by the tick marks, and the numbers beside each tick give grain size (top line, given as % sand/silt/clay), magnetic susceptibility (middle line, given as $10^{-8}$ $m^3$/kg), and color (on bottom and underlined, given as hue YR value/chroma where YR is yellow red). Refer to Figure 2 for legend.**

Stratigraphic columns for two traverses across Sugar Creek #12 are shown in Figures 4 and 5. Each core was placed with respect to the elevation of the current lake bottom and the distance across the reservoir (note vertical exaggeration). Grain size (top line, given as % sand/silt/clay), magnetic susceptibility (middle line, given as $10^{-8}$ $m^3$/kg), color (on bottom and underlined, given as hue YR value/chroma where YR is yellow red), and the results for the $^{137}$Cs analysis were used to correlate lithostratigraphic units across the basin as well as establish time lines. These methods were only partially successful due to the low number of sediment samples analyzed.

**West to East Traverse:** This traverse starts in the northwest corner of the lake near one of the main tributaries and extends eastward toward the deepest part of the reservoir near the embankment (Figures 1 and 4). The 1964 datum deduced by the $^{137}$Cs results can be extended with certainty across the entire basin. As this time line coincides with the construction of the dam, all sand and gravel present at depths greater than about 1.5 m is considered pre-construction material. Near the tributary source (western side), there are several sand deposits younger in age than 1964, some as thin as 30 mm. Yet none of these sand units extends into the deeper part of the basin. Volumetrically, silt and clay in approximately equal proportions dominate the sediment deposit along this traverse.

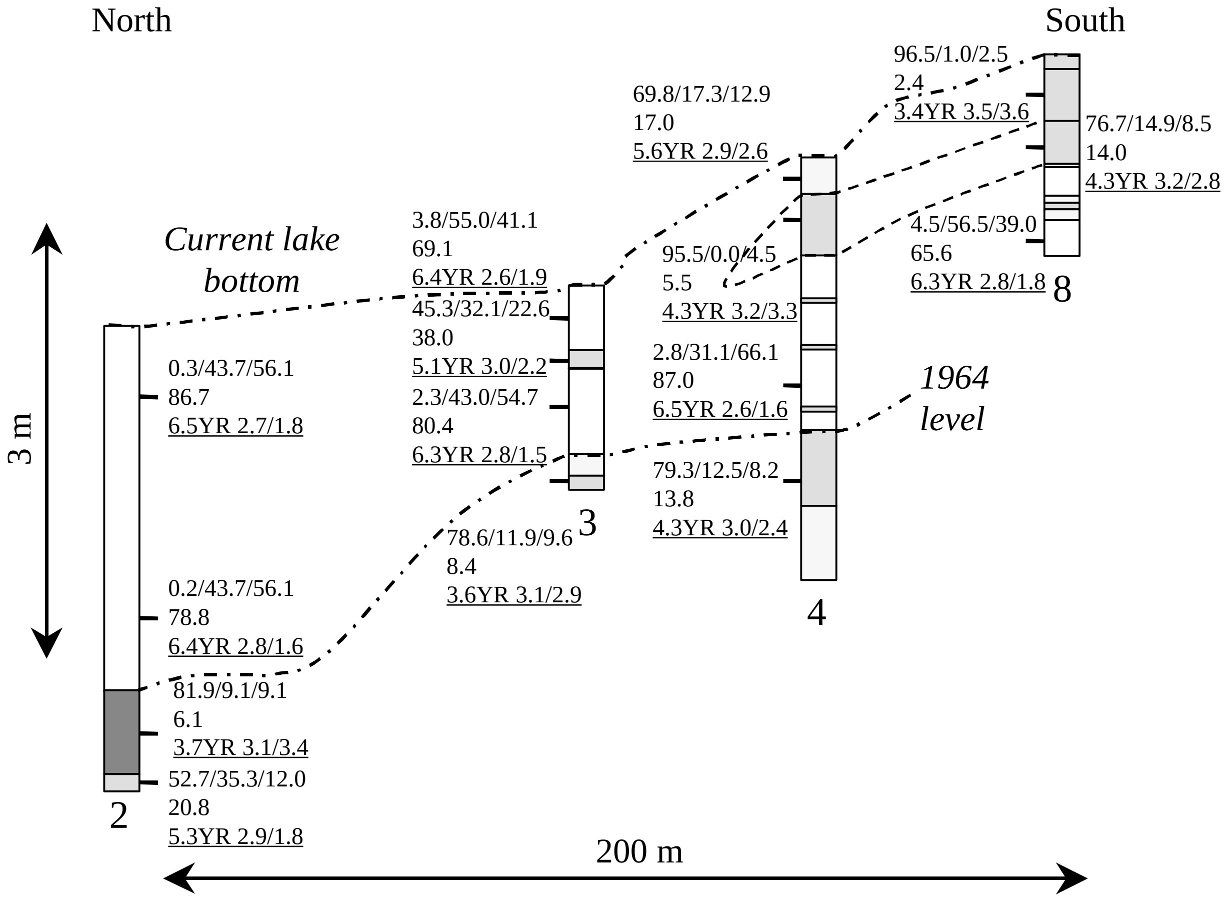

**Figure 5: A north to south representation of the subsurface stratigraphy obtained at Sugar Creek #12 for Cores 2, 3, 4, and 8, placed relative to the current lake bottom and distance across the reservoir (note vertical exaggeration). Lines show the current lake bottom, the 1964 datum, and common lithologic units. The location of the sediment samples examined are shown by the tick marks, and the numbers beside each tick give grain size (top line, given as % sand/silt/clay), magnetic susceptibility (middle line, given as $10^{-8}$ $m^3$/kg), and color (on bottom and underlined, given as hue YR value/chroma where YR is yellow red). Refer to Figure 2 for legend.**

**North to South Traverse:** This traverse starts near the northeast corner of the basin, runs essentially parallel to the embankment toward the tributary entering the southern end of the reservoir (Figures 1 and 5). The 1964 datum determined for Core 4 can be extended with certainty toward the north. Several sand layers were deposited after 1964 near the tributary source, some as thin as 10 mm. One sand unit in Core 8 can be correlated to Core 4 (Figure 5), and it most likely becomes the muddy sand unit in Core 3. Moreover, the thin-bedded sand units near the base of Core 8, demarcated by alternating red and brown colors, probably correlate with the sand lenses in Core 4 although the latter are separated by decimeter-scale layers of silt and clay. While there are some observable sand deposits, most of the sediment that has accumulated along the traverse is silt and clay in nearly equal proportions.

**Discussion**: The analysis of $^{137}$Cs in the deposited sediment proved instrumental in identifying the 1964 datum and determining average sedimentation rates at Sugar Creek #12 after 1964 (55.0, 50.8, and 29.6 mm/yr or 0.067, 0.062, and 0.036 mm/ha-yr; see above) and for Sergeant Major #4 from 1955 to 1964 (28.2 and 18.3 mm/yr or 0.019 and 0.012 mm/ha-yr) and after 1964 (25.4 mm/yr or 0.017 mm/ha-yr). The sediment deposited within these reservoirs is dominated by silt and clay. The likely sources of these sediments are hillslopes, agricultural fields, gullies, and riverbanks that are actively eroding. While the removal of silt and clay from agricultural lands depletes soil productivity, these size fractions also are more likely transporting agrochemicals (see review in Leonard, 1990).

The deposition of sand is restricted in space to their tributary sources. The occurrence of sand lenses in the deeper parts of the reservoir is most likely related to historically large runoff events.

## SUMMARY

A demonstration project was initiated to assess the sediment impounded by USDA-NRCS flood control dams at two locations in Oklahoma for the purpose of dam rehabilitation or decommissioning. This project currently is defining a chronology of land-use and hydrology in each watershed, using geophysical technology to map the subsurface sediment, employing vibracoring equipment to obtain continuous, undisturbed sediment cores, and determining the chemical and physical characteristics of the sediment. Preliminary results for the vibracoring activities are presented and discussed.

At both Sugar Creek #12, Hinton, OK and Sergeant Major #4, Cheyenne, OK, vibracores of the entire sediment deposit were obtained and examined. Radioactive $^{137}$Cs defined the 1964 fallout horizon in both reservoirs and permitted sedimentation rates to be accurately determined. Stratigraphic analyses showed that at Sugar Creek #12 (1) stratigraphic correlation of some lithologies and time lines across the basin were possible, (2) silt and clay dominate the depositional history of the reservoir, and (3) deposition of sand was limited to areas near its tributary source. This stratigraphic information will be combined with on-going activities to completely address sedimentation issues within these aging flood control dams.

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# DEER CREEK- SAFE PROJECT OR FLOOD HAZARD?

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## ABSTRACT

Debris basins in combination with concrete-lined downstream channels have been used extensively in Southern California to control flooding on alluvial fans undergoing urbanization. Most of these projects have been designed using a deterministic (design flood) approach for sizing both the debris basin storage capacity and downstream channel hydraulic conveyance capacity. Recently the Corps of Engineers addressed the issue of the level of protection afforded by a completed project, Deer Creek Debris Basin and Channel, from a probabilistic standpoint.

The Deer Creek watershed is comprised of two distinct areas. The headwaters portion of Deer Creek is a 3.7 square mile watershed in the San Gabriel Mountains east of Los Angeles that is very steep and has the potential to produce high sediment loads. The lower portion of Deer Creek flows through an alluvial fan now occupied by the City of Rancho Cucamonga in San Bernardino County, California. Although the Corps' Deer Creek Debris Basin and Channel has safely controlled all flood events on Deer Creek since completion of the project in 1984, some local residents expressed concerns with the adequacy of the project to control severe flood and debris events. An evaluation of the level of protection provided by the Deer Creek Project was performed that considered probabilistic estimates of debris yield, active channel capacity upstream of the debris basin, debris deposition pattern within the debris basin, performance of the debris basin for events exceeding its design capacity, coincident frequency of debris yield and flood events, operation and maintenance practices of the project owner, sediment transport and hydraulic conveyance in the downstream channel, and application of Federal Emergency Management Agency regulations for defining the level of flood protection on alluvial fans.

# DAM DECOMMISSIONING: DECISIONS AND UNRESOLVED SEDIMENT TRANSPORT ISSUES

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**Abstract** More than 300 dams have been removed in the United States, and the pace of dam decommissioning is likely to increase. Almost 1,000 dams will require Federal Energy Regulatory Agency (FERC) relicensing in the first half of this century. Many thousands more dams, not subject to FERC licensing, are also aging. Dams are decommissioned because (1) benefits no longer exceed operation costs, or (2) the expense to rehabilitate the structure is prohibitive, or (3) reservoir sedimentation decreases project benefits significantly, or (4) adverse impacts on fish passage require mitigation. There are at least two major issues when facing a dam decommissioning decision: how exactly to proceed, and how to predict the upstream and downstream impacts of sediment release on the stream channel system. How to proceed is explained using a systematic method for evaluating alternatives when considering dam decommissioning for fish passage mitigation. The method presented for evaluation examines (1) no action; (2) upgrading facilities; (3) partial dam removal; and (4) full dam removal. How sediment releases impact upstream and downstream channels is explained by citing additional case studies. It is shown that unanticipated impacts can occur following sediment releases that degrade fish habitat and navigation, and that impacts on long-term geomorphology are yet poorly understood. A case is made for additional and accelerated research before additional unnecessary mistakes are made.

## INTRODUCTION

Over the past 100 years the US has led the world in dam building. The US Army Corps of Engineers has catalogued approximately 75,000 dams greater than 1.5 m high along the waterways of the US (Graf, 1999). The average life expectancy of a dam is 50 years. Approximately one-quarter of all US dams are now more than 50 years old, and this figure will reach 85% by the year 2020 (American Rivers, 1999). As these aging dams come up for re-licensing or rehabilitation, people are questioning the need for many of the dams. A dam may have outlived its intended purpose and no longer have any official use, or the environmental impacts of the dam may outweigh its benefits (Baxter, 1977; Brooker, 1981; Goldsmith and Hildyard, 1984; Stanford and Hauer, 1992; Ligon et al., 1995; Collier et al., 1996). For example, aging dams, especially smaller projects, are producing fewer benefits due to reservoir sedimentation upstream and inefficient turbines, gates, and ancillary facilities. Sedimentation and age also contribute to an increase in flood risk due to dam overtopping and potential dam failure. The cost to rehabilitate many smaller dams may be prohibitive. Coupled with these problems are growing efforts to reverse adverse impacts of dams such as constituting barriers to fish migration, upstream aggradation and downstream scour, changes in upstream and downstream geomorphology and riparian habitat, and water quality degradation.

At least 121 dams have been removed in the US since 1930, and the rate of dam removal has accelerated during the 1980s and 1990s (American Rivers, 1999). These dam removals have been conducted in ignorance of potential negative impacts from the release of associated sediment stored in reservoirs. As progressively larger dams are removed in the future, the potential for sediment-related hazards grows concomitantly. Yet in almost every potential dam removal situation, there will be some lost benefits which local government agencies and citizens will not want to sacrifice. As a result, it is imperative to examine a broad range of options to help justify the final decision. These options range from *no action* to *full dam removal.* Each option has its own associated cost and benefits that can not (and should not) be determined without careful investigation. The impacts of each alternative may extend far downstream of the original project and may dictate the final solution. For example, a common concern involves the transport and fate of sediments that may have been trapped in the reservoir for decades. Downstream deposition of previously trapped sediments may create flooding, navigational, or environmental concerns. The rate of sediment scour, the sloughing of incised channels made by reservoir drawdown, and possibly even the type of embankment material all contribute to the list of factors that must be examined.

The impacts of sediment release following dam decommissioning are poorly understood. The few documented case studies available describe some of the possible hazards: downstream fish kills and in-filling of riffle-pool habitat; unanticipated release of PCB-contaminated sediments, and blockage of upstream navigational channels. Other potential impacts include a degradation of aquatic and riparian habitat, increased deposition and/or scour at bridge crossings, destabilization of streambanks and streambeds, and decreased water quality.

The purpose of this paper is to discuss (1) a systematic method of evaluating options when dealing with decommissioning and fish migration mitigation, and (2) the need to better understand the upstream and downstream processes of sediment transport and geomorphology following dam removal.

## SYSTEMATIC PROCEDURE FOR EVALUATING DAM DECOMMISSIONING OPTIONS

A total of 952 dams are due to be relicensed in the first half of this century (FERC, 2000). This number does not include the thousands not covered under FERC relicensing authority. For example, in the Pacific Northwest alone, there are 3,348 dams, more than half of which are less than 12m high. Of these structures, 74% are more than 30 years old and 37% are more than 50 years old (Perkins, 2000). And this is not a problem confined to the Pacific Northwest. As illustrated in Table 1, approximately 41% of all dams located in the US are 40 years old or older. The decommissioning of a dam is generally based strictly on economic criteria and occurs primarily when the purpose for which the dam was constructed is no longer being met, or is no longer considered important. In other words, the liability associated with the physical structure is no longer supported by project benefits. The economics for decommissioning may also be based on changes in environmental considerations that have occurred such as the restoration of fish habitat or fish migration routes. In the latter case, the primary intent of dam removal may be negated for a period of decades if the manner in which the reservoir is drained results in substantial downstream channel change because of excess sediment release. If sedimentation is a factor in the evaluation, case studies indicate that the entire retirement process is subject to the sediment management plan (Task Committee, 1997).

**Table 1 – Number of Dams Built in Each Decade in the United States (USACE, 1998)**

| | Pre-1800 | 1800-99 | 1900-49 | 1950-59 | 1960-69 | 1970-79 | 1980-89 | 1990-present | Total |
|---|---|---|---|---|---|---|---|---|---|
| Number | 23 | 2,459 | 13,978 | 11,366 | 19,264 | 13,035 | 5,006 | 2,373 | 67,504 |
| Percent of Total | 0 | 4 | 21 | 17 | 29 | 19 | 7 | 4 | 100 |
| Cumulative Percent | 0 | 4 | 24 | 41 | 70 | 89 | 96 | 100 | - |

The decision to remove an existing dam involves a complex interaction between various environmental and societal factors. The rational and thorough consideration of each of these factors and their interrelationships can involve an extremely complex and costly scientific and engineering analysis for a single proposed removal project. Initial project planning of a possible dam removal candidate should begin similar to that of any typical watershed assessment. Any pertinent information about the water resources of the watershed should be obtained. Lists of intended and current beneficial reservoir uses should be compiled. All known water quality and quantity problems in the area must also be considered. After examining the current beneficial uses, all potential stakeholders should be identified and contacted. State environmental, fish and wildlife, and historical preservation agencies should also be involved in the process as soon as feasible.

Each of these tasks will greatly facilitate the making of the final decision. Information concerning local hydrology may influence project scheduling or may help support decisions concerning the long-term liability with respect to dam breaching. Determining the beneficial users will help identify the stakeholders. It would be a mistake to consider a stakeholder only someone that has direct interest in the water. Many local residents may consider the reservoir as an aesthetic pleasing addition to the landscape. Reservoirs, particularly those on public lands, may have uses that were initially unanticipated that local residents will quickly point out. Identifying upstream watershed activities may give an indication of the sediment quality trapped within the reservoir that can significantly alter the cost of decommissioning.

From the initial meeting with stakeholders and agencies, a long list of possible alternatives is likely to emerge. Suggestions will likely range from no-action to full dam removal. To build consensus for the decision, it is best not to summarily dismiss any reasonable recommendation. Instead, the next phase of the project evaluation will be to determine the benefits, disadvantages, and obstacles of each alternative. Often, several ideas can be combined into a single project. The process involves conducting preliminary cost estimates for each alternative. During this phase, costs can be limited to the real expenditures necessary for upgrading the existing facilities or removing the dam. It is important to include the future cost of dam removal and the liability in the no action alternative since no structure will last forever. The result is a short-list of potential alternatives that can be brought back to the regulators and stakeholders for additional discussion.

The next phase is to examine the benefit/cost ratio for each final alternative. At this point, refined cost estimates will be necessary and should be expanded to include any indirect costs. Benefits are much more difficult to quantify. For example, full dam removal eliminates future liability concerns but what is the exact dollar figure that should be assigned to that benefit. Non-cash benefits are even more difficult to value. If the reason for decommissioning is being driven by restoration of anadromous fish runs that has been listed as an endangered species, determining the value of a single fish is a widely debated topic. Furthermore, determining the number of fish likely to return in the future is an exercise in best reasonable judgment at best. Recent attempts to develop methodologies to overcome these obstacles are still in their infancy. Anderson and Barber (2000) proposed a framework for prioritizing small dam removal, however the process relies on relative magnitudes rather than specifically trying to determine economic value. Consequently, evaluation of a single project with their methodology is not currently possible. Nevertheless, in cooperation with the stakeholders, some reasonable estimate will likely need to be determined.

One technical issue that can dramatically effect project costs is the behavior and treatment of sediments stored within the reservoir. The remainder of this paper focuses on the issues that engineers and scientists must address in determining the best restoration and/or removal strategy.

## SEDIMENT TRANSPORT AND GEOMORPHOLOGY ISSUES

The release of reservoir sediment following dam decommissioning may potentially create severe hazards along affected river channels upstream and downstream from the dam. A rapid downstream flux of sediment may: degrade aquatic and riparian habitat; impair channel-based recreation such as fishing or rafting; reduce bank stability and put structures such as bridges or irrigation intakes at risk; cause channel-bed aggradation and enhance overbank flooding; reduce water quality by increasing turbidity, and by decreasing dissolved oxygen as a result of buried organic matter being exposed to decay; and result in the downstream deposition and transport of contaminants adsorbed onto fine sediment particles (Allen et al., 1989; Knighton, 1989; Richardson, 1991; Kattelmann, 1996). Upstream impacts are similar but are generally inverted to downstream impacts (Hotchkiss, 1999). Removal of the reservoir pool generally permits increased water velocities that may cause excessive bank scour. In addition, streambanks can cave and collapse following channel incision, mudslides may occur, and unanticipated releases of contaminated sediments may follow dam removal (Brandt, 1999; Maclin and Sicchio, 1999).

Only a few studies to date have been designed to address the sedimentation issues associated with dam decommissioning (e.g., Williams, 1977; Simons and Simons, 1991; Randle and Lyons, 1995). Flume experiments have largely focused on the impacts of sediment overloading to a downstream rectangular channel with uniform sediments (Park and Jain, 1986; Schumm et al., 1987), a scenario which does not adequately represent the channel geometries and grain-size distributions likely to be involved in dam removal. Field studies of actual channels impacted by reservoir-sediment releases have described channel response to a given set of parameters (discharge, channel morphology, sediment-release scenario; e.g. Wohl and Cenderelli, 2000), without the ability to manipulate those parameters and observe the corresponding channel responses. As a result, design of best-case dam removal scenarios using existing information has to be largely indirect in that it is based on inferences rather than demonstrated relations among channel geometry and water and sediment discharge regimes.

Partial or complete dam removal initiates a channel re-forming process upstream. The channel planform and dimensions will depend upon the reservoir depositional history. For example, with well-mixed sediments in the incoming stream to a reservoir, coarse sediments will deposit farthest upstream with a progressive fining in the downstream direction. As the reservoir ages, the finer materials will be buried by the downstream-progressing, coarse-grained delta. Depending upon the state of the deposits at the time of dam removal, the upstream deposits may or may not be stratified vertically and longitudinally. Current regime theory (Julien, 1995; Brookes and Shields, 1996) and classification schemes (Rosgen, 1996) cannot predict channel evolution in such settings.

The potential downstream channel responses to increased sediment load are as follows:

1) *Channel-bed aggradation*. This may take the form of fining of the bed material (Montgomery et al., 1999), in-filling of pools (Lisle, 1982; Wohl and Cenderelli, 2000), an increase in braiding (Hilmes and Wohl, 1995), or an increase in average bed elevation (James, 1989; Madej and Ozaki, 1996).

2) *Change in alluvial planform*. The most likely responses to an increase in sediment discharge would be a change from a meandering to a straight planform, or a change from the existing planform to a braided channel pattern (Hilmes and Wohl, 1995).

3) *Increased sediment transport rate.* This has the potential to alter channel bed and bank stability, altering bedform configuration or the habitat for riparian vegetation communities, for example.

The potential upstream channel responses due to partial or total dam removal include:

1) *Channel-bed incision.* A channel will form within the sediment deposits upstream that will incise at a rate controlled by the water release and sediment characteristics. Clay layers even a few years old can retard incision and erosion; once breached, erosion can proceed very quickly, producing hyperconcentrated flows (Brandt, 1999).

2) *Bank caving and channel widening.* Self-formed channels within upstream deposits will widen in response to bank caving and incipient meandering. Meandering may be encouraged if incision reaches the original armored thalweg. Limited experience demonstrates that the formed channel will eventually replicate its original shape. Preliminary channel width predictions are proportional to the square root of discharge (Atkinson, 1996).

3) *Unstable and erratic rates of erosion.* Erosion rates can change dramatically as the evolving channel encounters changes in the grain size and cohesive characteristics of the bed material.

Although 1-D models such as HEC-6 (Hydrologic Engineering Center, 1993) or quasi-2-D models such as GSTARS (Yang et al., 1998) may adequately simulate the response of simple (straight) alluvial channels to sediment release scenarios, these models do not adequately approximate conditions along complex (meandering, braided) alluvial channels or along bedrock channels where finer reservoir sediment may be moving across a coarse, largely stable channel substrate (Wohl and Cenderelli, 2000; Rathburn and Wohl, in review). In addition, application of these models is labor-intensive, and may not be practical if the objective is to provide general guidelines for removing a smaller dam.

Current formulations of the equations of motion may not capture the processes likely found in the process of sediment transport following dam removal. For example, Klumpp and Greimann (2000) explain that the Exner equation assumes that the amount of sediment in suspension does not change significantly over time when compared to the change in bed elevation - an assumption likely violated under high transport rates of fine materials. They also point out the weaknesses inherent in all formulations that split sediment load into bed material load and suspended load. Their recent efforts to overcome these limitations are promising (Greimann and Klumpp, 2000).

Unanticipated results may occur when draining a reservoir or removing a dam. For example, Wohl and Cenderelli (2000) describe that 7,000 $m^3$ of sediment were released from Halligan Reservoir along the North Fork Poudre River in northern Colorado that decimated a self-sustaining trout run (more than 4,000 fish were killed) and filled in pools for more than 10 km downstream. Similar unanticipated problems occurred upstream from the Hudson Dam in New York following dam removal. An inadequate understanding of the erosional characteristics of the sediment deposits led to much higher transport rates than predicted, resulting in channel blockage and the transport of PCB-contaminated sediments far downstream (Shuman, 1995). These types of scenarios can be avoided if dam removal is undertaken so as to provide water and sediment discharge regimes appropriate to flushing sediment through the downstream channel.

## CONCLUSIONS AND RECOMMENDATIONS

Thousands of dams have been built with only a partial understanding of the long-term spatial and temporal impacts on the surroundings. Experience to date suggests the same trend is occurring when removing dams - exemplified by, at times, unanticipated and adverse consequences.

Because dam removal will only accelerate in the coming decades, it is recommended that

1. A national informational database be created where studies on dam removal may be archived;
2. The considerations in this paper and those of the ASCE Task Committee on Guidelines for Retirement of Dams and Hydroelectric Facilities (1997) be carefully taken into account;
3. Federal agencies such as the Environmental Protection Agency, the U.S. Forest Service, and the National Science Foundation jointly sponsor research programs focusing on unanswered questions regarding sediment transport issues associated with dam removal. Such issues include
    a. how numerical simulation models can better capture the complex transport processes associated with potential sediment overloading of downstream systems;
    b. defining the connections between the mechanical processes of sediment transport and the health of downstream ecosystems;

c. evaluating effective means for stabilizing sediment deposits in place upstream; and
d. how erosion of deposited materials depends upon the depositional history.

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# DAM REMOVAL AND RESERVOIR EROSION MODELING: ZION RESERVOIR, LITTLE COLORADO RIVER, AZ

**By D. J. Semmens, Doctorate Student, Department of Watershed Resources, University of Arizona; and W. R. Osterkamp, Hydrologist, U. S. Geological Survey, Tucson, Arizona**

**Abstract:** Zion Dam, on the Little Colorado River near St. Johns, Arizona, is a partially breached earthen dam that soon may fail. Abundant stored sediment provides an opportunity to repair downstream channel incision and bottomland degradation, results of intense grazing, regional and local ground-water extractions, and decades of water and sediment depletion caused by Zion Dam and up-basin storage facilities and diversions. Efforts to quantify the volume of stored sediment, the potential for its entrainment, and its re-distribution downstream depend on a channel-evolution model that will be augmented with bank-stability and channel initiation algorithms to help estimate sediment release from storage. Output from this composite model will provide input for the HEC-6 model to predict downstream sites and magnitudes of deposition. The modeling efforts are designed to anticipate the ability to flush sediment from a reservoir by artificial and natural flows that promote bank failure and thereby increase the volume of sediment deposited downstream.

## INTRODUCTION

**Project Background:** Zion Dam, an earthen dam 150 m (500 ft) long and 7.6 m (25 ft) maximum height, was constructed on the Little Colorado River (LCR) near St. Johns, AZ in 1905 to store water for irrigation downstream in Hunt Valley (fig. 1). It washed out that year when Salado Dam, 19 km (12 mi) upstream, failed. The dam was rebuilt by 1908, and failed again in 1915 when Lyman Dam, 32 km (20 mi) upstream, failed. In 1918, reconstruction of Zion Dam was completed producing a reservoir of area 2.5 $km^2$ (~1 $mi^2$). Irrigated farming in Hunt Valley peaked from 1918 to 1922, after which time sedimentation in the reservoir had reduced the initial storage capacity of $7.4 \times 10^6$ $m^3$ (6,000 ac-ft) to about $1.23 \times 10^6$ $m^3$ (1,000 ac-ft) by 1925, and irrigation was necessarily ceased as a result (Bureau of Reclamation, 1955). Since then, however, Zion Reservoir has been used by local ranchers for watering livestock, and the dam was repaired again in the mid-1970s after being breached a third time.

In 1997, Zion Dam was partially breached by a natural pipe that formed through its center. Piping is a particularly common geomorphic process in the area due to the high clay content of the floodplain soils, and the dam is constructed exclusively of this local material. After draining the reservoir and excavating a substantial portion of the center of Zion Dam, the pipe collapsed in upon itself and has temporarily re-sealed the dam. An unknown party, probably the private owner of the dam, has since excavated a formerly buried irrigation pipe that allows the reservoir to drain slowly, which has helped prolong the life of the failing dam.

Motivation for removing Zion Dam comes primarily from the Zuni Pueblo, which is interested in restoring the channel and native riparian vegetation on sacred lands downstream. Prior to European settlement and construction of the dam, the downstream reach was characterized by a broad, shallow channel, cottonwood-willow riparian forest, and perennial flow. Oral accounts of the valley in the early 1900s indicate the occurrence of numerous travertine springs that augmented natural flows and sustained a rich grassy marsh in much of the valley. Travertine deposits remain conspicuous at numerous sites along and near the river. Land use and water development, however, have caused dramatic changes in this section of the LCR valley.

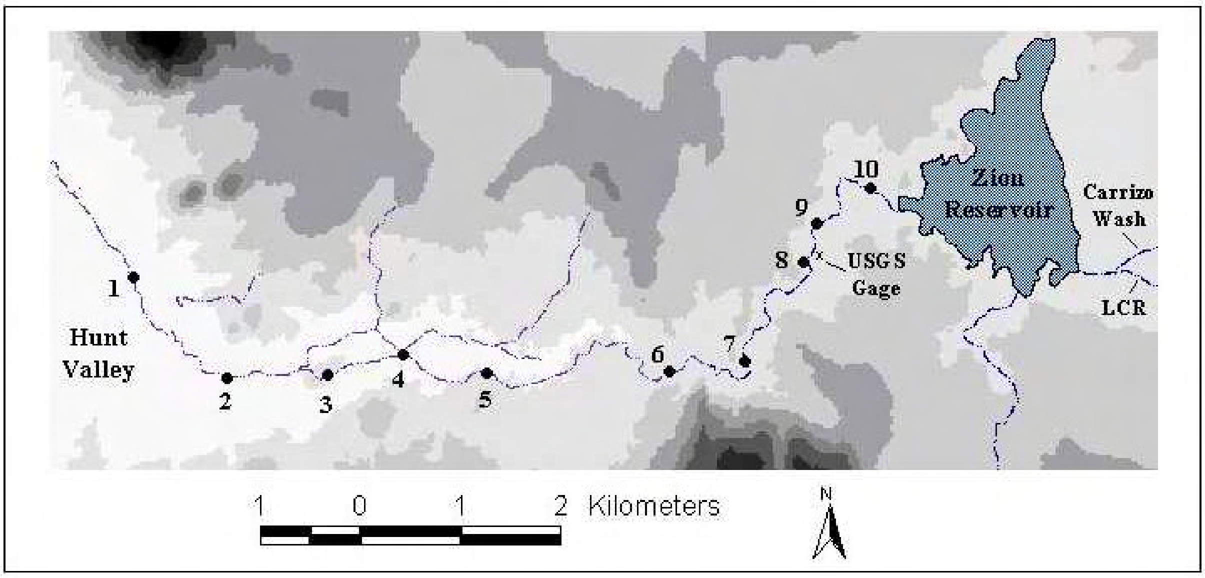

**Figure 1.** A simplified topographic map of the project area between Zion Reservoir and upper Hunt Valley, with numbered locations of cross-sectional measurements.

Streamflow below Zion Dam is ephemeral, the channel is deeply incised, and bottomland vegetation is mostly salt cedar, sage, and saltbrush. Regional pumping has lowered the potentiometric surface of artesian aquifers and dried up springs, and Zion and Lyman Reservoirs capture nearly all natural flow. During the last 80 years, flows passing Zion Dam have been sediment starved and have caused channel incision of as much as 5.34 m (17.5 ft) and averaging about 3.9 m (12.7 ft) in the 10 km (6.25 mi) project reach. As the channel bed was lowered, the uppermost alluvial deposits drained, lowering in response the near-surface water table. Native riparian species were replaced by the exotic salt cedar within the incision and by native desert scrub above the terrace scarp; no distinguishable floodplain is present. Channel incision decreases as the river passes into Hunt Valley, approximately 8.5 km (5.3 mi) downstream of Zion Dam, where the gradient decreases significantly.

Plans for controlled releases from an upstream reservoir, and to deepen its current breach channel make Zion Reservoir an ideal site to test a reservoir erosion model. Surface-water rights obtained by the Zuni Nation, although still under adjudication, will likely be delivered as controlled releases from Lyman Reservoir and provide an opportunity to determine the flows best suited to promote reservoir erosion and deposition downstream. Plans to physically breach the dam, combined with an already limited water-storage capacity, alleviate the need to simulate a catastrophic breaching event. In addition, occasionally dry conditions at the reservoir have made it relatively easy to survey the reservoir floor.

**Objectives:** The purpose of this study is to evaluate reservoir erosion and aggradation downstream for a range of natural flows and potential controlled releases from a reservoir upstream, and to develop a preferred sediment-management plan based on the results. Encompassed in this overall goal are several specific objectives:

- Simulate erosional channel network development and evolution within the reservoir
- Simulate cohesive bank failures, their contribution to the volume of sediment eroded from Zion Reservoir, and their impact on the morphology or reservoir channels
- Determine if dense channel vegetation downstream of the dam provides sufficient channel roughness to promote the re-deposition of entrained reservoir sediment
- For possible controlled releases from Lyman Reservoir upstream, identify the discharges and flow durations (within the range available) that most effectively promote erosion in the reservoir and aggradation downstream
- Assess the long-term course of reservoir erosion, and potential methods of promoting the recovery of a stable channel within the reservoir

## CHANNEL AGGRADATION MODELING

**Data Collection:** Data collection for the HEC-6 model of channel aggradation below the reservoir consisted primarily of representative cross-section measurements (locations are noted on figure 1), and grain size analysis of both channel and reservoir sediment. Sediment loads entering the model reach were estimated from average USGS suspended sediment measurements approximately 80 km (50 mi) downstream, which where plotted as a function of discharge. Roughness coefficients at each cross-section were estimated as the sum of the coefficients for the channel type and the vegetative component. The latter was estimated using an empirical formula derived by Phillips et al. (1998). A USGS gage near cross-section 8, installed in 1998, will provide important stage and discharge information for model calibration.

**Initial Results:** For simulated controlled releases of 2.8, 5.7, and 8.5 $m^3/s$ (100, 200, and 300 $ft^3/s$, respectively) over a period of 5 days, preliminary model results indicate that deposition in the approximately ten-kilometer reach below Zion Dam will be limited by the amount of coarse sediment present in reservoir. Silt and clay, which comprise 70-85% of the reservoir sediment, are predicted to bypass the project reach entirely. The small sand and negligible gravel fractions will deposit almost entirely within the reach immediately downstream of the dam (fig. 2). Deposition and erosion alternate throughout the rest of the project reach, with erosion occurring in steeper sections and deposition in the more gently sloped sections. This pattern is strongly correlated with the depth to which the channel is currently incised, providing some indication that the model is behaving properly. The lack of any significant flows in this reach over the last two years has made model calibration impossible.

All three simulated release rates from Lyman Reservoir are predicted to result in a small amount of deposition where the river passes onto Zuni Reservation land (approximately kilometer 8.75, figure 2) at the upper end of Hunt Valley. Although not presented in figure 2, similar results have been obtained for a substantial range of channel roughness, input sediment load, and flow duration values.

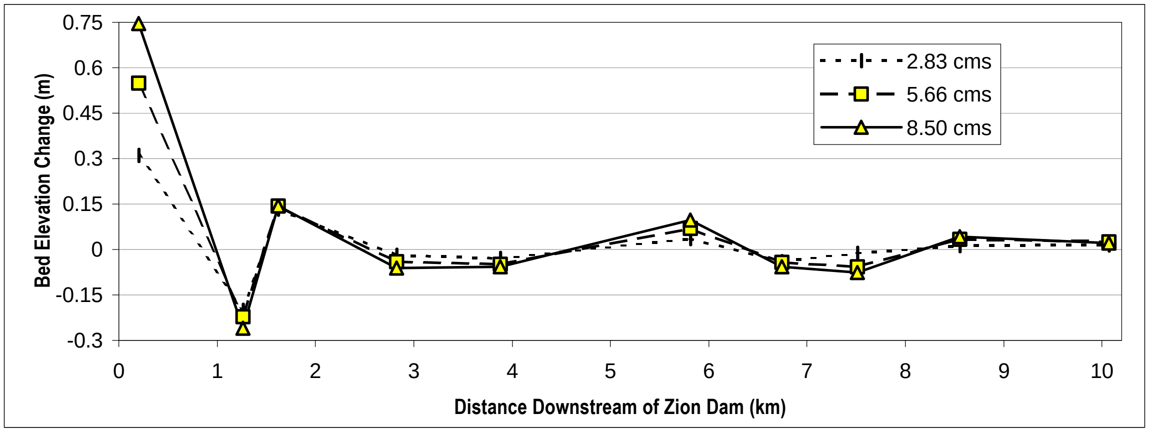

**Figure 2.** Relative elevation change of the thalweg for three simulated discharges.

**Discussion:** Changes in channel slope correlate directly with the amount of simulated deposition and/or erosion throughout the study reach, as well as with field observations of channel depth. The lowest slope in the reach, however, is located immediately below Zion Dam, and traps most of the inflowing sediment, leaving little to affect aggradation downstream where it is desired most. The small amount of aggradation at the lower end of the study reach may indicate that a more proactive approach, such as a check dam, will be necessary to expedite aggradation in this area.

## RESERVOIR-EROSION MODELLING

**Reservoir-erosion Modeling:** A sediment-management plan for a project commonly requires a sediment-transport model to evaluate impacts of dam retention and removal alternatives. Despite many dam-removal studies, however, relevant peer-reviewed publications are limited. Perhaps the best example of a reservoir-erosion model is the Elwha Reservoir Model (Randle et al., 1996; USBR, 1996), developed for the draining of the Elwha and Glines Canyon Reservoirs, Elwha River, Washington. The Elwha Reservoir Model integrates empirical relations for erosion and redeposition of coarse sediment with a model for fine-sediment transport to predict erosion, redistribution, and downstream release of sediment during concurrent incremental removal of both dams. It is based partly on measurements of the erodibility and transport of reservoir sediment during drawdown in the upper reservoir, and cannot be applied elsewhere without conducting similar studies. The Elwha Reservoir Erosion Model demonstrates the need for the capability to simulate a wide range of geomorphic processes with a minimal data. Such a model should ideally be physically based, distributed, and easily adaptable to site-specific conditions. The reservoir erosion model being developed for Zion Reservoir takes the first step in this direction by integrating subroutines appropriate for simulating erosion in a medium-sized, dry reservoir.

The extensive amounts of computational time and data collection required to calibrate two- and quasi three-dimensional distributed models of flow and sediment transport have made them less attractive than one-dimensional models, but this is changing. Improved surveying technology has substantially increased measurement precision, and reduced the time required (2 to 4 seconds per measurement) to collect the elevation data for input into and calibration of fully distributed models. In addition, the rapidly increasing speed and availability of computer technology is breaking down the computational time barrier to the use of complex two and quasi three-dimensional models.

**Model Description:** The primary objective of the reservoir erosion model is to quantify the volume of sediment that will be eroded from the reservoir under a variety of flow conditions. Implicit to this objective is the ability to simulate the formation and growth of a network of erosional channels in the reservoir, and the failure of cohesive banks as the channels become incised. It will therefore be necessary to test the effectiveness of computational techniques for channel initiation and bank failure when incorporated into a single comprehensive reservoir erosion model, and to improve upon these if they are not successful.

A fully distributed, deterministic model developed by Jonathan Nelson (USGS) to simulate flow and sediment transport in meandering natural channels serves as the foundation for the modeling efforts. It is a quasi three-dimensional computational model for flow and boundary stress fields in natural channels that is combined with bed- and suspended-load transport algorithms (Nelson and Smith, 1989a). By retaining streamwise convective accelerations in the lowest order momentum equations, the flow model has been successfully used to predict the velocity, boundary shear stress, and surface elevation of flow through meandering channels with natural topography (Nelson and Smith, 1989b). When coupled with a bedload transport algorithm, the resultant channel evolution model yields predictions of finite amplitude morphology of both point and alternate bars in curved and straight channels, respectively (Nelson and Smith, 1989b).

This particular model has been chosen because it offers two key advantages over more widely used models. First, it is one of a new generation of physically-based models employing new computational approaches in fluid mechanics and capitalizing on an improved understanding of the basic mechanics of sediment transport in turbulent flows. As such, it is particularly valuable in situations such as at the Zion Reservoir where important management decisions must be made without the benefit of historic data. Secondly, the model has a versatile modular framework that allows it to be tailored specifically to the conditions at a site. It is therefore ideally suited to modifications that will enable it to simulate bank failures and channel network development.

The well-constrained conditions of a single-outlet network of parallel-banked channels developing on an approximately planar, unvegetated surface (fig. 3) are ideal for the investigation of channel-head spacing, headward migration rates, and channel self-similarity at different scales. Natural and atrificial flows from the LCR, rather than locally derived surface runoff, will greatly increase the rate at which the drainage network develops, and will make it much easier to monitor network evolution. These site conditions thus provide a rare non-laboratory opportunity to validate a numerical model for drainage network development without years of tedious data collection.

**Bank Stability:** Bank failure is an important process in most dam removals because channels rapidly cut into saturated sediment that commonly is high in fine grain sizes. The influence of bank failures on channel morphology and sediment load is widely recognized, but has not been included in a reservoir-erosion model. The Zion Reservoir erosion model will incorporate a bank-stability algorithm (Simon et al., 1999) to account for the sediment contribution from mass wasting. Previous studies have combined bank-stability algorithms with sediment-transport models (e.g. Simon et al., 1991; Darby and Thorne, 1996; Simon and Darby, 1997), but all have limited computational interaction between the banks and the flow. This new algorithm has greater interaction between hydraulic and gravitational processes than earlier versions, and is well suited for combination with a 3-dimensional flow and sediment-transport model.

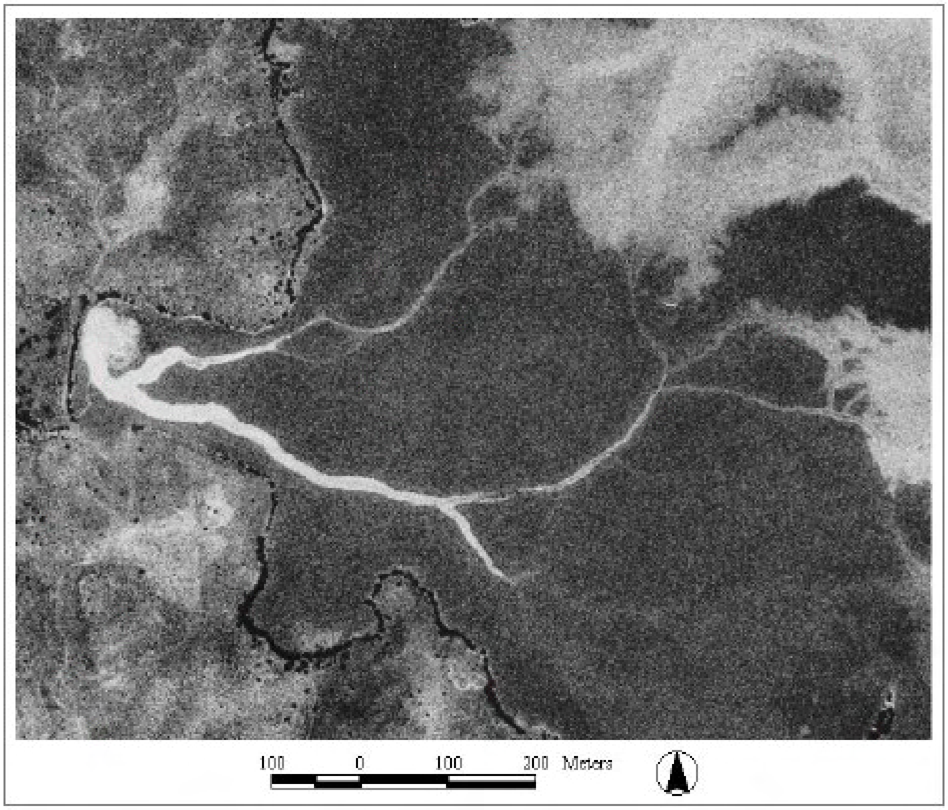

**Figure 3.** Digital orthophoto of the lower portion of Zion Reservoir in which a network of channels formed during a dam breach in the mid-1970s.

The bank-stability algorithm developed by Simon et al. (1999) will be evaluated in terms of its effect on channel width. Simulations will be run with and without this component of the model to visually assess its impact on channel width, and to get a quantitative estimate of the volume of sediment derived from bank mass failure. It will also be possible to simulate a discontinuous flow release pattern from Lyman Reservoir as a means of promoting bank failure and thereby enhancing reservoir erosion. If the water allocated for release from Lyman Reservoir is divided into a series of short flows separated by periods of no (or lower) flow, the potential for bank failure and hence available sediment may be greatly enhanced.

**Channel Development:** The channel-network component of the reservoir-erosion model is partly based on a model of Howard (1994), whose channel-initiation technique is being tested for its ability to predict the number and locations of erosional channels that develop upstream of a breach. This technique, which relies on the assumption of detachment-limited conditions, converts a cell in the simulation matrix from nonalluvial to alluvial if the bedload-transport rate exceeds the potential rate. The assumption of detachment-limited conditions is often applied to the erosion of cohesive material (e.g. Izumi and Parker, 1995), and may hold for erosion in Zion Reservoir where fine material constitutes 80 to 90% of the reservoir sediment.

Simple normal flow will most likely be used to simulate unchannelized flow across the upper portion of the reservoir. Problems with the selection of finite wavelength that have been associated with drainage basin evolution models based on normal flow (Izumi and Parker, 1995) will be avoided in this application. The low critical shear strength of reservoir sediment, combined with a single water entry point upstream should cause a small number of channels to rapidly connect with the reservoir inlet, and avoid the difficulty of fine scale selection.

**Data Collection:** Data collection for the reservoir erosion model consists of a detailed survey of the reservoir floor, and sediment property measurements. A Trimble GPS Total Station 4800 and 4700 Rover Unit with real time kinematic (RTK) technology were used in to conduct the reservoir survey. These instruments have a precision of 1 cm in the horizontal and 2 cm in the vertical dimensions, and may therefore be used to generate a high-resolution map of reservoir channel morphology. Points were surveyed at irregular intervals and imported into ARC/INFO to interpolate an elevation surface for model input.

Sediment data collected include sediment cores, effective cohesion, and critical shear strength. Six sediment cores have been used to map the sediment thickness and grain size distribution within the reservoir. Submerged jet device and borehole shear tester measurements were made at three locations, and revealed that critical shear strength and cohesion, respectively, are uniform throughout the lower reservoir. Soil moisture content was also found to have little variability.

Water entering and exiting the reservoir is measured at several USGS gaging stations. Water from the 847 $km^2$ (331 $mi^2$) LCR drainage below Lyman Dam (USBR, 1955) is measured just upstream of the confluence with Carrizo Wash (fig. 1). Carrizo Wash, with a directly contributing drainage area of 2616 $km^2$ (1022 $mi^2$), (USBR, 1955) is gaged off of highway 666 approximately 14.4 km (9 mi) above Zion Reservoir. Reservoir outflow will be monitored at a third USGS gage located approximately 1.7 km (1.1 mi) below Zion Dam.

**Planned Simulations:** The reservoir erosion model will be used to test a variety of natural flood flows and controlled releases from Lyman Reservoir. Some of these include:

- Short duration high magnitude flow such as 8.5 $m^3/s$ (300 $ft^3/s$) for 5 days (the maximum permissible release rate from Lyman Reservoir is assumed to be 8.5 $m^3/s$).
- Longer duration, lower magnitude flow such as 4.25 $m^3/s$ (150 $ft^3/s$) for 10 days.
- Alternating high and low flows designed to promote bank failure and the transport of sediment downstream
- Natural flows with 1, 5, 10, 50, and 100-year return periods.

## SUMMARY AND CONCLUSIONS

Preliminary simulations of controlled releases from an upstream reservoir have shown that sediment derived from erosion in Zion Reservoir will likely cause significant aggradation in the gently-sloped segment immediately downstream. The desired locus of deposition in Hunt Valley, in contrast, will not experience significant aggradation due to the higher slope in this segment. Construction of a sediment retention structure below the project reach may aide in speeding gully infilling and channel restoration at this site.

The development of a reservoir erosion model will provide a tool to make realistic estimates of the volume of sediment that will be eroded from Zion Reservoir, which can be used to refine sediment management plans for the project reach downstream. Dry, unvegetated conditions in the reservoir, combined with plans for controlled releases from an upstream reservoir and plans to physically breach the dam also make this an excellent location to test a new, more comprehensive reservoir erosion model.

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