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I. Reservoirs: Sedimentation, Monitoring, and Management

I. RESERVOIRS: SEDIMENTATION, MONITORING, AND MANAGEMENT

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A SURVEY OF RESERVOIR SHORELINE EROSION PROBLEMS AT BUREAU OF RECLAMATION RESERVOIRS

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INTRODUCTION

Shoreline erosion is a process that occurs at all reservoirs to some degree. Within the Bureau of Reclamation (Reclamation), problems associated with shoreline erosion are most frequently addressed at the Area Office level although in some instances the solution is based on legislative or legal mandates. The scope of the problem throughout the agency has not previously been summarized.

This survey was patterned after a similar effort within the Corps of Engineers (Allen and Wade, 1991). This approach involved querying each of the five regional office divisions within Reclamation responsible for operation and maintenance of facilities. This report provides the findings of this query conducted in November 1992. See figure 1 for a description of the regions within Reclamation.

METHODS

The data in this paper represent an estimate of shoreline erosion at Reclamation facilities based upon responses received from regional offices in 1993. All of the data for this report were supplied in response to the query sent to the regional offices. The query did not require a uniform format of response, it was intended to consolidate existing information but not require new data collection efforts.

The form used to request the information of the regional offices in the query of November 1992, is attached as figure 2.

The regional responses varied from a project by project tabulation of reservoir shoreline erosion to a summary response for one region indicating no problems with shoreline erosion. One of the five regions provided no response. Overall, the responses provided a good indication of erosion problems within the regions that responded.

The data was summarized by regions:

- number of reservoirs in each region

- number of reservoirs with erosion problems

- type of erosion problems

- miles of shoreline with minor, moderate and severe erosion

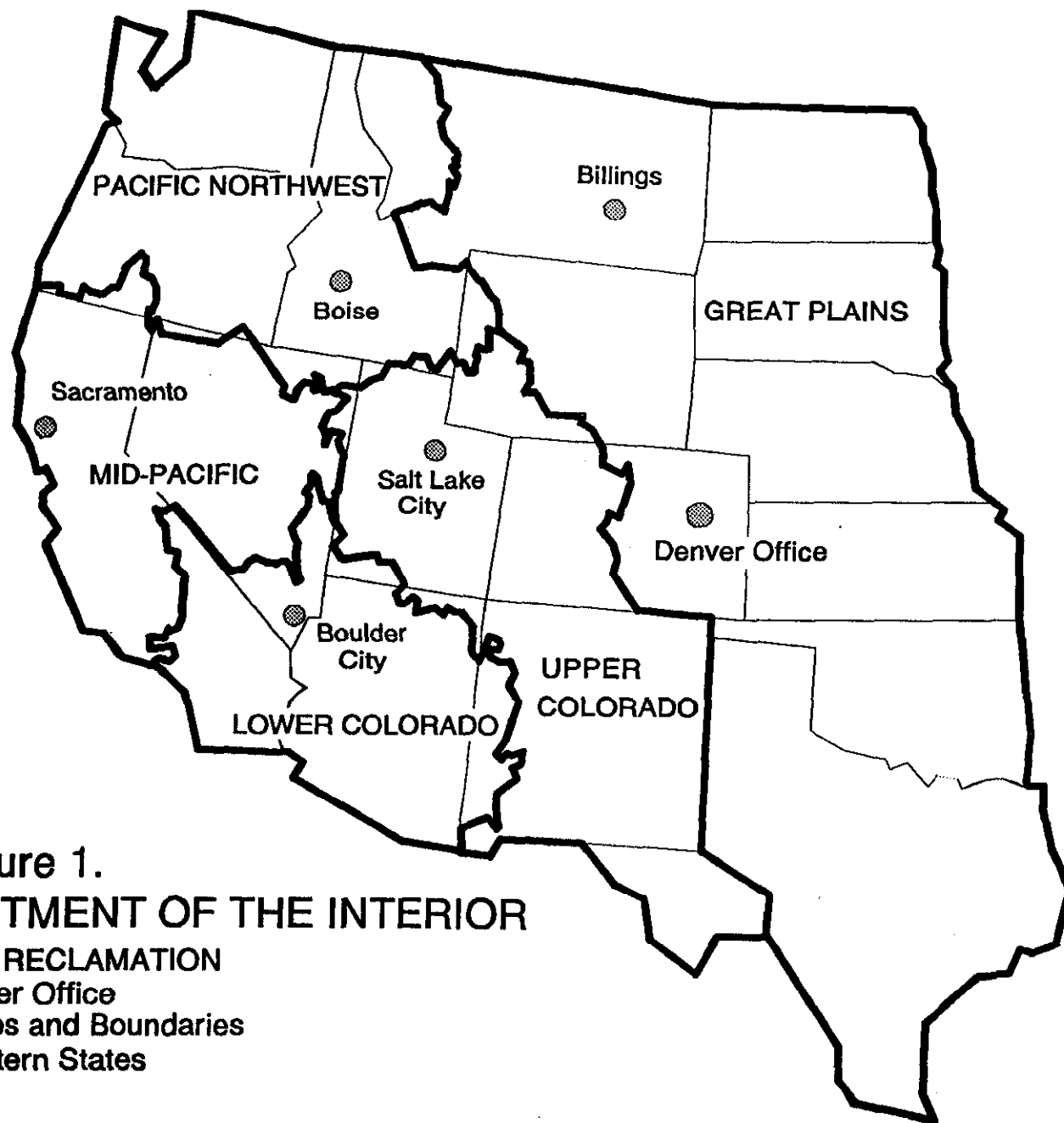


Figure 1.
UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
Denver Office
Regional Offices and Boundaries
17 Western States

INVENTORY OF RESERVOIR SHORELINE EROSION

Please answer each question as completely as possible:

1. Total number of reservoirs in your region, and an estimate of the total length of shoreline at these reservoirs.
2. Provide the name(s) of the reservoir(s) where shoreline erosion is of concern and specify the nature of the impact using the following list:
 - a. Archaeological/cultural resources
 - b. Private property (e.g., structures, land)
 - c. Water quality
 - d. Project life
 - e. Fish and wildlife resources/habitat
 - f. Government property (e.g., structures, land)
 - g. Other resources (specify)
3. For each reservoir with shoreline erosion problems, please provide an estimate of miles of shoreline affected and the severity of the problem (i.e., minor, moderate, severe).
4. Name, title, mail code, and telephone number of contact person in your region.

Figure 2. Request for information sent to regional offices in November 1992.

The major categories of damage caused by erosion are:

Archaeological/cultural resources

Private property

Water quality

Fish and wildlife resources and/or habitat

Government property

Recreation resources

Concern about archaeological/cultural resources was expressed from others outside the original distribution of this inquiry. Erosion of cultural resources was identified as a significant problem at many Reclamation reservoirs. Specific data regarding individual projects was provided by the regions in their responses.

RESULTS

Tables 1 and 2 give a regional breakdown of the shoreline erosion reported in this survey. The region names have been abbreviated as follows:

GP Great Plains

LC Lower Colorado

MP Mid-Pacific

UC Upper Colorado

PN Pacific Northwest

Table 1. Reservoir Shoreline Erosion Estimates by Region					
Region	Res. w erosion	Total res. reported	Miles of erosion	Miles surveyed	Total miles
GP	57	82	1395	3262	3877
MP	33	39	1147	1580	1580
PN	24	33	66	1627	2415
LC	No problems reported				1813
UC	No report				2888
	114	154	2625	6469	12573

Table 2. Existing or Potential Impact Categories for Shoreline Erosion.								
Region	Archaeol.	Priv. Prop.	Water Quality	Project Life	FW Res. & Hab.	Govt. Prop.	Rec.	Other
GP	51	1	24	4	19	20	25	
MP	15	3	16	10	15	31	1	1
PN	20	3	4		9	10	1	1
Totals	86	7	44	14	43	61	27	2

Table 3 provides a breakdown of the severity of the erosion occurring at sites where a categorization of erosion was undertaken.

Table 3. Categorization of Shoreline Erosion by Region.				
Region	Minor	Moderate	Severe	Total
GP	525	527	341	1395 ¹
MP	570	334	16	920 ²
PN	16	12	35	63 ³
Total	1111	873	392	2378
¹ 2 miles not rated ² 227 miles not rated ³ 3 miles not rated				

DISCUSSION AND SUMMARY

Based on the information received in this survey of 154 reservoirs in three regions, 114 reservoirs are experiencing some type of shoreline erosion problem. A total of 2,625 miles are being affected of the 6,467 miles of reservoir shoreline surveyed. Shoreline erosion is damaging or threatening archaeological/cultural resources at 86 reservoirs and concern about the loss of government property (land and structures) was expressed for 60 reservoirs. Impacts to water quality, fish and wildlife habitat, and degradation of recreational use were also frequently mentioned in this survey. About 47 percent of the reported erosion was classified as minor; about 37 percent was classified as moderate and 16 percent was rated as severe.

About half of the shoreline length identified as eroding was reported for the Great Plains region. This region contains half of the reservoirs identified as having a shoreline erosion problem as well. This region is the largest in the agency, having about 30 percent of total length of shoreline for Reclamation reservoirs.

REFERENCES

Allen, Hollis H. and F. John Wade. 1991. The scope and nature of shoreline erosion problems at Corps of Engineers Reservoir Projects: A preliminary assessment. Miscellaneous Paper W-91-3, Department of the Army, Waterways Experiment Station, Corps of Engineers, Vicksburg, MS. 16p.

NOTES

SELECTED SEDIMENTATION INVESTIGATIONS AT FERC
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(The discussions in this paper represent only the personal views of the author and may or may not be those of the Commission.)

Abstract

Sedimentation is an increasingly serious natural hazard problem worldwide in both developed and developing countries. The World Bank recently estimated that worldwide reservoir storage capacity loss from siltation alone is about 6 billion U.S. dollars in replacement costs.

Sedimentation problems tend to be dynamic, multi-dimensional, and multi-disciplinary. Despite the advances in sedimentation research in recent years, we still do not completely understand all the underlying physics and mathematics involved in modeling the sedimentation processes.

We also lack the data needed to calibrate, verify, and run the models. Uncertainties are everywhere. Today, we can have, at best, an approximation of the problem.

In recognizing the seriousness of the problems, FERC is working with a 10-agency work group and an international task force to develop guidelines for incorporating sedimentation consideration in water resources development. Both groups are currently chaired by the author.

In addition, this papers will discuss several ongoing major sedimentation related investigations of its licensed hydro projects at FERC. It also discusses why FERC is concerned about sedimentation problems and what it has accomplished.

I. INTRODUCTION

Federal Energy Regulatory Commission (FERC) is solely a regulatory agency which does not build or operate hydropower projects. Its major responsibilities are to license and regulate nonFederal hydropower developments.

In issuing hydropower licenses, an important problem we often encounter is sedimentation. At our licensed hydro projects, sedimentation problems can often prove to be troublesome and even disastrous. However, careful project planning and management can greatly mitigate or completely avoid many such problems.

According to the Interagency Sedimentation Work Group's classification (Fan, 1988), there exist five types of sedimentation problems. These are watershed, stream, reservoir, estuary, and coastal problems. At FERC, the major sedimentation problems we are concerned with are reservoir and stream sedimentation problems. In this paper, only the issues related to the stream and reservoir sedimentation will be discussed.

II. MAJOR SEDIMENTATION ISSUES AT FERC

At FERC, there are two major types of stream and reservoir sedimentation issues: generic and special. The generic sedimentation issues are sometimes similar to those of other agencies. FERC's special sedimentation issues are those believed to be distinct from that of other federal agencies, i.e. Corps of Engineers, Bureau of Reclamation, etc.

FERC's generic sedimentation issues normally involve engineering, operational constraints, environmental impacts, economic feasibility, legal interpretations, regulatory requirements, or combinations of the above.

For example, from an engineering standpoint, the major concerns of FERC in regard to reservoir sedimentation are the loss of storage capacity, the blockage of inflow access for power generation, increased maintenance due to the wearing of plant structures and machineries, and the environmental impact in the vicinity of the project.

Environmentally, reservoir sedimentation may have deteriorating effects on water quality, eutrophication, aquatic life, and recreation. Upstream from the dam, severe siltation may block water passage and create backwater that could flood over stream banks and inundate low land areas. Below the dam, degradation and bank stability issues may also cause problems.

FERC's major special sedimentation issues include small hydro problems, selection of models, sediment management in reservoirs, reservoir decommissioning, and common sedimentation database. Since the generic issues have been discussed elsewhere (Fan, 1989), this paper will only discuss some major ongoing investigations concerning the special sedimentation issues at FERC.

III. THREE-PHASE MODEL EVALUATION

There exist today many computer sedimentation models. However, there is no single sedimentation model which is usable under all conditions. More importantly, inputting the same data into different models often produces significantly different results. Without any guidelines, we often expend significant time and resources.

In recognition of the seriousness of this issue, an Interagency Sedimentation Work Group was established in 1987. The group was charged to investigate state-of-the-art computer sedimentation models and to guide the public in the selection and utilization of each of the models. The group has representatives from ten major Federal agencies. The author was selected to chair the group.

To address this model evaluation problem, the group first developed a three phase approach: (1) setting up an inventory of the sediment models and methods now in use, (2) reviewing the models carefully selected by the group, and (3) testing the selected models with several common data sets of different hydrologic and hydraulic conditions.

With the enthusiastic support of its member agencies, the group completed the first two phases in less than 2 years. It developed an inventory of nearly 50 models and published a 550-page report entitled "Twelve Selected Computer Stream Sedimentation Models Developed in the United States."

The major findings of the report (Fan, 1988) are:

1. All the sedimentation models being reviewed are heavily data dependent. In applying them, one is often limited to the character ranges of the data used to develop the models.
2. Computer modeling of sedimentation problems is still in the developmental stages. It only approximates the solution to a problem. It cannot totally substitute for professional experience. Expert interpretations of computer outputs are often required.

The group's third and final phase (model testing) of the study was unfortunately delayed for over two years due to lack of Federal funds. In 1991, the project was reactivated with the support of a scientific cooperation agreement between the American Institute in Taiwan (AIT) and Taipei Economic and Cultural Representative Office.

Under this Bilateral Agreement, a group of self-supported Taiwan scientists are conducting a comprehensive, fact-finding evaluation of selected sedimentation models developed in the United States. FERC is representing the AIT to provide all the necessary administrative support to help carry out this Bilateral Agreement. FERC has supplied the project models and their documentations, coordinated activities of the concerned parties, sponsored workshops, and published proceedings.

IV. GUIDELINES FOR MANAGING SEDIMENTS IN RESERVOIRS

Managing sediments in reservoirs has become an increasingly serious problem worldwide. In a recent report, the World Bank has confirmed the seriousness of the problem. The Bank estimated that on a global basis the average replacement cost of the annual reservoir storage capacity loss due to siltation alone is approximately \$6 billion.

In the United States, reservoir siltation has significant impact on our licensed hydropower developments. Also, sediment management in reservoirs is quite difficult and controversial. Without any guidance, a great deal of staff and licensees' efforts have been wasted.

To mitigate these problems and the resulting confusion, FERC has proposed a plan to develop guidelines that provide its staff with step by step procedures and pertinent information on how to address sedimentation problems. The guidelines shall be clear and straightforward.

The guidelines are limited in scope and address primarily the issues of managing sediments in reservoirs that are currently encountered at FERC. Presently, the guidelines are designed to cover 5 major areas: selection of sediment inflow estimation techniques, preservation of reservoir storage, sedimentation aspects of dam removal, understanding stream sedimentation models, and data problems.

These guidelines, when completed, would help FERC speed up design review and check compliance, saving the Commission both time and financial resources. At present, the plan has five major parts: Guidelines on Selection of Sediment-Inflow Estimation Methods, Guidelines for Preserving Reservoir Storage, Guidelines on Selection of Computer Models, Guidelines on Assessment of Sedimentation Impacts of Dam Decommissioning, and Guidelines on Data Needs, Monitoring and Analysis.

V. SMALL HYDRO INVESTIGATION

FERC's licensed hydro projects are often smaller and located on smaller tributaries. As previously discussed, the analysis of sedimentation problems is complex and often requires the use of computer models. However, the application of the models usually requires a great deal of field data which are not readily available. In addition, the collection of sedimentation related field data can be expensive and time-consuming and may not be justified for the small hydro owner. Therefore, a simplified and approximate solution is more suitable for small hydro study.

Also, in smaller reservoirs, because of smaller surface area and water storage, flow withdrawal from the power plant can force inflow sediments to run straight through the plant. Therefore, a

smaller reservoir's operational mode has a greater impact on its sedimentation problems than that of large reservoirs.

Furthermore, in most instances, these smaller reservoir may silt up faster. This was confirmed by Dr. Dendy based on his analyses of over 1000 reservoirs in the United States (Dendy, 1967).

VI. RESERVOIR STORAGE CAPACITY RECOVERY THROUGH SEDIMENT FLUSHING

Flushing is a method of hydraulically clearing existing sediment accumulation in a reservoir with high velocity flow during the flood season and to store clearer water during the low flow period. This method is more effective in a narrow gorge-type reservoir. In a wide flood plain type of reservoir, it may only clean sediment deposits up to the size of the original stream channel.

At FERC, in the 80's, flushing was proposed to recover the storage capacity of Cowlitz Falls reservoir on Cowlitz River in Washington. Recently, FERC's licensee, Pacific Gas and Electric Company, has attempted to use a combination of flushing and other techniques to provide a long-term solution for passing sediments from upstream sources through its Rock Creek and Cresta reservoirs on Feather River in California. The licensee used both hydraulic and numerical models to carry out its study. The study resulted in the collection of a great deal of scientific data.

VII. RESERVOIR DECOMMISSIONING

In recent years, some dams built in the early 20th century have been completely filled with sediments and can no longer meet the needs for which they were originally constructed. In some instances, the dams were built with cribs which have become badly deteriorated. Removal of these dams needs to be investigated, especially if they are unsafe and are very costly to repair.

At FERC, several dam removal problems have been encountered. They are as follows:

1. In 1973, the Fort Edward Dam on the Hudson River in New York was totally removed from the site. The amount and effects of material that was transported from the reservoir area were substantially underestimated. Sediment and debris from the reservoir caused serious damages to the navigation channel and the towns downstream.

2. In 1992, FERC approved a request from the American Hydropower Company to remove its Musser Dam (FERC#3706) in Pennsylvania. The dam was built in a timber A-frame structure. It was removed because it had been severely deteriorated. The environmental impact of its removal is not expected to be significant.

3. In recent years, over ten other dams have been considered for removal in order to help mitigate their respective environmental problems. The dams under consideration for removal include Cushman (#460), Wisconsin Valley (#2113), Condit (#2342), Edward (#2381), Thunderbay Bay River (#2404 & 2419), Pine River (#2486), Snoqualmie (#2493), Stronch (#2580), Basin Mills (#10981), and others.

4. Several years ago, the applications for license and relicense of the Elwha and Glines Canyon dams on the Elwha River in Washington were reviewed by FERC. These dams were built over 50 years ago. Dam removal was considered as a mean to alleviate their environmental problems. FERC staff had planned to assess the problems associated with the sediments accumulated behind the dams, if the dams were removed. The problems are currently being investigated further by Department of the Interior.

VIII. COMMON SEDIMENTATION DATABASE

In its evaluation of computer sedimentation models, the Interagency Sedimentation Work Group has found that all existing computer sedimentation models are heavily data dependent. Their applicability is often limited by the character ranges of the data that were originally utilized for the development of the models. Therefore, adequate data are often essential to the successful calibration and application of the models.

However, such required data are usually not readily available to the general public. Hence, the availability of a common database would not only expedite FERC's regulatory review but would also be a great saving to our nation.

IX. CONCLUSIONS

1. Sedimentation is a vital concern for hydro development. Appropriate design or management can significantly mitigate many, if not all, of the adverse impacts of sedimentation problems.

2. FERC's sedimentation issues are often quite distinct from those of other Federal agencies. They are multi-disciplinary and can be either related to engineering, operational, environmental, economical, legal, regulatory, or combinations of the above.

3. Sedimentation problems are multi-dimensional, cumulative, and closely related to streamflow. Therefore, an integrated approach is the most appropriate way to solve the problems. Piecemeal treatment may provide a temporary solution to the problems at one location, but can often create new problems at other places in the basin.

4. Reservoir decommissioning involving dam removal and restoration of the stream often require analysis of sediment transport and other related issues.

5. At FERC, the preparation of guidelines for sedimentation analysis and model selection, the development of a common database, the improvement of data accessibility, technology transfer, and interagency cooperation are all urgently needed.

6. Each of the cases previously discussed should not be viewed as an isolated incidence. At present, FERC has received a large number of hydro relicensing applications. We believe that some of these projects may present sedimentation problems similar to those discussed above.

X. REFERENCES

1. Dendy, F. E., 1967, "Sediment Deposition in Reservoirs in the United States," ARS-Paper #41-137, U.S. Department of Agriculture.
2. Fan, Shou-shan, 1988, "Summary Report," Twelve Selected Computer Stream Sedimentation Models Developed in the United States, Interagency Sedimentation Work Group.
3. Fan, Shou-shan, 1989, "Reservoirs," Chapter 5, Civil Engineering Guidelines for Planning and Designing Hydroelectric Developments, American Society of Civil Engineering.

THE INTERNATIONAL COORDINATING COMMITTEE ON RESERVOIR SEDIMENTATION: CATALYST FOR PROGRESS

By R. H. Hotchkiss Associate Professor, Dept. of Civ. Eng., Univ. of Nebraska-Lincoln, Lincoln, NE; G. Di Silvio, Professor, Universita Degli Studi Di Padova, Istituto Di Idraulica "Giovanni Poleni", Padova, Italy

Abstract: The International Coordinating Committee on Reservoir Sedimentation (ICCORES) was formed in December 1992 to accelerate applied research in reservoir sedimentation and operation. The committee consists of a Chairman and Secretary and a representative from the world's leading water-related research organizations: the International Association for Hydraulic Research (IAHR), the International Association for Hydrologic Sciences (IAHS), the International Commission on Large Dams (ICOLD), the International Research and Training Centre on Erosion and Sedimentation (IRTCES), the International Association of Water Quality (IAWQ), and the International Association of Water Resources (IAWR). ICCORES is currently preparing a 42-chapter book on reservoir sedimentation that will cover all aspects of the problem from consequences and impacts to planning and design for sustained performance. Case histories adequate for calibrating computer models will appear as a separate volume. Those interested in participating should contact their organizational representative. ICCORES will also participate in several aspects of IHP-V Project 2.2, Sedimentation Processes in Reservoirs and Deltas. This paper appeared in essentially the same form in Hotchkiss and Di Silvio (1995).

INTRODUCTION

Reservoir sedimentation consumes about one percent of the world's total reservoir storage each year (Mahmood, 1987). Closure of new dams around the world was most active in the 1960s and 1970s, but has since steadily declined (Zhang and Qian, 1985). Combined with the slowing pace of new construction, many dams around the world are approaching their limit of useful life due to sedimentation problems. Thus, as Carl Nordin stated (1992), hydropower is not necessarily a renewable resource, nor is the reservoir storage responsible for other project benefits. It is evident that we must respond to the current and worsening worldwide reservoir sedimentation problem. To that end, ICCORES was established in 1992.

GENESIS AND FORMATION

The idea of concentrating efforts in reservoir sedimentation originated with Egbert Prins, who in 1991 was serving as Secretariat for IAHR. While organizing the North African Division of IAHR in Khartoum, Sudan in November of that year, he suggested the idea of a "megaprogramme" on reservoir sedimentation and operation to Professor Rollin Hotchkiss from the University of Nebraska (USA). Prof. Hotchkiss was the IAHR/IHP lecturer in Sudan at the time and was discussing reservoir sedimentation problems and mitigation with government and university officials. Prins and Hotchkiss sketched out strategies and potential activities of such a megaprogramme, spurred on and inspired by the challenge of reservoir sedimentation problems they saw firsthand in Sudan.

Professor Peter Laursen of the University of Karlsruhe accommodated requests by Prof. Hotchkiss to add special sessions to the already-planned 5th International Symposium on River Sedimentation in Karlsruhe, Germany, in April 1992. The special sessions were well attended, and several presentations from around the world highlighted the discussion of forming a "megaprogramme."

Professor Giampaolo Di Silvio from the Università Degli Studi Di Padova continued organizational efforts, including discussing the participation of a "megaprogramme" in the IHP-V scheduled to begin in 1996. He organized a special meeting in Bergamo, Italy, in December, 1992, where representatives from four international organizations were to meet and formally create a new committee. The meeting, sponsored by ISMES of Italy, welcomed Albert Rooseboom representing ICOLD, Enzo Todini from IAHS, Ying Tan from IRTCES, and Giampaolo Di Silvio representing IAHR. After much discussion ICCORES was formed with a letter of intent, later ratified by each organization. Both IAWQ and IAWR have since joined ICCORES. Current representatives from all organizations are listed in Table 1.

Table 1. Representatives serving in ICCORES

Position	Name	Organization	Address
Chairman	Giampaolo Di Silvio	IAHR	Università Degli Studi Di Padova, Istituto Di Idraulica, Via Loredan 20-35131, Padova, Italy
Secretary	Rollin H. Hotchkiss	IAHR	University Of Nebraska, Dept of Civil Engineering, W348 Nebraska Hall, Lincoln, NE 68588-0531
Delegate	Robert Strand	ICOLD	U.S. Bureau Of Reclamation, D-5753 Federal Center, P.O. Box 25007, Denver, CO 80225
Delegate	TAN Ying	IRTCES	IRTCES, P.O. Box 366, 20 Chegongzhuang Xilu, Beijing, China
Delegate	Giampaolo Di Silvio	IAHR	see above
Delegate	Charles Onstad	IAHS	USDA-ARS, Southern Plains Area, 7607 Eastmark Dr., Suite 230, College Station, TX 77840
Delegate	Lambertus Lijklema	IAWQ	Agricultural Univ. of Wageningen, Dept. of Natural Conservation, PO Box 8080, Wageningen, 6700ER
Delegate	Glenn Stout	IAWR	205 N. Mathews Ave., University Of Illinois @ Urbana, Urbana, ILLINOIS 61801-2352

INTENT AND PURPOSE

Quoting from the Letter of Intent, the above-named representatives wrote, "We, the undersigned, representing our specific organizations, are concerned about the worldwide degradation of reservoirs in terms of sedimentation. We desire to coordinate our efforts,

recognizing that within each organisation there exists independent but similar sentiments, and that like initiatives have been developed by other parties. We propose to form the International Coordinating Committee on Reservoir Sedimentation (ICCORES, formerly referred to as "Megaprogramme")."

The stated objective of ICCORES is to "...coordinate efforts to improve water resources management with specific reference to reservoir sedimentation: to design, operate, and maintain facilities for long term economic and environmental sustainability and to eliminate unnecessary duplication of efforts." All efforts are to follow agreed upon principles of cooperation: 1) cooperate on the basis of full equality and independence; 2) exchange data and information; and 3) pursue publications on the topic.

Moving towards the objective of ICCORES was to be initially accomplished by sponsoring an international symposium in 1996. Subsequent ICCORES meetings and progress have expanded the initial goal considerably.

ICCORES PROJECTS

ICCORES representatives met again in June 1992 in Washington, D.C. in conjunction with the first International Conference on Hydro-Science and Engineering. Sam Wang, conference chair, graciously provided meeting rooms and facilities for the ICCORES meetings. Delegates at that time decided to pursue three courses of action: 1) publication of a book on reservoir sedimentation and operation; 2) participation in a design or mitigation project somewhere in the world to demonstrate emerging technology for sediment mitigation; and 3) involvement in the upcoming IHP-V.

Monograph

Work on a book of reservoir sedimentation and operation is well underway. Initial book topics were suggested in Washington and then discussed via 17 invited papers at the May 1994 UNESCO East-West encounter held in St. Petersburg, Russia. Professor Snishchenko of the Russian State Hydrological Institute hosted several ICCORES sessions as a part of his conference. The ICCORES papers will be published by UNESCO shortly.

Professor Maury Albertson of Colorado State University had also begun an effort to publish a similar effort. Attending the St. Petersburg meeting, he discussed his ideas for a book with ICCORES delegates. The two book ideas were successfully combined into a single effort. An editorial board has since been organized with representatives from each sponsoring organization, and an executive committee was established to push production efforts forward.

A meeting of the executive committee held in Ft. Collins in July 1994 produced section and chapter headings for the book (Table 2). Section editors were also identified. Chapters are now being written, and the book will be near completion for the special international conference to be held in Ft. Collins in 1996. The purpose of the conference will be to collect additional papers from interested parties from around the world to supplement the book.

Field Project

Efforts to ally ICCORES with a dam project or sediment mitigation project have been less successful. In order to receive support from international banks, ICCORES must be formally involved with a country that has a project funded by one of the banks. To date no country or project has been identified.

Table 2. Proposed table of contents for Reservoir Sedimentation Engineering

Section 1.	INTRODUCTION, INTERNATIONAL PERSPECTIVES AND PROBLEMS
Ch. 1.1	Reservoir sedimentation and sustainable development of water resources--the international perspective
Ch. 1.2	Major issues with sedimentation of reservoirs--regional reports
Ch. 1.3	Operation and maintenance problems due to sedimentation in reservoirs
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Section 2.	PROCESSES
Ch. 2.1	Hydrology and sediment yield
Ch. 2.2	Hydraulics of inflow
Ch. 2.3	Sediment transport
Ch. 2.4	Distribution of deposited sediment
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Ch. 4.2	Empirical and Semi-empirical models
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Ch. 5.1	Planning for reservoir sediment storage
Ch. 5.1	Planning for reservoir sediment storage
Ch. 5.3	Field investigations for sediment planning of reservoirs
Ch. 5.4	Design considerations for low-level outlets

Table 2. Proposed table of contents for Reservoir Sedimentation Engineering (continued)

- Ch. 5.5 Design of silt related hydraulic structures
- Ch. 5.6 Environmental
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Section 6. MANAGEMENT

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- Circulated guidelines for case study preparation and presentation
- Ch. 9.1 Inventories of case histories of reservoir sedimentation analyses and investigations
- Ch. 9.2 Individual case histories
- Ch. 9.3 Computer calibrated data sets

Training and Documentation Centre

Plans are underway to propose a Training and Documentation Centre for material dealing with reservoir sedimentation. Outstanding work has been sponsored worldwide in this topical area, but many of the products remain in their original language, especially Chinese and Russian. As part of the upcoming IHP, we will propose that a centre for training and documentation be established in Italy, initially with contributions from Italian funds. Besides translating significant documents into a common language (English), the Centre will organize stages and courses at

different levels for engineers and technicians from developed and developing countries of the world working in the field of reservoir sedimentation. The Centre will also participate in national and international research projects. Teachers, experts, and consultants for the activities of the Centre will be sought in the scientific and professional international community with the assistance of ICCORES.

Including ICCORES in the next IHP is on schedule. The revised outline of the fifth phase names ICCORES as a cooperating partner in Project 2.2, sedimentation processes in reservoirs and deltas. Proposed products of our cooperation include case studies, research reports, proceedings, and guidelines for coping with reservoir sedimentation.

INVITATION

We invite you to participate. We are particularly interested in two areas. The first is the compilation of detailed case histories involving successful (or unsuccessful) efforts to mitigate reservoir sedimentation. These case histories may document either retroactive efforts to deal with existing problems or may highlight designs that were incorporated into the project from its inception to ensure sustained performance. We seek data that is of sufficient quality to be used in calibrating existing and emerging computer codes that address reservoir sedimentation. Secondly, we seek cooperation with a project where we might illustrate state-of-the-art methods of sediment control. In order to become a partner to such a project, we would need to be identified by a country and the project to the international funding bank.

If you would like to participate in either of these two activities, or would otherwise like to participate in ICCORES projects, please contact your organizational representative in Table 1. Together we hope to be able to extend the useful life of reservoirs around the world to serve additional generations.

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ELWHA RIVER RESTORATION PROJECT
SEDIMENT ANALYSIS AND MODELING SUMMARY

by

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Abstract

Removal of two hydroelectric dams on the Elwha River of Washington's Olympic Peninsula is an alternative being considered to restore the ecosystem and native anadromous fisheries. Elwha and Glines Canyon Dams block anadromous fish passage to more than 70 miles of the Elwha River and its tributaries, limiting anadromous fish to the lower 4.9 river miles. Lake Aldwell, formed behind Elwha Dam in 1913, stores an estimated 4 million cubic yards (mcy) of sediment. Further upstream, Lake Mills was created in 1927 with the closure of Glines Canyon Dam and contains an estimated 14 mcy of sediment.

Removal of these dams would require development and analysis of alternative plans to manage the reservoir sediments and analysis of the effects of reestablishing the natural sediment supply to the Elwha River downstream of the dams. Removing the dams in controlled increments and allowing a portion of the reservoir sediments to erode downstream through natural processes is the alternative evaluated in this report. The impacts of this alternative on the river's sediment concentration, riverbed aggradation, and corresponding increases in flood stage were mathematically modeled.

Model results predict that between 15 and 35 percent of the coarse sediment (sand, gravel, and cobble) and about half of the fine sediment (silt- and clay-size) would be eroded from the reservoirs during removal of the dams. Fine sediment concentrations released from the reservoirs would be high (typically between 200 and 10,000 ppm) during periods of dam removal. Release concentrations would be relatively low (less than 200 ppm) during periods of high lake inflow when dam removal would stop. After the dams are removed, fine sediment concentrations would be low and near natural conditions during periods of low flow. Concentrations would be high during progressively higher floodflows as erosion channels widen in the reservoirs.

Coarse sediment would aggrade river pools in the relatively steep reach between the two lakes and would increase 100-year flood stages up to 0.5 feet. In the more mild slope reach below Elwha Dam, general riverbed aggradation would be between 0 and 10 feet. This would raise 100-year flood stages between 0 to 5.5 feet—with an average increase of 2.6 feet. Coarse sediment that reached the river's mouth would enlarge the delta to a size and character similar to that of predam conditions.

INTRODUCTION

This paper is a summary of a U.S. Bureau of Reclamation report being prepared by the same authors. Details of the study will be presented later in the full report.

The Elwha River is a coarse-bed stream located on the Olympic Peninsula of northwestern Washington state. The river flows northward 45 miles from the base of Mount Olympus to the Strait of Juan de Fuca (Strait) near Port Angeles, Washington, falling about 4,500 feet in elevation. The Elwha River is the fourth largest on the Olympic Peninsula and its watershed includes over 100 miles of stream channel. The watershed has a drainage area of 321 square miles, 83 percent of which are in the Olympic National Park. The average daily discharge is about 1,500 cubic feet per second (ft³/s). Minimum flows typically occur during summer and range from about 300 to 500 ft³/s. High flows are typical from November through February and from May through June.

Elwha Dam (4.9 river miles upstream from the Strait) was constructed during the period 1910-13. This 105-foot high concrete gravity dam forms Lake Aldwell which has a capacity of 8,000 acre-feet. Glines Canyon Dam (at river mile 13) was constructed about 8.5 river miles upstream from Elwha Dam during the period 1925-27. This 210-foot high concrete arch dam forms Lake Mills which has a capacity of 40,500 acre-feet (Federal Energy

Regulatory Commission, 1993). Both lakes are presently maintained at or near full capacity and provide minimal flood control.

The river flows through several steep, narrow, bedrock canyons between wide alluvial reaches of mild slope. The widest floodplain and mildest slope of the river is near the mouth. Upstream from Lake Mills, riverbed material consists of sand, gravel, cobbles, boulders, and bedrock outcrops. The river bed degraded downstream from both dams following dam closure and now consists primarily of boulders, and bedrock. Currently, because of riverbed armoring, fish spawning habitat is limited to a few side channels near the mouth and isolated pools up to river mile (RM) 3.

All of the existing infrastructure along the Elwha River is downstream from Glines Canyon Dam. Existing infrastructure includes features such as: roads, bridges, homes, wells, a diversion dam and water intakes, national park facilities, and Lower Elwha S'Klallam Tribal lands and facilities. The Elwha River valley is rich in cultural resources with human occupation dating from prehistoric times.

SEDIMENT MANAGEMENT ISSUES

The amount and rate of reservoir sediments released downstream would result in both short-and long-term impacts. Over the short term, release of fine lakebed sediments (silt and clay) would affect water quality (suspended sediment concentration and turbidity). Release of coarse delta sediments would affect flood stage, channel migration, and the coastal shoreline (Randle and Lyons, 1995). On the other hand, gravels released from the reservoirs could restore suitable fish habitat in downstream reaches.

Because of the pristine character of the watershed, water quality issues are primarily related to suspended sediment concentration and turbidity. This water quality issue is important to municipal, industrial, and private water users as well as to fish and the aquatic environment of the river and estuary. Water quality would primarily be affected by the erosion and release of silt and clay from the reservoirs and by reestablishment of the natural sediment loads downstream.

DATA COLLECTION

The Elwha Report to Congress (U.S. Department of the Interior, 1994), the Federal Energy Regulatory Commission's Draft Staff Report (1993), and supporting documents contain a great deal of information including topography and sediment size data for both reservoirs and the river channel. Additional data collection efforts necessary to address sediment management issues primarily focused on:

- the establishment of a new stream gauge upstream from Lake Mills,
- a drawdown test of Lake Mills,
- geologic investigations of sediments in Lake Mills and Lake Aldwell (Gilbert and Link, 1995),
- reservoir surveys of Lake Aldwell and Lake Mills forebay,
- aerial photography of the river corridor, and
- topographic surveys and geologic mapping of the river channel and reservoirs.

The 18-foot drawdown experiment of Lake Mills was conducted in April, 1994 to determine the erodibility and size distribution of the delta sediments and the effects of the experiment on sediment transport downstream. The lake's water level was lowered 18 feet over a one-week period and then held at a constant elevation for one week before refilling. Lake inflows during the drawdown test were between 900 and 1,800 ft³/s—below average for April. Data collection included: daily stream gauging (including streamflow, suspended sediment, bed material and bedload), repeat cross-section surveying, geologic mapping of the delta surface, time-lapse photography, and aerial photography.

The Lake Mills delta was found to consist mostly of sand and fine gravel. These sediments were likely derived from upstream shale beds and consisted of platelets and rod-shaped particles.

SEDIMENT MANAGEMENT PLAN

This alternative would allow the sediments presently trapped in Lake Mills and Lake Aldwell to be eroded from the reservoirs (to the extent possible) and transported downstream to the Strait by natural processes. This sediment management alternative represents a minimum cost option. Except for controlling lake elevations during reservoir drawdown and the rate at which each dam is removed, the river would initially be allowed to erode reservoir sediment without mechanical intervention (such as hydraulic dredging). However, regrading of the remaining sediment to a stable slope may be necessary. Elwha and Glines Canyon Dams would be removed concurrently to minimize the duration of high sediment concentrations in the river.

Glines Canyon Dam Removal and Lake Drawdown: Lake Mills drawdown would begin in June of a given year to the extent practical using the existing spillway and penstock (the low-level outlet is inoperable). High lake inflows from the spring snow melt are expected to refill the lake—at least to spillway crest elevation. Lake drawdown would again continue following the return to lower flows. The top portion of the dam would be removed in the dry. Further dam removal and lake drawdown would be accomplished by cutting a sequence of notches (by drill and blast techniques) into the dam's concrete arch section. Notch openings would alternate on the dam's left and right sides. Each notch would be about 25 feet wide and 15 feet high. After each notch opening, the lake would drawdown as lake water drained through the notch. Lake drawdown would continue until outflow through the notch equaled lake inflow.

For an inflow of 1,400 cfs, water depth through the notch would be about 7.5 feet. This would expose a portion of the dam above water (about 7.5 feet) and allow removal under dry conditions. The next 15-foot high notch would be on the dam's other side and would lower the lake another 7.5 feet. Lake inflows would have to be 1,400 cfs or less for a two-week period in order to complete work necessary to open another notch. Notch openings in the dam and removal of the upper 7.5 feet could continue about every two weeks during periods of low lake inflow (1,400 cfs or less).

Lake drawdown and dam removal would continue through the summer and early fall of the first year until lake inflows increased during the winter high flows—typically November through January. During these high flow periods dam removal could not continue (because of inundation) and the lake level would remain relatively constant. Following the return to low flows, dam removal would continue again until the high flows from the spring runoff occurred—once again preventing dam removal. After the spring runoff, the dam would be completely removed during the summer and fall of the second year.

Elwha Dam Removal and Lake Drawdown Schedule: Lake Aldwell would first be drawn down about 15 feet to elevation 182 feet using the south spillway and penstocks (there is no low-level outlet). A diversion channel would be excavated through the bedrock of the left abutment at the present location of the north spillway channel. This would enable lowering the lake about 40 feet in August of a given year to elevation 140 feet. The lake would remain near this elevation for about a year while the exposed portion of the dam and upstream fill material are removed.

Lake drawdown would resume in August of the next year and continue until complete removal in October. Lake drawdown would progress in 5-foot increments, as portions of the dam and fill material are removed, until complete removal at about elevation 90 feet.

NUMERICAL SEDIMENT MODELING

Various numerical models were used to predict reservoir sediment erosion and its effects on sediment concentration and riverbed aggradation in the river downstream. These models include:

- Sediment Transport and River Simulation (STARS) model (Orvis and Randle, U.S. Bureau of Reclamation, 1987);
- HEC-6 model: Scour and Deposition in Rivers and Reservoirs, Version 4.1A (U.S. Army Corps of

Engineers, 1994); and

- a new reservoir sediment erosion model (referred to as the reservoir model) was developed to predict the erosion, redistribution, and downstream release of sediments during concurrent removal of both dams and corresponding lake drawdown.

Reservoir Sediment Erosion, Redistribution, and Release Downstream: The HEC-6 model was used to predict the river's capacity to vertically incise a channel through the redistributed delta sediments of Lake Mills during removal of Glines Canyon Dam. HEC-6 model results predicted how sediment release rates would vary between notch openings in the dam. However, the HEC-6 model requires knowledge of the erosion width and does not predict sediment terrace development in the reservoir during the erosion process. Therefore, the new reservoir model was applied to the coarse- and fine-grained sediments from both Lake Mills and Lake Aldwell. Fine-grained sediments include clay- and silt-size (< 0.075 mm) and coarse-grained sediments include sand-, gravel, and cobble-size (> 0.075 mm). The reservoir model integrates empirical relationships for the erosion and redeposition of coarse sediment with a model for fine sediment developed by G. Smillie and W. Jackson (written communication, National Park Service, Fort Collins, Colorado, 1995).

Not all of the reservoir sediment is expected to erode during dam removal. Some portion of the sediments would remain stable in the reservoir area over the long term because the reservoirs are much wider than the river. Therefore, predicting erosion widths during dam removal is critical to determining how much sediment could be eroded downstream. Observations from the 1994 Lake Mills Drawdown test were used to develop an empirical relationship for the erosion and redistribution of coarse sediment within the delta.

The reservoir model simulated dam removal and lake drawdown in four phases:

In the first phase, portions of the delta would be eroded and redistributed downstream toward the dam. No coarse sediment would be released past the dam site. Terraces of coarse sediments would be left behind along the reservoir margins. The amount of fine sediment concentration released downstream would tend to increase over time because more fine sediment would be resuspended and because lake water volumes would decrease. Dam removal operations and lake drawdown would be discontinued during periods of high lake inflow. These high flows would tend to flush the lake and thus reduce fine (suspended) sediment concentrations within the lake.

At the beginning of the second phase, coarse sediment from the delta would reach the dam and cover the fine sediment of the lakebed downstream. There would no longer be a lake, but rather a stub dam with the remaining reservoir full of sediment. Both fine and coarse sediment would be released downstream with each increment of dam removal. Erosion widths would be a function of discharge. The rate at which sediment is transported past the dam would be initially high after a sudden increment of dam removal. This rate would decrease exponentially with time. During periods of high river discharge into the reservoir area, dam removal operations would be suspended and sediment erosion and release downstream would occur from channel widening.

The final stages of dam removal occur during the third phase. At the beginning of the third phase, dam removal would have progressed to a point where the river has vertically eroded a channel through the layer of coarse sediment and the fine lakebed sediments near the dam would be exposed. Rates of fine sediment release would be initially high, then decrease with subsequent dam removal.

At the beginning of the fourth phase, the dam would be removed down to predam river level. During periods of low discharge, the amount of coarse and fine sediment released downstream would equal the amount of sediment supply from upstream. Additional release of reservoir sediments past the damsite would occur due to channel widening from progressively higher discharges.

Hydrologic Scenarios.—Model simulations were performed using historic flows as the lake inflow. Historic mean daily discharges for the Elwha River were obtained from U.S. Geological Survey measurements at the McDonald Bridge gauging station. Four different hydrologic scenarios were simulated, each based on 3 years and 4 months of historic flow:

- | | |
|---------------------------------------|---------------------------------------|
| 1) June 1, 1968 to September 30, 1971 | 3) June 1, 1971 to September 30, 1974 |
| 2) June 1, 1950 to September 30, 1953 | 4) June 1, 1989 to September 30, 1992 |

Each of these historic periods were selected based on annual peak mean-daily discharges. Hydrologic scenario 1 includes the lowest peak discharges for any three consecutive water years of record. Scenario 4 includes the highest peak discharges for any three consecutive years of record. Scenarios 2 and 3 were arbitrarily chosen to represent the range between the extremes of scenarios 1 and 4. Scenario 2 includes a year of relatively high annual-peak discharge followed by years of relatively low and then moderate annual-peak discharge. Each year of scenario 3 has a progressively higher annual-peak discharge. Reservoir model output from the simulation of the Glines Canyon Dam removal was used as model input for the simulation of the Elwha Dam removal. Attenuation or storage of the released water and sediment between the two lakes was ignored.

Reservoir Model Results.—The predicted release of fine and coarse sediment from Lake Mills and Lake Aldwell for each of the four hydrologic scenarios has many similarities. In general, fine-sediment concentrations released past the dam tend to increase with time between periods of high lake inflow. Predicted concentrations tend to be near zero during periods of high lake inflow. No coarse sediment is released until the delta front has reached the dam. Rates of fine and coarse sediment release are highest immediately after each notch opening in the dam. Following dam removal, the erosion and release of coarse and fine sediment would be low and close to natural conditions most of the time. However, floodflows of progressively higher magnitude would continue to widen erosion channels through the reservoir and produce high rates of both coarse and fine sediment release downstream. Peak concentrations would typically be of short-duration and the magnitudes of these events would tend to decrease with time. Example results from hydrologic scenario 3 are presented in figure 1.

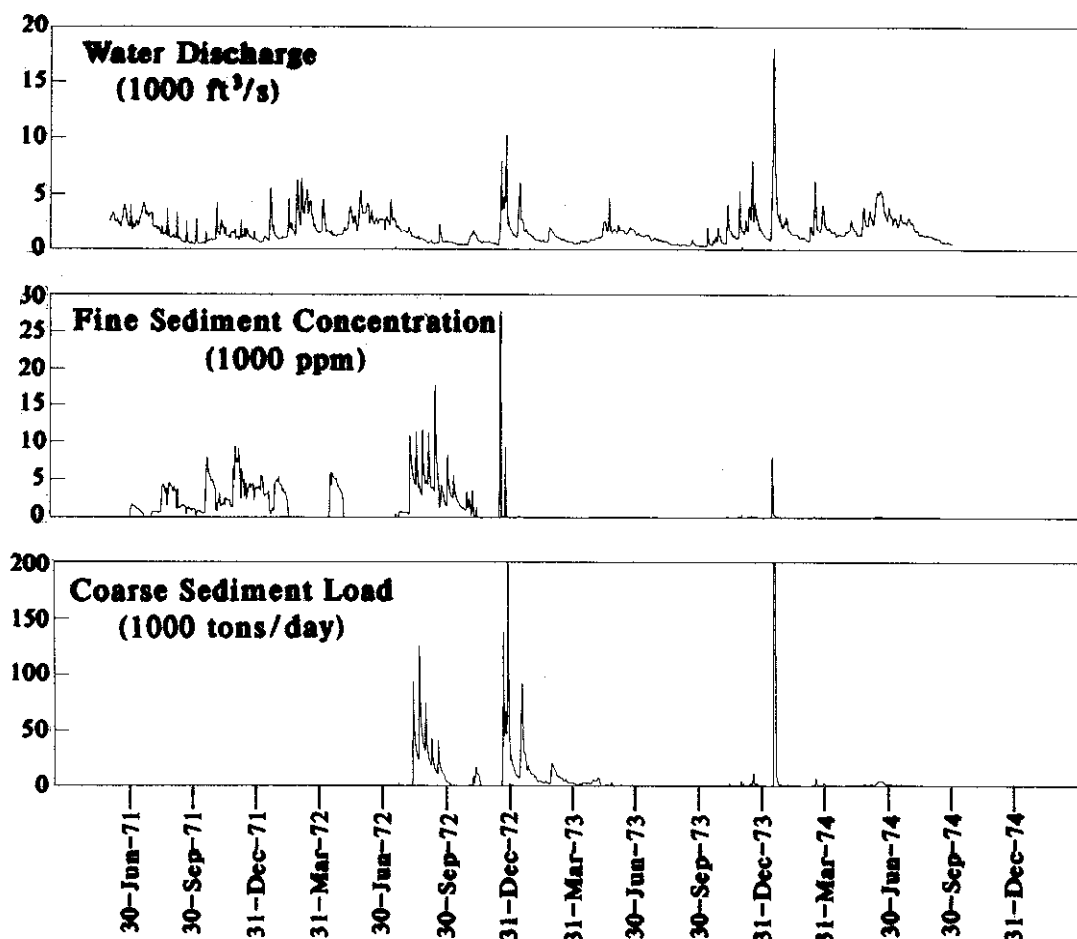


Figure 1.—Reservoir model results of water discharge, fine sediment concentration, and coarse sediment load released from Lake Mills and Lake Aldwell during and following concurrent dam removal.

Downstream Riverbed Aggradation: Both the STARS and HEC-6 models were applied to the downstream river channel.

STARS Modeling.—The coarse sediment transport capacity of the river was computed for various locations along the river using a special version of the STARS model. Transport capacity was computed for existing channel conditions and also for channel conditions assuming various amounts of riverbed aggradation. The amount of riverbed aggradation was determined at each cross section such that the computed transport capacity would increase but without increasing water surface elevation by more than an assumed increment. From these calculations, the reach-limiting transport capacity was determined for various amounts of riverbed aggradation (see figure 2). Computed reach-limiting transport capacities for the lower reach—below Elwha Dam—were much less than that of the middle reach—between the two lakes. Therefore, the lower reach is controlling from a sediment management perspective.

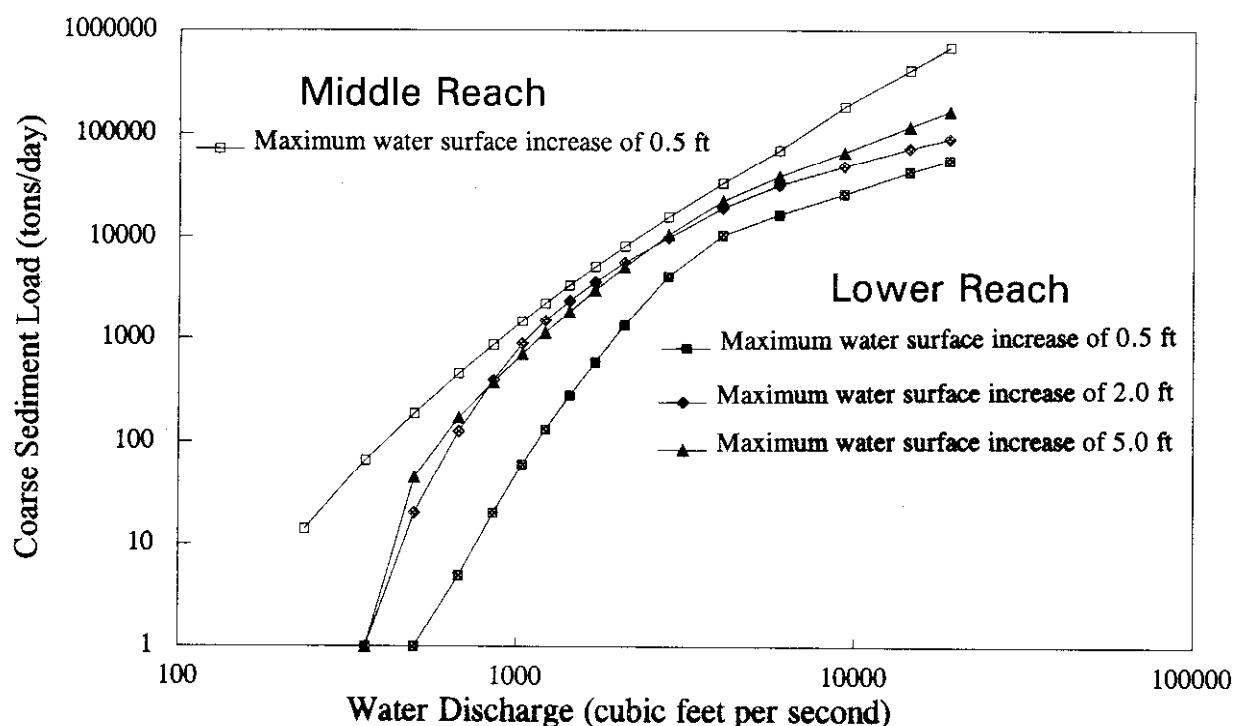


Figure 2.—STARS model results of coarse sediment transport capacity versus discharge, assuming various amounts of riverbed aggradation and river stage increase.

HEC-6 Modeling.—The short- and long-term impacts of coarse sediment release, resulting from the removal of Glines Canyon and Elwha Dams, were numerically modeled for the lower reach. The middle reach between the two lakes was not modeled with HEC-6 because the spacing of the river cross-section survey data was not sufficiently close to compute accurate river hydraulics and sediment transport. However, the middle reach is relatively steep and less susceptible to riverbed aggradation than the lower reach.

Results from the reservoir sediment erosion model were used as the upstream boundary condition in the HEC-6 simulations of the lower reach. Hydrologic scenarios 1 and 4, representing the historic three-year extremes, were both used to simulate short-term conditions. Hydrologic scenario 4 had the largest volume of reservoir sediment erosion but a relatively high sediment transport capacity from the larger discharges. Hydrologic scenario 1 had relatively low volume of reservoir sediment erosion but also a relatively low capacity to transport it. Hydrologic

scenario 3 (June 1971 through September 1974) was considered to be the worst case with progressively higher annual-peak discharge. This scenario was used to model the concurrent removal of both dams and the superposition of sediment release from each without regard to lag times.

Short-term model simulations of 3.3 years were continued for another 50 years using measured mean-daily flows for the period 1920-1970 and assuming the natural upstream sediment yield. Contrary to what had been expected, long-term simulations predicted more riverbed aggradation than the short-term simulations. The HEC-6 modeling results for the lower river reach predict that riverbed aggradation would result from the removal of both dams and that river stage for a given discharge would increase. Most of the riverbed aggradation would be from gravel-size and coarser particles. In general, the model predicted that sand-size particles (finer than 2.0 mm) would tend to pass through the lower reach but that gravel-size particles would tend to accumulate. About 1 mcy of gravel were input in the short-term simulation of hydrologic scenario 3 but an additional 1.5 mcy of gravel were input over the 50 years of the long-term simulation.

The amount of riverbed aggradation, in the upstream end of the modeled reach (RM 4 to 5), was greater after the short term (3.3 years) than after the long term (53.3 years). Downstream from RM 4, the amount of riverbed aggradation is greater over the long term than the short term. The amount of riverbed aggradation (excluding the upstream 0.1 mile below Elwha Dam) ranged from near zero at some cross sections to 9.6 feet near RM 3.4. This resulted in increases in 100-year-flood elevations ranging from zero at some cross sections to 5.5 feet at RM 1.05—with an average increase of 2.6 feet (see figure 3).

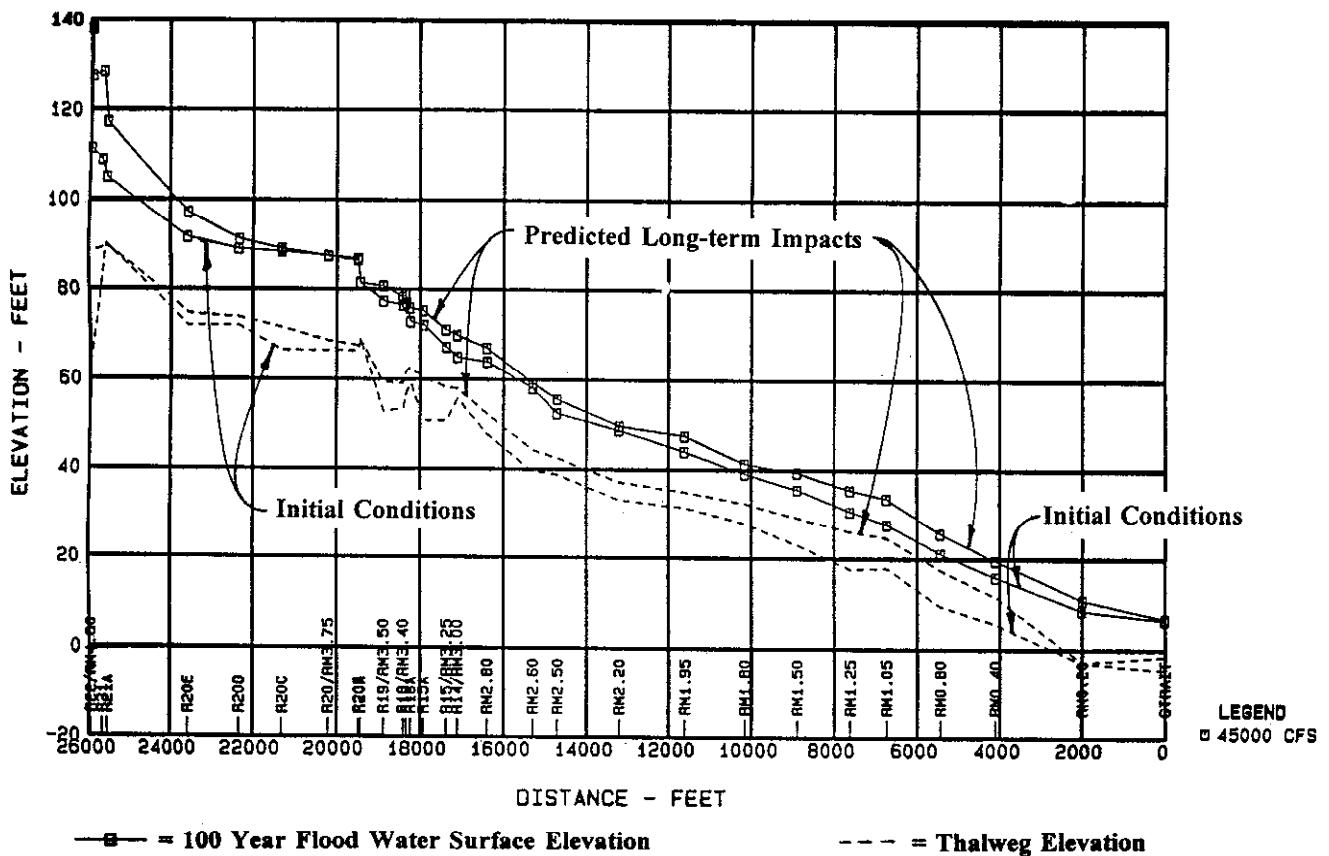


Figure 3.—HEC-6 model results comparing existing thalweg and water-surface-elevation profiles, corresponding to the 100-year flood, with conditions after 53.3 years.

DISCUSSION

Development of the reservoir model was, in part, based on results from the 1994 Lake Mills drawdown experiment and model results agreed well with measurements and observations. This model is a useful tool to predict how much sediment would erode from the reservoir and the pattern and magnitude of the sediment released downstream.

For a variety of reasons, the HEC-6 model simulations of the lower reach likely under predict the amount of gravel transport and over predict the amount of riverbed aggradation and corresponding increases in river stage. Fine sediment was not modeled in the HEC-6 simulations because it is not representative of the bed. However, large sediment concentrations tend to increase transport capability because of the increased density and viscosity of the water-sediment mixture. During aggradation, the topography of the river channel and its roughness would change so that the river's sediment transport capacity is increased. The HEC-6 model can only account for vertical changes in the riverbed and the channel roughness is assumed to be a constant over time. Therefore, model results tend to represent an upper limit of actual riverbed aggradation and corresponding increases in flood stage.

CONCLUSIONS

With monitoring and mitigation, the River Erosion Alternative constitutes a viable sediment management plan for the removal of Glines Canyon and Elwha Dams. Mitigation is needed for increases in river stage and fine sediment concentration. Extensive monitoring and control of the dam removal rate is needed to avoid unforeseen problems with riverbed aggradation, flooding and water quality (based on modeling results and judgement).

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A RESERVOIR SEDIMENTATION SURVEY INFORMATION SYSTEM -- RESIS

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ABSTRACT

All Reservoir Sediment Data Summary forms (SCS-ENG-034), Form 34's, on file through 1985, and a few surveys completed between 1986 and 1995, have been converted to electronic format and compiled into an INFORMIX database called RESIS, a Reservoir Sedimentation Survey Information System. The database was compiled through a joint effort of Natural Resource Conservation Service (NRCS) and Texas Agricultural Experiment Station (TAES) staff in 1994. It was used to study trends in reservoir sedimentation as part of the Sedimentation Subtopic in the third Resources Conservation Act (RCA III) analyses (Bernard et. al., 1995). Issues identified during the RCA III analyses include the decline in the number of surveys being made, some inconsistencies in data sheet numbering, the lack of detailed sediment dry weight information and the paucity of land use data for the periods surveyed. The database currently resides on a computer at the NRCS National Soil Survey Center in Lincoln, Nebraska and is being managed by the author. Long-term management responsibility is being studied.

INTRODUCTION

In 1994, the Natural Resources Conservation Service (NRCS) worked with the Texas Agricultural Experiment Station (TAES) to compile an INFORMIX database titled RESIS, the Reservoir Sedimentation Survey Information System. This cooperative effort was carried out as part of the third Resources Conservation Act (RCA III) activities of the NRCS.

RESIS is a relational database consisting of 14 tables. It contains records on 1,824 reservoirs and 4,141 individual sedimentation surveys. The data consists of electronic transformation of all Reservoir Sediment Data Summary forms (SCS-ENG-034), Form 34's, submitted for publication through 1985. The author has added a few survey records submitted from 1986 through 1995.

The sedimentation data on the Form 34's represents the cooperative effort of various U.S. government agencies over many years. The Subcommittee on Sedimentation of the Inter-Agency Committee on Water Resources (ICWR) has directed the collection and standardization of the data. NRCS worked with TAES in the development of the RESIS database.

NRCS acknowledges the assistance of Dr. Paul Dyke, and his staff, in compiling the database. Dr. Dyke is the Director of the Integrated Information Laboratory, Texas A & M University, at the Blackland Experiment Station in Temple, Texas. NRCS also acknowledges the assistance of Dr. Jay Atwood, an NRCS Agricultural Economist with the Natural Resources Inventory Division, who manages the NRCS economic modeling and database project at Texas A & M. Dr. Atwood designed the initial structure of the database and populated the tables utilizing ASCII text files of the original data on floppy

diskettes. Dr. Atwood also performed the initial queries utilized in the Sedimentation Subtopic analyses for RCA III.

BACKGROUND

Reservoir Sediment Surveys

Sedimentation surveys of existing reservoirs have provided the basic data that engineers and scientists have used historically to determine the volume of sediment storage required for new reservoirs. Large reservoirs trap almost all the sediment delivered to the pool so, over time, average annual rates (volume per year) of sediment accumulation can be determined by periodically measuring the changes in storage capacity of the reservoir. These rates can be compared to the watershed drainage area to develop a volume per year per square mile relationship. Historically, this information has been used to estimate sedimentation rates in other, similar areas.

Undisturbed samples of the sediment are collected during the sedimentation survey and analyzed to determine the dry unit weight of the deposits. This allows the volume (acre-feet) of sediment to be converted to weight (tons). The tons of sediment deposited, divided by the trap efficiency of the reservoir, converts the deposition to tons of sediment yield to the reservoir. Sediment yield can be divided by a sediment delivery ratio to estimate the tons of erosion from the watershed. Land use and sources of erosion can then be compared to sediment yield from one watershed to another.

Reservoir Sediment Data Summary Forms (SCS-ENG-034)

The value of reservoir sedimentation information led federal agencies to develop standardized procedures and data collection forms (Figure 1). The eight federal agencies on the Subcommittee on Sedimentation of the Inter-Agency Committee on Water Resources (ICWR) directed the collection and publication of all data sheets from all agencies. The sedimentation data has been published every five years through 1980 in "USDA Miscellaneous Publication No. 1362".

Analyses of the published sediment data was difficult due to the format and bulk of the data. The first attempt to convert the paper copies of the data sheets into an electronic format to facilitate analysis was made by NRCS in 1972. The conversion to a database management system on a dedicated central processing unit made some regional analyses possible but the data was not easily transportable to other systems so few researchers attempted to use it. The magnetic tape data was eventually converted by NRCS to ASCII files on floppy diskettes by 1992.

RESERVOIR SEDIMENTATION SURVEY INFORMATION SYSTEM (RESIS)

Meetings of staff working on various studies as part of the third Resources Conservation Act in 1992 resulted in a collaborative effort between NRCS and the Blackland Experiment Station out of Texas A & M University to convert the ASCII files to a format compatible with the INFORMIX database management system. The conversion to INFORMIX was completed in January, 1994 and numerous queries were run to develop trends in reservoir sedimentation as part of the Sedimentation Subtopic analyses for RCA III.

Figure 1. SCS-ENG-034 Form: Reservoir Sediment Data Summary

U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

RESERVOIR SEDIMENT DATA SUMMARY

SCS-ENG-034
02-85

		NAME OF RESERVOIR				DATA SHEET NO.				
DAM	1. OWNER					2. STREAM				
	4. SEC.	TWP.	RANGE		5. NEAREST P.O.	6. COUNTY				
	7. LAT. ° ' "	° ' "		8. TOP OF DAM ELEVATION	9. SPILLWAY CREST ELEV.					
RESERVOIR	10. STORAGE ALLOCATION	11. ELEVATION TOP OF POOL		12. ORIGINAL SURFACE AREA, ACRES	13. ORIGINAL CAPACITY, ACRE-FEET	14. GROSS STORAGE, ACRE-FEET		15. DATE STORAGE BEGAN		
	a. FLOOD CONTROL									
	b. MULTIPLE USE									
	c. POWER									
	d. WATER SUPPLY							16. DATE NORMAL OPER. BEGAN		
	e. IRRIGATION									
	f. CONSERVATION									
	g. INACTIVE									
WATERSHED	17. LENGTH OF RESERVOIR				MILES		AV. WIDTH OF RESERVOIR			
							MILES			
	18. TOTAL DRAINAGE AREA				SQ. MI.		22. MEAN ANNUAL PRECIPITATION			
							INCHES			
	19. NET SEDIMENT CONTRIBUTING AREA				SQ. MI.		23. MEAN ANNUAL RUNOFF			
SURVEY DATA	20. LENGTH				MILES		AV. WIDTH		MILES	
	21. MAX. ELEV.				MIN. ELEV.		25. ANNUAL TEMP: MEAN			
							RANGE			
	26. DATE OF SURVEY	27. PERIOD YEARS	28. ACCL. YEARS	29. TYPE OF SURVEY	30. NO. OF RANGES OR CONTOUR INT.	31. SURFACE AREA, ACRES	32. CAPACITY, ACRE-FEET	33. C/I. RATIO, AC.-FT. PER AC.-FT.		
	26. DATE OF SURVEY	34. PERIOD ANNUAL PRECIPITATION		35. PERIOD WATER INFLOW, ACRE-FEET			36. WATER INFL. TO DATE, AC.-FT.			
SURVEY DATA	26. DATE OF SURVEY	37. PERIOD CAPACITY LOSS, ACRE-FEET				38. TOTAL SED. DEPOSITS TO DATE, ACRE-FEET				
SURVEY DATA	26. DATE OF SURVEY	39. AV. DRY WGT, LBS. PER CU. FT.		40. SED. DEP., TONS PER SQ. MI.-YR.		41. STORAGE LOSS, PCT.		42. SED. INFLOW, PPM		

Figure 1. SCS-ENG-034 Form: Reservoir Sediment Data Summary (cont.)

26. DATE OF SURVEY	43. DEPTH DESIGNATION RANGE IN FEET BELOW, AND ABOVE, CREST ELEVATION														
	PERCENT OF TOTAL SEDIMENT LOCATED WITHIN DEPTH DESIGNATION														
26. DATE OF SURVEY	44. REACH DESIGNATION PERCENT OF TOTAL ORIGINAL LENGTH OF RESERVOIR														
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	-105	-110	-115	-120	-125
	PERCENT OF TOTAL SEDIMENT LOCATED WITHIN REACH DESIGNATION														
45. RANGE IN RESERVOIR OPERATION															
WATER YEAR	MAX. ELEV.	MIN. ELEV.	INFLOW, AC.-FT.	WATER YEAR	MAX. ELEV.	MIN. ELEV.	INFLOW, AC.-FT.								
46. ELEVATION-AREA-CAPACITY DATA															
ELEVATION	AREA	CAPACITY	ELEVATION	AREA	CAPACITY	ELEVATION	AREA	CAPACITY							
REMARKS AND REFERENCES															
48. AGENCY MAKING SURVEY 49. AGENCY SUPPLYING DATA 50. DATE _____															

RESIS is a relational database consisting of 14 tables that contain all the information on all Form 34's on file through 1985. A few additional records from 1986-1995 have been added. RESIS has records for 1,824 reservoirs and 4,141 individual sedimentation surveys. Table 1 is a short description for each table and it shows the distribution within the tables of the numbered blocks of information from the Form 34's. Each table contains the data sheet number for each reservoir. This is the primary sorting key that connects all the data in each table to the pertinent reservoir. The principal secondary sorting keys used in querying the database include the pool identification and the date of each survey.

The "rsedrca_reg" and "rsed_damlnk" tables were added to the database to more accurately locate each reservoir. Some reservoirs had section, township, range location recorded on the Form 34's and some also included latitude and longitude. However, most reservoirs only included a county and a nearest post office as location information. In order to use most of the data in the RCA III analyses, it was necessary to put as many reservoirs as possible into a Major Land Resource Area (MLRA) and a four-digit hydrologic unit. The "rsedrca_reg" table was created to accomplish this task.

Other databases had matched the alphabetic abbreviation for each county in the United States to MLRAs and four-digit hydrologic units. This matching list became the "rsedrca_reg" table. Each reservoir in RESIS is matched to a unique MLRA and a unique four-digit hydrologic unit through this table.

The "rsed_damlnk" table was added later to increase the number of reservoirs with latitude and longitude information for GIS analyses. All the records in the National Inventory of Dams (NID) database include latitude and longitude information for each reservoir. RESIS and NID were compared and 900 common dams were identified. Physical description data from NID is referenced by data sheet number in the "rsed_damlnk" table for future applications.

USES TO DATE

The primary use of RESIS to date has been to complete analyses of reservoir sedimentation trends for RCA III (Bernard, et. al., 1995). The analyses were done at the four-digit hydrologic unit and Major Land Resource Area levels. RESIS data is also being used to help validate the sediment yield predictions generated by the Hydrologic Unit Model for the United States (HUMUS) and the Soil and Water Assessment Tool (SWAT) analyses being made for RCA.

Some minor database queries have been performed to generate information for researchers. Individual state reports have also been compiled and distributed to each NRCS state office. These reports list descriptive information and summarize the sedimentation data for each reservoir. The state reports have also been grouped by NRCS regions and each of the six new regional offices have been sent a copy.

ISSUES

RCA III analyses highlighted a number of issues relative to the data in RESIS. One issue involves the lack of recent data. Table 2 indicates that the number of reservoir sediment surveys reported on Form 34's has been dropping since 1970. This trend may be

Table 1. Overview of the RESIS database tables.

Table	Form 34 Blocks	Description
rsed01_descrip	1-9, 15-25	Details the ownership, location, top of dam and spillway crest elevations, dates of operation, drainage area and climate of reservoir drainage.
rsed02_respurp	10-14	Gives the pool elevations, surface area, and capacities of the pools by purpose of operation.
rsed03_period	26-28	For each survey on each reservoir, the elapsed time since the previous survey is recorded.
rsed04_surv-def	29-32	For each survey date on each reservoir, the survey method and scope is detailed.
rsed05_precflow	34-36*	Precipitation and water inflow for each survey period are recorded for each reservoir.
rsed06_deposits	37-42	Aerated, submerged, and total sediment deposits, sample number, and average dry weight estimates are given for each survey date.
rsed07_depth_def	43	Defines reservoir pool layers denoted by elevation for areal sediment distribution.
rsed08_depth_sed	43	For each survey, the percentage of sediment deposits occurring in each depth layer.
rsed09_reach_sed	44	For each survey date, gives the percentage of the sediment deposits occurring by distance segment and reach for each reservoir.
rsed10_range_opr	45	Water inflow and maximum and minimum reservoir elevations are given by water year.
rsed11_elev_cap	46	For each reservoir, the storage capacity by elevation stage is given (may have multiple dates).
rsed12_remarks	47	Footnote explanations and other remarks.
rsed13_agency	47	Agencies collecting and reporting data.
rsedrca_reg	---	For each reservoir, the associated county, Major Land Resource Area (MLRA), and 4-digit hydrologic unit area are recorded for use in RCA III queries.
rsed_damink	---	Matches reservoirs in RESIS with National Inventory of Dams database records.

* Block 33 not included

continuing today based on experience within NRCS. It appears that surveys have not been a high priority task for federal agencies starting in 1980. About 45 percent (1,853) of all surveys recorded in RESIS were actually done between 1965 and 1980. There were 947 surveys completed from 1965 to 1970 and 916 surveys completed from 1971 to 1980.

Table 2. Number of Reservoir Surveys by Time Period

<u>Period</u>	<u>Number of Surveys by Period</u>
1904-1930	19
1931-1950	871
1951-1970	2,257
1971-1985	945
1986-1995	<u>49</u>
Total	4,141

The RCA III analyses required data to be reported at the MLRA and four-digit hydrologic unit level. This type of identification is not recorded on Form 34's. The majority of reservoirs in the database also do not have latitude and longitude information. However, all the reservoirs did have a county location noted. The "rsedrca_reg" table was constructed to match the alphabetic abbreviation for each county with MLRA and hydrologic unit data.

Data from the National Inventory of Dams (NID) was matched to data in RESIS to increase the number of reservoirs in RESIS with latitude/longitude references. The RESIS/NID link is made in the database table titled "rsed_damlnk". Latitude and longitude for the center point of the dam creating a reservoir is needed for every reservoir in RESIS for georeferencing. Without this level of location information, the database cannot be easily used in any GIS application.

Since the data sheet number is the primary sorting key in the database, it is important that each reservoir have its own unique number. Current instructions for completing Form 34's indicate that the first two digits of a reservoir's data sheet number should be the two digits denoting the river basin map number in the hydrologic atlas compiled by the Subcommittee on Hydrology of the ICWR. The number following the two digits is supplied by the Subcommittee on Sedimentation when the data is published. Since it is possible to update RESIS more often than the historic publication dates for ICWR, there will be a need to coordinate with the Subcommittee on Sedimentation to insure continuity for numbering data sheets.

One of the more difficult tasks associated with sediment surveys is the collection of undisturbed samples for determining the dry unit weight of the deposits. Enough samples should be collected to adequately define both the areal and vertical distribution of sediment volume weights throughout the reservoir. Very few surveys contain adequate sampling information. Too many surveys show assumed dry densities. The average dry density of the sediment deposits is used to convert the volume (acre-feet) of deposits to weight (tons) for comparison with erosion, suspended sediment measurements or sediment budget data. A comparison of changes in reservoir sedimentation rates with erosion reductions due to land treatment programs will not be accurate without accurate determinations of the dry unit weight of the sediment.

The last issue involving RESIS records is the paucity of land use data reported with each survey. Scientists in the United States have been examining the relationships between land use and sediment yield since the advent of water resources planning. The lack of land use records for the period of time between sediment surveys limits the usefulness of RESIS for further defining, or possibly quantifying, the land use/sediment yield relationship.

FUTURE PLANS

The RESIS database is currently being used, maintained and managed by NRCS. A number of tasks need to be completed prior to the release of the database to other public and private entities. A user's guide needs to be completed. The database needs to be error-checked and missing latitude and longitude information should be added. Queries to generate standard reports, like a new version of the Form 34, also need to be completed. The format for the standard reports should be reviewed and approved by the ICWR Subcommittee on Sedimentation. The future location for RESIS, a sponsoring agency and the extent of public use is still under consideration at this time.

NRCS is pursuing the application of computers, sonar and Global Positioning Satellite (GPS) technology to reservoir sediment surveys. Stage storage relationships in a reservoir can be generated electronically using this type of technology mounted in a boat (Texas Water Development Board, 1994). The amount of staff and time required to complete a reservoir sediment survey time is greatly reduced with this technology. The initial cost of such a system is high but it is still cost-effective. The Texas Water Development Board's Hydrographic Survey Team was able to complete eleven surveys at less cost with the new system than it would have cost to do three surveys using traditional methods (Brazos Basin Update, 1995).

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DGPS AND GIS IMPROVE LAKE SEDIMENTATION SURVEY PROCEDURES

By Scot A. Sullivan, P.E., Texas Water Development Board, Austin, Texas

Abstract: The Texas Water Development Board (TWDB) has adopted a new data-collection program based on Differential Global Positioning System (DGPS) and Geographical Information System (GIS) technology to update reservoir storage volumes in the state of Texas. Utilizing DGPS interfaced with electronic depth-sounding equipment, vast amounts of underwater data can be collected quickly, accurately, and affordably. The collected data is processed using GIS to determine the surface area and volume information of the reservoir for individual elevations or water depths. The twelfth in a series of on-going hydrographic surveys was recently completed for the Brazos River Authority (BRA) on Possum Kingdom Lake. Bathymetric data was collected along approximately 700 pre-designed survey track lines spaced about 500 ft. apart over the 17,700 surface acres of the reservoir. The field survey was performed during a 13-day period in June 1994. A report, detailing the results of the survey, was completed and submitted to the BRA by the end of August 1994.

INTRODUCTION

Sedimentation-General A significant natural process affecting the nation's water resources is the movement and deposition of sediment. During rainfall events, sediments become suspended in the runoff waters. Depending on the amount of water movement, significant amounts of sediment can become suspended and transported along the waterway. When the velocity of the water decreases, the sediment settles out. The primary locations for the settling of sediments are the lakes and reservoirs built to capture runoff.

Identification of Problem The Texas Water Development Board is the responsible state agency for forecasting the future water-supply needs of the state. Realistic water-supply plans, outlining the surpluses and shortfalls of water around the State, cannot be developed without accurate information regarding surface-water storage capacities. A review of reservoirs across the state conducted by the TWDB revealed very few surveys were being performed and that the reported daily storage volumes of the reservoirs were still calculated from the original design tables. Further investigations focused on the performance of some quick reconnaissance surveys of some small reservoirs. The results from these surveys revealed significant changes in storage capacities-- up to a 30% decrease in reservoir storage capacities. Since the majority of the state's water-supply reservoirs were built in the 1950s and 1960s, large quantities of sediment may have accumulated. This could significantly affect predicted water supplies and the ability to meet future needs.

In reviewing resources available at the time to perform reservoir surveys, several problems were noted including prohibitive costs, lack of uniform standards, extensive land surveying costs, and long delays in delivering a report. Sediment survey procedures were still based on guidelines outlined in a 1936 Technical Bulletin, "Silting of Reservoirs," written by Henry M. Eakin. Staff believed that new technology could be incorporated to significantly improve these old procedures.

Solution A review of current technological advances and their suitability for dealing with these problems resulted in the Legislative creation of the TWDB's Hydrographic Surveying Program in 1992 and the purchase of the equipment listed in Appendix A. The core technology around which the TWDB's Hydrographic Survey Program was developed was the use of differential GPS (DGPS). Using this positioning technology, accurate positions of moving objects could be determined in real-time or "on-the-fly." A GPS receiver is set up over a benchmark with known coordinates established by the hydrographic survey crew. This receiver remains stationary throughout the survey and monitors the movements of the satellites overhead. Positional corrections are determined by this receiver and transmitted every second via a radio link to a second GPS receiver located on the boat. The boat receiver uses the corrections, or differences, in combination with the satellite information it receives to determine, "differentially," its location. Horizontal positions of the moving vessel are determined by this technology within a horizontal accuracy of three meters. The calculated vertical information from the GPS receivers is ignored because the real-time error is too high. Vertical information is supplied instead by the boat's depth sounder.

REVIEW OF 1994 POSSUM KINGDOM LAKE SURVEY

In February 1994, the TWDB contracted with the BRA to perform a hydrographic survey of Possum Kingdom Lake. It was the twelfth survey performed by the TWDB since full-time operations began in mid-1993.

Possum Kingdom Lake-General Possum Kingdom Lake is a narrow, winding lake bounded by limestone cliffs. It encompasses 17,700 surface acres when at the normal pool elevation of 1000 feet above mean sea level (msl) based on the National Vertical Datum of 1929 (NGVD '29). Compared to other reservoirs in Texas, it is approximately the 23rd largest in surface area, has a length of over 50 miles, and has a maximum width of about 3.5 miles. The reservoir was built in 1941 and had a reported storage capacity of 724,739 acre-feet (ac-ft). A sediment survey performed on the lake in 1974 by URS/Forrest and Cotton, Inc. revised the volume to 570,243 ac-ft.

Survey Preparations Activities conducted by the TWDB before the field survey included determination of the reservoir's surface area by digitization of the lake boundary from six USGS quad sheets. AutoCad Release 12 software was used to digitize the 1,000-ft contour interval based on the North American Datum of 1927 (NAD '27) on these maps. Track lines were then superimposed on this boundary at 500-foot intervals using Innerspace's ITI FIELD Version 3.4351 survey software. Survey setup files were developed from this information to provide track line guidance information to the field crew during the survey. First order benchmarks were also investigated in the area of the reservoir. An undisturbed benchmark suitable to use as a reference position was located by staff of the BRA. After heavy rainfall in May raised the water surface elevation to within one foot of the normal pool elevation, the field survey was scheduled for June after consultation with the BRA.

On June 6, TWDB staff arrived at the reservoir site and performed a static GPS survey to establish a horizontal survey control point at the reservoir. The reference monument chosen to provide horizontal control information during the survey was a United States Geological Survey

first-order monument. Staff positioned a GPS receiver over this monument and positioned a second receiver over a previously determined point at the reservoir for the shore station hereinafter referred to as TWDB #13 control point. Satellite data, with up to six satellites visible to the receivers, were gathered for approximately one hour at both locations in order to determine the coordinates of TWDB #13. The data were retrieved and processed from both receivers, using Trimble Trimvec software, to determine coordinates for the shore station benchmark. The NAVSTAR satellites use the World Geodetic System (WGS '84) spherical datum (WGS '84 is essentially identical to NAD '83).

Field Survey and Data Processing During the period June 8 - 21, 1994, the hydrographic survey vessel collected precisely orientated data along approximately 700 pre-designed survey track lines that were needed to cover the 17,700 surface acres of the lake. DGPS was used to orient the survey vessel along the pre-planned track lines. Bathymetric data were collected by a depth sounder. The positional and bathymetric data were collected every second during the navigation of the track lines. The data were stored electronically on the boat's computer. At the end of each day, the data were downloaded onto diskettes. The diskettes were edited in the office for bad data points, and the bathymetric data were corrected to elevations based on the daily reservoir pool elevations. The water surface ranged from 998.97 to 999.29 feet during the field survey.

Since the data were in latitude, longitude, and elevation format (i.e. X, Y, and Z values), staff determined that a Geographical Information System (GIS) technology would be an appropriate processing system choice. These systems allow complex data manipulations to occur within the same data set. The TWDB's Hydrographic Survey Program initially processed collected data on Intergraph's Microstation software. After an agency decision to standardize software programs, a switch was made to Environmental Systems Research Institute (ESRI) ARC/INFO GIS software. The TIN module of the ARC/INFO software creates a digital terrain model from the collected data.

The following is a generalized review of the steps to process the data. The edited latitude, longitude, and elevation data set were converted to a ARC/INFO decimal degree data file along with the NAD '83 boundary file. Using the TIN module, the data points and the boundary file were used to create a Digital Terrain Model (DTM) of the reservoir's bottom surface. This module uses a method known as Delauney's criteria for triangulation. A triangle is formed between three non-uniformly spaced points, including all points along the boundary. If there is another point within the triangle, additional triangles are created until all points lie on the vertex of a triangle. All of the data points are preserved for use in determining the solution of the model by using this method. The generated network of three-dimensional triangular planes represents the actual bottom surface. Once the triangulated irregular network is formed, the software then calculates/interpolates elevations along the triangle surface plane by solving the equations for elevation along each leg of the triangle. Information for the entire reservoir area can be determined from the triangulated irregular network created using this method of interpolation.

There were some areas where interpolation could not occur because of a lack of information along the boundary of the reservoir. "Flat triangles" were drawn at these locations. ARC/INFO

does not use flat triangle areas in the volume or contouring features of the model. These areas were determined to be insignificant on Possum Kingdom Lake. Therefore no additional points were required for interpolation and contouring of the entire lake surface.

Figures and maps developed from the three-dimensional triangular surface included a shaded bottom relief figure, a shaded depth contour interval figure, and various contour interval maps of the bottom surface. New volume and area tables were also developed from the model. Examples of the contour map and location of survey data map have been reproduced and follow Appendix A.

ANALYSIS OF THE POSSUM KINGDOM LAKE SURVEY

During the June 1994 Possum Kingdom Lake field survey, over 250 miles of data were collected in nine working days. Results of the survey indicate that Possum Kingdom Lake now encompasses around 17,624 surface acres and contains a volume of 556,220 ac-ft at the normal pool elevation of 1,000.0 feet msl. The lowest elevation encountered of 894.09 feet, or 106 feet of depth, was located approximately 300 feet from the dam and 275 feet from the north shoreline. The storage volume calculated was approximately 2.5 percent less than the 1974 record information for the lake. The original low flow outlet at elevation 874.8 feet has been silted in and closed. The low flow outlet invert elevation was therefore considered to be at elevation 911.5 feet, and the dead storage, or amount of water stored below any outlet works, was calculated to be 4,402 ac-ft. The conservation storage capacity, the amount of water between the normal pool elevation and the dead storage elevation, was calculated to be 551,818 ac-ft.

The sedimentation survey performed in 1974 by URS/Forrest and Cotton Inc. estimated that Possum Kingdom Lake had lost 154,496 ac-ft, or 21.0 percent of its capacity due to sedimentation in the 33 years that had passed since completion of the reservoir. This equates to an average loss of 4,681.7 ac-ft per year during the 33 year period. The estimated reduction in storage capacity between the 1974 and 1994 survey was 14,023 ac-ft, or 2.5 percent. This equates to an average loss of 701.15 ac-ft per year during the last 20 years.

There are many factors to consider when analyzing the information from the previous and more recent surveys. Repeating the TWDB survey in five to ten years or after major flood events should remove any noticeable error due to improved calculation techniques and will help isolate current sedimentation rates and the storage loss due to sedimentation now occurring in Possum Kingdom Lake.

REFERENCES

- Eakin, H. A., revised by C. B. Brown. 1939. Silting of Reservoirs. United States Department of Agriculture. Technical Bulletin No. 524.
- Sullivan, S., D. Thomas, S. Wilson, and S. Segura. 1994. Volumetric Survey of Possum Kingdom Lake. Texas Water Development Board.

APPENDIX A DESCRIPTION OF EQUIPMENT

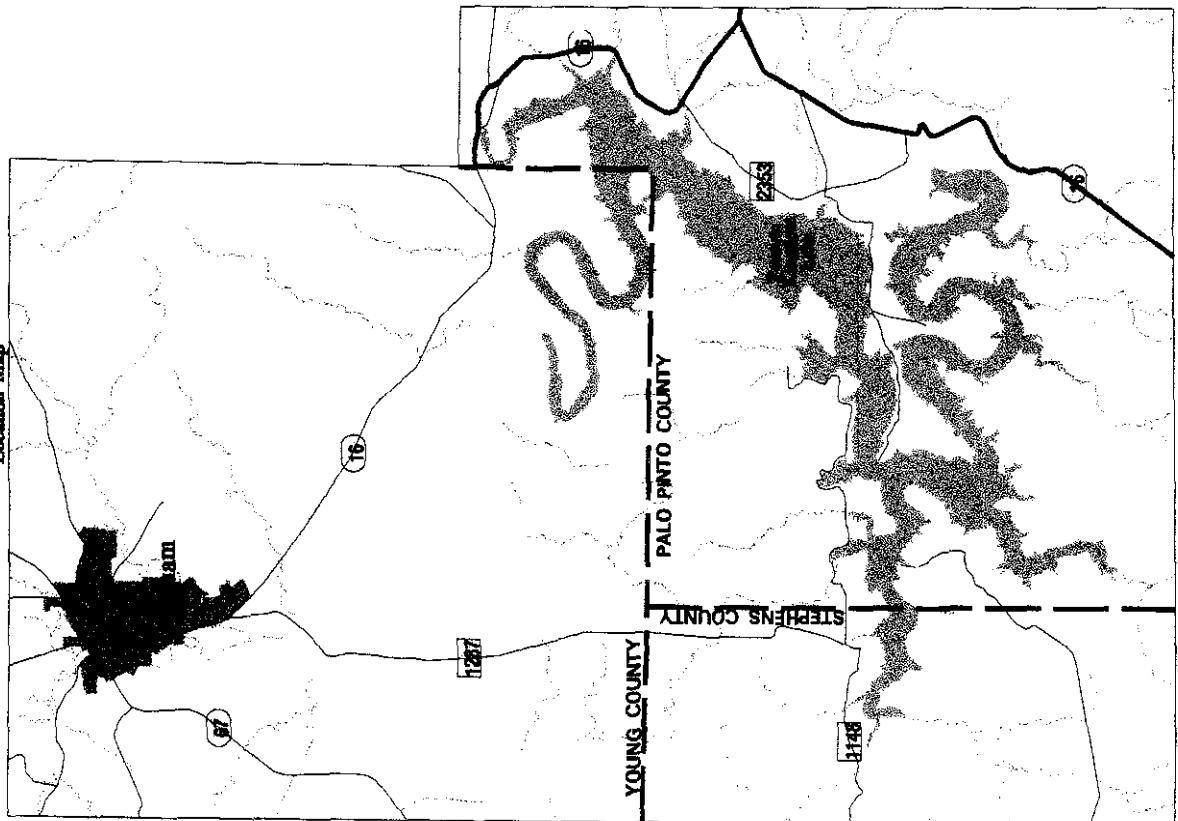
The equipment used in the performance of the hydrographic survey of Possum Kingdom Lake consisted of a 23-foot aluminum tri-hull SeaArk craft with cabin, equipped with twin 90 horsepower Johnson outboard motors. Installed within the enclosed cabin are an Innerspace Technology, Inc.(ITI) Helmsman Display (for navigation), an ITI Model 449 Depth Sounder using an 8 degree, 208 kHz transducer and Model 443 Velocity Profiler, a Trimble Navigation, Inc. 4000SE GPS receiver, a Motorola Radius radio with an Advanced Electronic Applications, Inc. packet modem, and an Industrial Computer Source 486 computer with a Princeton 14-inch monitor. The computer was supported by a Panasonic dot matrix printer and a Roland DXY-1200 plotter. Power was provided by a Kohler water-cooled generator through a American Power Conversion Smart 600 in-line uninterruptible power supply.

The shore station included a Trimble 4000SE GPS receiver, Motorola Radius radio and Advanced Electronic Applications, Inc. packet modem, and an omni-directional antenna mounted on a modular aluminum tower to a total height of 40 feet. The combination of equipment provided a data link with a reported range of 25 miles over level to rolling terrain that does not require that line-of-sight be maintained with the survey vessel in most conditions.

The processing system in the office consisted of a SUN SPARC20 workstation with the Solaris 2.3 operating system. Software loaded on the system included ESRI's GIS ARC/INFO software with the additional TIN module. Maps and figures were generated on a CalComp electrostatic plotter.

POSSUM KINGDOM LAKE

Location Map



PREPARED BY: TWDB AUGUST 1994

POSSUM KINGDOM LAKE

Location of Survey Data



1" = 20000'

EXPLANATION	
	Lake Boundary
	Inlets
	Data Points

PREPARED BY: TWDB AUGUST 1994

POSSUM KINGDOM LAKE

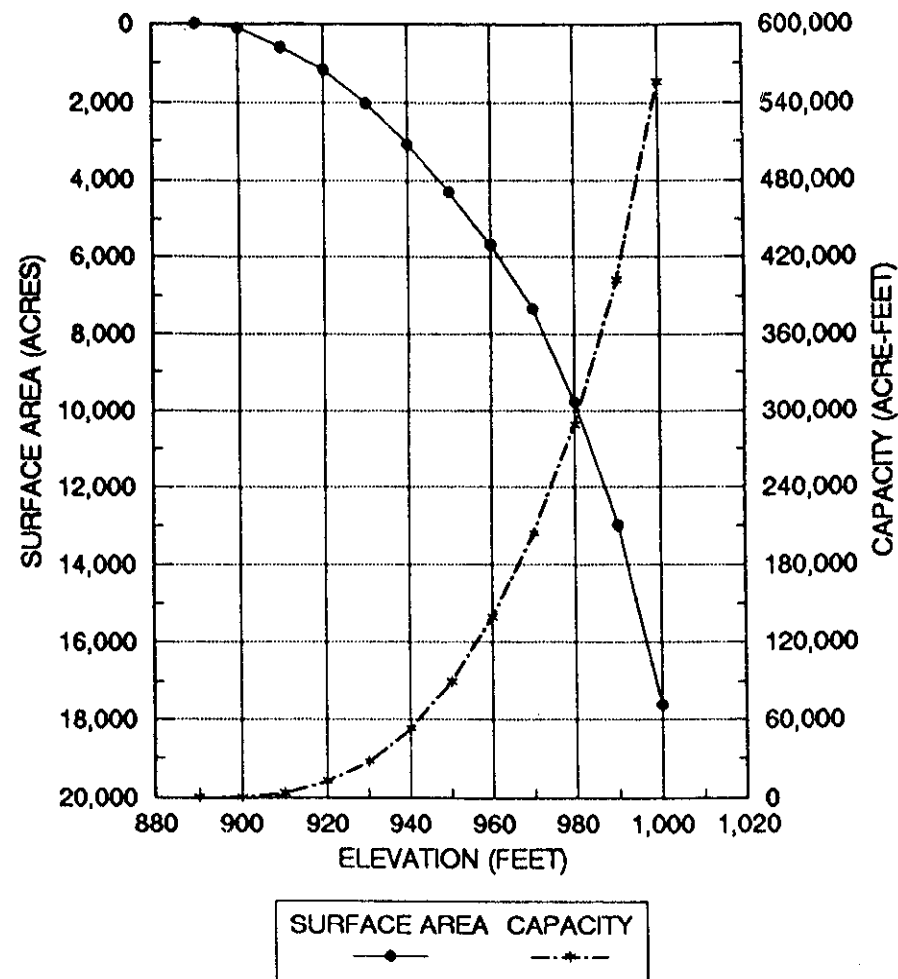
Depth Ranges

I-43



EXPLANATION	
	0 - 30'
	30 - 55'
	55 - 80'
	80 - 105'
	Islands

PREPARED BY: TWDB AUGUST 1994



POSSUM KINGDOM LAKE

JUNE 1994 SURVEY
Prepared by: TWDB August 1994

NOTES

NOTES

EVALUATION OF PROPOSED SEDIMENT CONTROL PROJECTS IN THE RIO PUERCO BASIN

By Christopher A. Gorbach, P.E., Planning Team Leader,
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Abstract: Approximately 60 percent of sediments deposited in Elephant Butte Reservoir originate in the Rio Puerco¹ basin. Projects to control these sediments have been proposed since the 1920's. Recently the Albuquerque Office of the Bureau of Reclamation reviewed the potential for such projects to determine whether they could be justified under current conditions. For purposes of this investigation possible benefits included reduced effect on downstream water supply due to diminishing reservoir yield and reduction of channel maintenance costs. From Reclamation's perspective, benefits due to reduced erosion in the basin were considered to be secondary. The investigation concluded that off-site, downstream benefits could not justify a major investment in sediment control projects in the Rio Puerco basin. Probable water supply benefits below Elephant Butte Dam were determined to be insubstantial and channel maintenance cost reductions would not sufficient to provide the necessary justification.

INTRODUCTION

The aptly named Rio Puerco (Muddy River) drains a 7,300 square mile basin in northwestern New Mexico and flows into the Rio Grande at Bernardo near the center of the state. The Rio Puerco is an ephemeral stream for all but its highest reaches. The river flows mainly during the summer and fall when intense thunderstorms frequently occur over the basin. Approximately 90 percent of the Rio Puerco flow at the mouth near Bernardo occurs during the months of May through October. Because of the semi-arid climate, land use history, extreme variability in precipitation and streamflow, and the geology and soils of the basin, the Rio Puerco carries a very heavy sediment load. The sediment load in terms of concentration is especially high. Below the confluence, approximately 60 percent the sediment load of the Rio Grande comes from the Rio Puerco basin whereas only about 2 percent of the water originates there.

Sediment loading in the Rio Grande from the Rio Puerco has been of concern to water users and managers for many decades. The main concerns are channel aggradation in the Rio Grande and sedimentation of Elephant Butte Reservoir. Means of controlling the Rio Puerco's sediment load have been the subject of considerable study and investigation. In 1928, the Middle Rio Grande Conservancy District recognized the problem in its Official Plan [Burkholder, 1928]. The District had commissioned Kirk Bryan [Bryan and Post, 1927] to do extensive studies of the Rio Puerco and to develop a sediment control plan. In 1941, the U.S. Department of Agriculture [1941] issued a final report on a thorough investigation of the Rio Puerco basin and proposed a comprehensive plan for sediment control. Neither of these plans was implemented. More recently, the U.S. Army Corps of Engineers [1985] studied a plan to construct major dams on the Rio Puerco and Rio Salado² for flood and sediment control. The Corps determined that reinforcement of levees along the Rio Grande would provide a more cost effective means of providing flood control. In addition, right of way problems were a significant obstacle to finding a suitable dam site on the Rio Salado and the project was not pursued.

In response to continuing concerns about the effects of the Rio Puerco on the Rio Grande, the Bureau of Reclamation undertook a preliminary reconnaissance study to determine whether adverse impacts on the Rio Grande and Elephant Butte Reservoir due to sedimentation would justify development of a sediment control project on the Rio Puerco under current conditions.

Reduction of sediment load in the Rio Grande below the mouth of the Rio Puerco would address the following previously identified needs:

¹ The Rio Puerco referred to here is sometimes called the Rio Puerco of the East to distinguish it from the another Rio Puerco that is a tributary of the Little Colorado River.

² The Rio Salado referred to in this report is that Rio Salado which flows into the Rio Grande from the west between Bernardo and San Acacia. Another Rio Salado adjacent to the Rio Puerco is a tributary of the Jemez River.

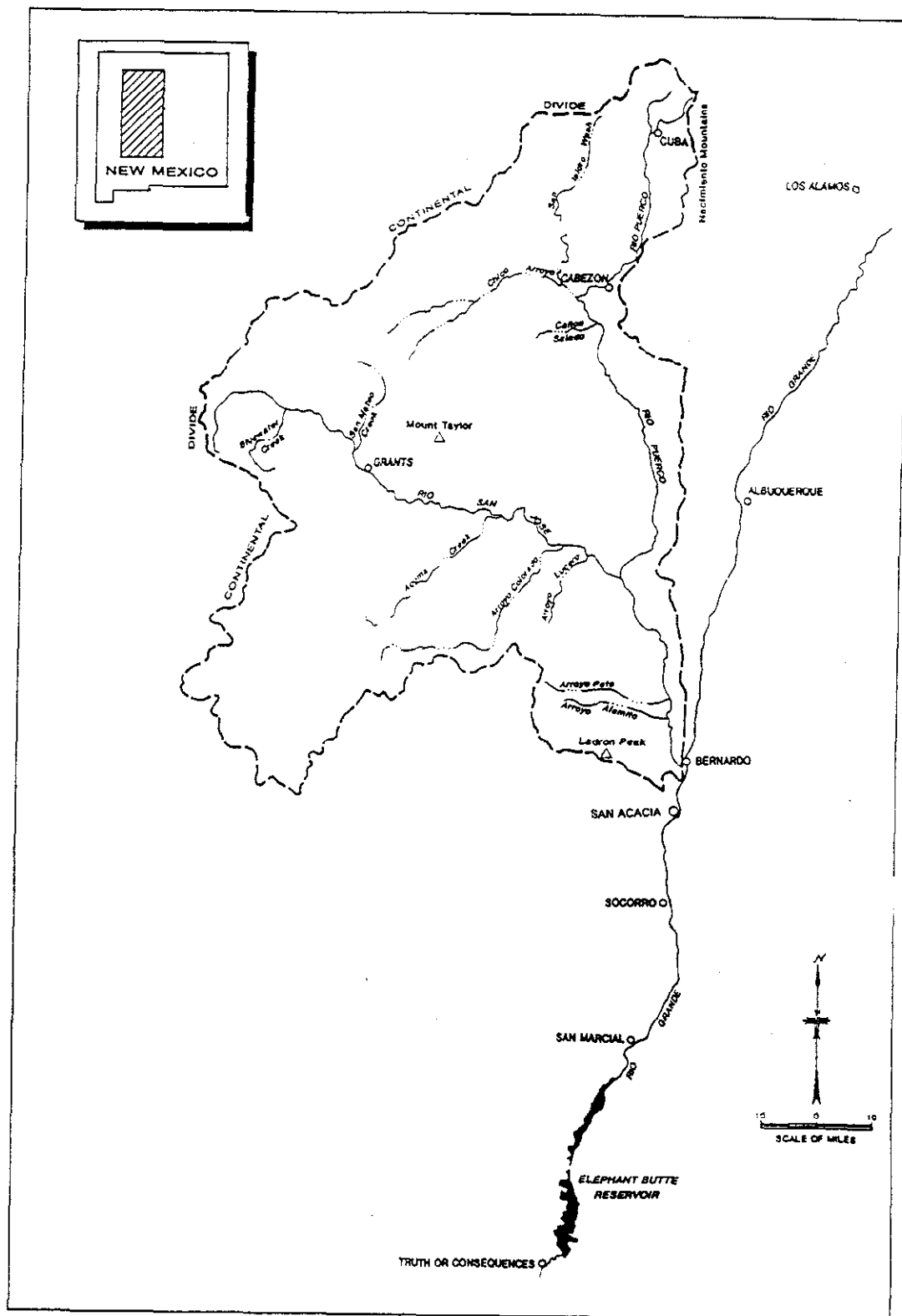


Figure 1: Map of the Rio Puerco Basin

1. Reduction of water losses due to sediment deposition in Elephant Butte Reservoir,
2. Reduction of Rio Grande channel maintenance costs,
3. Enhancement of water conveyance efficiency in the Rio Grande between the Rio Puerco and Elephant Butte Reservoir,
4. Miscellaneous benefits of enhanced flood control and protection to infrastructure facilities,
5. Preservation and enhancement of recreational values,
6. Reduction in loading of adsorbed trace metal and radionuclide contaminants to the Rio Grande and Elephant Butte Reservoir.

KEY FINDINGS

Reclamation's investigations concluded that potential downstream water supply benefits did not appear to justify investment in sediment control projects on the Rio Puerco at the present time [Bureau of Reclamation 1994]. The following key findings of the Reclamation study led to this conclusion:

The sediment load of the Rio Puerco, and for many other basins in New Mexico, is significantly lower now than it has been in the past. Reduced sedimentation may be due to climatic change, geomorphic processes, better land management, or upstream structural improvements.

The rate of sediment deposition in Elephant Butte Reservoir is significantly reduced.

The surface area of Elephant Butte Reservoir, for a given volume in storage, has not increased drastically in the 80 years of operation to date. This increase has been less than 10 percent. A great increase in reservoir evaporation due to sediment deposition is not anticipated in the next 100 years.

The effect of increased probability and magnitude of reservoir spills on the overall water supply below Elephant Butte Dam will be small over the next 100 years.

Sediment deposition at and above Elephant Butte Reservoir is and will continue to be a significant problem. However, a sediment control project on the Rio Puerco would not provide a cost effective means of reducing these effects.

DISCUSSION OF KEY FINDINGS

Trends in Sediment Yield from the Rio Puerco Basin: Annually, the Rio Puerco discharges approximately 2.5 million tons of suspended sediment into the Rio Grande at Bernardo, New Mexico. Total sediment loads (i.e. suspended load plus bed load) are not measured on the Rio Puerco, but based on comparison of total sediment loads on the Rio Grande above and below the confluence a reasonable estimate of the total load of the Rio Puerco can be made. This estimate is about 2.75 million tons per year on the average.

Suspended sediment concentrations in the Rio Puerco are particularly high. On average, suspended sediment concentration in the Rio Puerco is more than 100 times that in the Rio Grande above the confluence. Based on U.S. Geological Survey records for the years 1976 through 1992 that were compiled by Resource Technology, Inc. for a recent Corps of Engineers study [Resource Technology Inc., 1994], the average suspended sediment concentration of the Rio Puerco at Bernardo is approximately 107 tons per acre foot or 79,000 milligrams per liter. By comparison the average suspended sediment concentration in the Rio Grande at Bernardo, just above the mouth of the Rio Puerco, is around 0.78 tons per acre foot. In extreme events suspended sediment concentrations as high as 680,000 milligrams per liter have been measured in the Rio Puerco [Bondurant as reported in Nordin, 1963].

Overall however, sediment production from the Rio Puerco basin shows a decreasing trend over time. Gellis [1991] showed that suspended sediment concentrations and suspended sediment loads measured at several streamflow stations in New Mexico, including the Rio Puerco at Bernardo, Rio Grande at San Marcial and at Otowi, and Arroyo Chico, showed decreasing trends in both suspended sediment load and concentration. Gellis shows evidence that this trend is widespread and that it appears in records of the Pecos River, the Animas River, and the Rio Penasco near Dayton, NM. Bryan and Post [1927] gave an estimate of the average annual sediment load of the Rio Puerco for the period between 1885 and 1927 on the order of 9,000 acre feet per year, or about 13 million tons. For the period between 1962 and 1972, Simons, Li and Associates (SLA) [1981] computed that the total sediment load of the Rio Puerco at Bernardo averaged 5.1 million tons annually. More recently, between 1976 and 1992, the sediment load at Bernardo has decreased to about half this value. While the sediment yield of the Rio Puerco basin has diminished, the sediment contribution of the Rio Puerco to the Rio Grande is apparently becoming proportionally greater. A likely factor in this trend is reduced sediment load in the Rio Grande above the Rio Puerco attributable to dams at Cochiti, Galisteo Creek, and the Jemez River. About half the drainage basin above Elephant Butte Reservoir is now controlled by major dams and reservoirs. Channel stabilization works and natural trends in sediment reduction are also probable contributing factors. Between 1962 and 1972, the total annual sediment load of the Rio Grande at San Acacia³ averaged 11.5 million tons. Approximately 44 percent of the total sediment load of the Rio Grande at San Acacia apparently derived from the Rio Puerco during that time; now approximately 60 percent of the Rio Grande's sediment load comes from the Rio Puerco.

According to SLA calculations, between 1962 and 1972 the average annual sediment load of the Rio Puerco consisted of .75 million tons of bed material (i.e. sand) and 4.4 million tons of silts and clays. The sediment load the Rio Grande at San Acacia consisted of 4.8 million tons of bed material and 6.7 million tons of silt and clay load. Accordingly, the Rio Puerco contributed 16 percent of the bed material load at San Acacia and 66 percent of the silt and clay load. At San Marcial between 1962 and 1972, the load of the Rio Grande was 36 percent bed material and 64 percent fine materials. A study by the Bureau of Reclamation [1990a] indicates that more recently the sediment load of the Rio Grande at San Marcial is approximately half sand and half silts and clays.

There has also been a concurrent trend toward decreased total flow of the Rio Puerco at Bernardo. Average annual flow between 1976 and 1992 was 23,000 acre feet, significantly lower than the period of record average (1940-1992) of 32,000 acre feet. This change cannot be attributed to lower precipitation.

Causes of these trends cannot be stated with certainty but they are consistent with the arroyo evolution models of Elliott [1979] and others. Among the prominent characteristics of the Rio Puerco are the deep gullies or arroyos in which the river and many of its tributaries run. Historical evidence and accounts of settlers indicate that the formation of these arroyos began late in the last century [Bryan and Post, 1927]. Before that time, according to anecdotal reports and other evidence, parts of the Rio Puerco valley were alluvial plains characterized by natural pastures and water meadows. Entrenchment and incision of the Rio Puerco was not unique; similar events occurred throughout the Southwest. The causes of arroyo incision are the subject of much interesting debate that is beyond the scope of this discussion.

According to the arroyo evolution models, lower reaches of the Rio Puerco, having incised during an episodic phase of gullying, began a process of widening the gully by lateral erosion of the arroyo walls. Once the arroyo had been widened, a process of floodplain building by deposition of sediment in the floor of the gully began. Working upstream in this manner, the Rio Puerco tends toward a new equilibrium state. Gellis [1991] attributes the reduction of sediment load of the Rio Puerco to this process.

Building of floodplains and colonization by vegetation on the lower reaches of the Rio Puerco would have the effect of attenuating flood peaks by retarding flood waters and promoting sediment deposition by reducing flow velocity and by straining or filtering effects of vegetation and trapped debris. Sediment yield reductions appear to be widespread among many basins in the region suggesting that climatic factors may have some role in these trends.

³ Values and quantities given for the Rio Grande at San Acacia and at San Marcial include both Floodway and Conveyance Channel stations.

Other causes may be improved range management practices, structural improvements in the watershed, or cyclical geomorphic processes. An interaction of some or all of these factors is a likely explanation for the changes.

Trends in Reservoir Sedimentation: Sediment from the Rio Puerco is deposited along the Rio Grande and in Elephant Butte Reservoir. The total annual sediment load of the Rio Grande at San Marcial, just above the reservoir, currently averages about 4.5 million tons. The Rio Puerco may account for about half the sediments deposited in the reservoir. A disproportionate share of the Rio Puerco's contribution to the sediment load is in the silt and clay size ranges.

According to the most recent reservoir survey [Bureau of Reclamation 1988], the remaining capacity of Elephant Butte Reservoir is about 2.06 million acre-feet. Storage has been reduced by 22 percent from the original 1915 capacity of 2.63 million acre-feet. During the life of the reservoir the average rate of sediment deposition has been about 8,000 acre feet per year, but this rate has not been constant. Deposition of sediment in Elephant Butte Reservoir was as high as 25,000 acre feet per year between 1915 and 1920. Thereafter the rate of sediment accumulation decreased to about 15,000 acre-feet per year from 1920 to 1935 and to about 10,000 acre-feet per year from 1935 to 1940 [Happ, 1948]. Since 1940, reservoir surveys show that reduction in reservoir storage capacity due to sediment accumulation has averaged about 3,200 acre feet per year. At a rate of 3,200 acre feet per year, the remaining capacity of the reservoir will be half filled in about 300 years. About 40 percent of the sediment that has been deposited in the reservoir to date accumulated in the first 10 years of operation. Seventy five percent accumulated during the first 25 years. Sediment load records for the San Marcial gaging station confirm the decreasing trend in sediment load above the reservoir.

The most recent reservoir survey shows that deposition in the reservoir between 1980 and 1988 averaged 5,600 acre feet per year. This was a period of increased reservoir inflow and it is not clear whether an increasing sedimentation trend is indicated. There was also significant deposition in the river and floodplain above the reservoir during this period.

Reduction of sedimentation in the reservoir can be attributed to construction of upstream dams which trap sediment and change the river flow regime, accumulation and storage of sediments in overbank areas and floodplains upstream of the reservoir, and reduced erosion and sediment production from the drainage basin.

Effects of Rio Puerco Sediments on Water Supply at Elephant Butte Reservoir: Deposition of sediment generally increases the surface area of a reservoir relative to storage volume and increases loss of water due to evaporation. In the case of Elephant Butte Reservoir, this change has not been drastic. Depending on the volume of water in storage, the reservoir surface area has increased by less than 10 percent. Construction of a sediment control reservoir on the Rio Puerco is a proposal that has been considered. This alternative would be likely to result in overall increase in evaporation losses because a relatively shallow reservoir on the Rio Puerco would have a higher evaporation loss rate than Elephant Butte Reservoir. Alternative sediment control projects would also be expected to reduce water yield from the Rio Puerco to some degree.

As sediments accumulate in the Elephant Butte Reservoir, the frequency and magnitude of reservoir spills can be expected to increase. More water will be spilled or released because storage space is unavailable. The net effect of decreased storage capacity on the future water supply will be primarily determined by the magnitude and patterns of reservoir inflow and by operational decisions. Changes in water uses, and infrastructure adaptations may be secondary factors.

The benefit of available reservoir storage capacity is realized when two conditions are met: 1) adequate water is available to fill the reservoir to capacity; and 2) a water shortage follows a full reservoir condition during which the stored water can be used to alleviate the shortage. When adequate water is not available to fill the reservoir, the potential to store water does not have a measurable water supply value; nor does absence of storage affect the water supply when shortages do not develop. Water in storage has value as a recreational and wildlife resource and certain non-use values may apply but these would be difficult to quantify.

The historical record shows that during the period of operation, a shortage closely following a spill has occurred only

once at Elephant Butte Reservoir. In 1942, the reservoir filled to capacity and spilled. A water shortage followed in 1951 after a series of years of below normal inflow to the reservoir. At that time, additional water that might have been stored in 1942 if there had been additional reservoir capacity, would have been available to alleviate the shortage.

A very simple reservoir operation model can be used to quantify roughly the effect that sediment accumulation in Elephant Butte Reservoir would have on future water supplies. For purpose of this study I used a very simple spreadsheet model to project a worst case scenario in which three severe droughts, like the one experienced in the 1950's, occur during the next century. The model forecasts total water shortages for conditions representing rates of sediment accumulation in the reservoir that would be expected if a sediment control project on the Rio Puerco were or were not undertaken. According to these projections, the additional water in storage that would be available to alleviate shortages over the next 100 years due to a sediment control project on the Rio Puerco can not be expected to exceed a total of 225,000 acre feet distributed over the 100 year period. This represents approximately 0.2 percent of the total reservoir inflow of about 100,000,000 that would be expected during this period.

Effects on the Rio Grande Channels: Adverse effects of sediment deposition are not strictly limited to the reservoir itself. A significant amount of sediment has been deposited in the Rio Grande channel and floodplain above the reservoir creating increased flood hazards and difficulties in maintaining channels for efficient conveyance of water into the reservoir. Happ [1948] determined that between 1915 and 1936 Elephant Butte Reservoir received 85 percent of the sediment passing a point fourteen miles above the reservoir. From 1936 to 1940 only 52 percent of the sediment passing that point reached the reservoir. He attributed the difference to increasing deposition in the river channel and floodplain above the head of the reservoir.

Bureau of Reclamation studies indicate that there has been significant and continuing aggradation of the Rio Grande above the reservoir. U.S. Geological Survey data show that the average bed elevation of the Rio Grande rose approximately 12 feet at the San Marcial gaging station, eight miles above the reservoir, between 1979 and 1987. Reduced channel capacity in the San Marcial reach sometimes constrains reservoir operations at Cochiti Dam and can affect the timing of water deliveries to Elephant Butte. Over the past ten years, channel aggradation in the San Marcial reach has necessitated the raising of levees in much of the ten mile reach between San Marcial and the reservoir. In 1991, high water nearly breached a railway embankment 1/2 mile north of the San Marcial Bridge.

The contribution of sediments from the Rio Puerco to damages caused by aggradation of the Rio Grande channel cannot be precisely determined. The bed sediments of the Rio Grande are predominantly sand and the direct contribution of the Rio Puerco to this problem may be relatively minor. Other sources, notably the Rio Salado, are thought to be more important contributors of sand [Corps of Engineers, 1985]. However, Rio Puerco sediments may have an indirect effect on channel sedimentation due to the tendency of fine suspended sediments to increase sand transport capacity [Nordin, 1963]. Deposition of fine sediments in overbank areas above Elephant Butte Reservoir is known to occur, but quantitative data is unavailable. Sedimentation of the Rio Grande above Elephant Butte Reservoir is the subject of continuing Reclamation investigation.

Effect of Extreme Events: The effects of extreme events occurring on the Rio Puerco on the sediment budget of the Rio Grande are not clear. Sediment damages from the Rio Puerco and Rio Salado floods of 1929 were severe and resulted in the abandonment of the town of San Marcial and extensive cropland losses. Information on the effects of extreme events is limited but the available evidence suggests that the sediment yield and transport in the 1929 flood was unusual. Large deposits of sediment were left at the confluences of the Rio Puerco and Rio Salado with the Rio Grande. However, major floods in 1941, 1954, and 1955 produced only minor sedimentation problems [Simons and Li, 1981c]. Large quantities of sediment coming out of the Rio Puerco basin in extreme events may be deposited at the confluence with the Rio Grande channel and stored for future transport downstream. The effects of this queuing of sediment in the system have not been thoroughly investigated.

CONCLUSION

Results of the recent Reclamation investigation suggest that a sediment control project on the Rio Puerco could reduce sediment deposition in Elephant Butte Reservoir by as much as 225,000 acre feet in the next 100 years. With

a sediment control project in place on the Rio Puerco, deposition in Elephant Butte would still amount to about 200,000 to 400,000 acre feet. Storage capacity at the end of 100 years is expected to be between 1.5 and 1.7 million acre feet without a sediment control project, and would be between 1.6 and 1.8 million acre feet with a project [Bureau of Reclamation 1994]. The small incremental benefits to the water supply downstream of the reservoir and in reduced channel maintenance costs do not appear to justify investment in costly projects or programs to reduce the sediment contribution from the Rio Puerco to the Rio Grande. This conclusion applies to a perspective of 50 to 100 years and does not preclude the possibility that a sediment control project on the Rio Puerco may become justifiable in the future. Changes in economic or hydrologic conditions and continued accumulation of sediment in Elephant Butte Reservoir may create circumstances more conducive to development of a project at a later time. The Rio Puerco basin is a dynamic system responding constantly to climate trends, management decisions, and other influences.

This conclusion should not be construed to mean that sediments do not present significant problems for maintenance and management of the Rio Grande and Elephant Butte Reservoir. It should also be pointed out that these findings and conclusions apply only to the off-site downstream effects of sediment deposition; they do not apply to the costs and damages caused by soil erosion in the watershed.

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NOTES

NOTES

THE INCIPIENT MOTION FORMULAS OF MUD WITH DIFFERENT DENSITIES

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Abstract The mud formed from fine cohesive sediments may have various flocculate structures. Their density are different depend on the depositing and consolidating conditions. For recent years, in the researches on estuary and coast mud, various values of mud density or sediment depositing concentration are paid more attention to and a lot of information on them have been accumulated. In this paper, Based on the electron-chemical theory of fine sediment flocculation, the expression of cohesive force between grains was deduced. The incipient formulas for shear stress and velocity were built. They are compared with those currently used and the data measured in experiments and coincided to each other. These functions may be used to describe the variations of threshold levels of mud with different depositing densities and are easy to use.

INTRODUCTION

The problems linked to mud very commonly exist in the estuary and coastal engineering, especially in harbors and channels, as well as in some reservoirs and lakes. The grain size of sediment in above environments is often very fine, and the specific surface area (ratio of grain surface area to its mass) is also very large. These factors will affect to the mud's characteristics of flocculation, deposition and consolidation, incipient motion and resuspension, making them different from common river sediments. To investigate the critical conditions of mud's incipient motion under flow is of great importance for hydraulic engineering.

Mud is formed from the deposition of fine cohesive sediments, which often have different flocculated structures during their forming process. Their densities are also different depending on the depositing and consolidating conditions. When its depositing density ρ' is less than 1.2 g/cm^3 , it is called the fluid mud. When ρ' is about $1.2\text{-}1.6 \text{ g/cm}^3$, called the mud. When ρ' is larger than 1.6 g/cm^3 , called the consolidated mud which actually is clay. The three types of mud may have some different phenomena in incipient motion under flow. But now a day, we can only consider them as homogeneous because no having enough data. In common, we use following parameters, such as the flow velocity U_c , the shear velocity u_{*c} , or the flow shear stress τ_{*c} , as a criteria of incipient motion. But ought to fully consider the effects of its depositing density. This solution is enough for regular engineering problems.

In the researches on estuary and coast, the incipient motion conditions of mud with different

depositing density or concentration have abstracted more and more researchers. A lot of experiments are conducted, either on fields or in laboratories accumulating much more valuable data. Simultaneously, many incipient motion formulas are presented on the base of theoretical analysis. But, for most researches, it is difficulty to reflect the variable values of incipient motion in different duration of deposition. In this thesis, based on the electron-chemical theory of fine sediment flocculation, incipient motion formulas with considering different depositing densities are presented. These formulas are applicable to both the fine and coarse sediments.

DEDUCTION OF FORMULAS

Sediment grains on the top of bed may move under the action of flow shear stress. At the status of critical incipient motion, forces acted on any particle are equilibrated each other. The main dynamic force to promote grain motion is the flow shear stress acting on the bed surface τ , which could be calculated as $\tau = \rho ghJ$. In which, ρ is the water density, h the flow depth, J the hydraulic gradient, g is the gravity acceleration. The main resistant forces are the effective gravity W and the cohesive force between particles F_c .

The gravity W can be expressed as $W = (\rho_s - \rho) g a_1 \pi d^3$. It can result in a resistant stress τ_1 acting on a unit area of bed surface. The stress τ_1 could be depicted as the form of

$$\tau_1 = \theta_m (\rho_s - \rho) g d \quad (1)$$

Here, ρ_s is the sediment density and d is the particle diameter. The coefficient θ_m can be calculated as $\theta_m = f a_1 / a_2$. In which, f is a resistance coefficient related to the grain motion, a_1 and a_2 are the grain's area and volume coefficients respectively.

The resistant stress τ_2 , as a result of cohesive force F_c , is very complex. We'll further discuss it in the following text.

At the critical status of sediment incipient motion, τ should be equilibrated by τ_1 and τ_2 . At same times, the flow shear stress is actually the critical incipient motion stress. This means that τ_c could be described as

$$\tau_c = \tau_1 + \tau_2 \quad (2)$$

For cohesive shear stress τ_2 , we can construct its expression on the base of electron-chemical theory of fine sediment flocculation. According to this theory (N.Qian,1989), the cohesion force F_c is the sum of attractive force F_a and repelling force F_r . The relevant potential energies E_c , E_a and E_r also have a similar relation. As we know, the cohesive force F_c is the gradient of E_c along with distance s between two particles. That is

$$F_c = \frac{dE_c}{ds} \quad (3)$$

Attractive force F_a comes from the Van der Waals force. Repelling force F_r is the result of the repulsion between two particles. The value of relevant potential energy, either E_a or E_c , depends on the distance s as shown by the curve (1) and (2) on Fig. 1. Similarly, the variation of total potential energy are also shown as curve (3). From this, we can find that grains could attract each other only in the scopes of a and b . This means, only in this two scopes, F_a will supersede F_r , ofcourse, E_a will supersede E_r . To simplify this problem, the role of repelling potential energy could be neglected. Then, the grain's cohesive force may purely considered as the result of attractive potential energy, $E_c = E_a$.

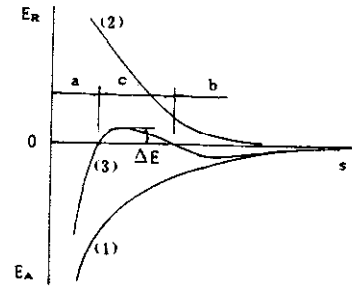


Fig. 1 Variation of attractive and repelling energy

According to Hamaker's, the attractive potential energy E_a could be expressed as:

$$E_a = \frac{A}{12} \left\{ \frac{d^2}{s^2 - d^2} + \frac{d^2}{s^2} + 2 \ln \left(1 - \frac{d^2}{s^2} \right) \right\} \quad (4)$$

where A is Hamaker constant. Using formula (3), F_c could be calculated out:

$$F_c = -\frac{A}{6} \left\{ \frac{d^2 s}{(s^2 - d^2)^2} + \frac{d^2}{s^3} + \frac{2d^2}{(s^2 - d^2)s} \right\} \quad (5)$$

For simplifying, we symbolize $F_c = A'd^2/s^3$ approximately, where A' is a coefficient. The effective area occupied by a grain may expressed as αs^2 , where α is its area coefficient. Since the distance between grains can be written as $s = (d + \delta) (S_{vm}/S_v)^{1/3}$, where δ is the thickness of film water around a grain, the cohesive stress τ_2 can be expressed as:

$$\tau_2 = A_k \frac{d^2}{(d + \delta)^5} \left(\frac{S_v}{S_{vm}} \right)^{5/3} \quad (6)$$

Here, $d^2/(d + \delta)^5$ can be simplified as $1/d^3$ because of the difficulty to determine the value of δ . In above deductions, many simplifying and replacing are made. So such as how to determine m and A_k in the formula, and whether or not the index of relative concentration is $5/3$, are all to answered and verified according to practical materials. Following the custom, S_v is replaced by S which is $S = \rho \cdot S_v$, S_{vm} by S_m also. In fact, S and S_m are the same values of deposition density and its maximum of mud respectively. The formula(6) is rewritten as following:

$$\tau_2 = A_k \left(\frac{S}{S_m} \right)^n \frac{1}{d^m} \quad (7)$$

Placing formulas(1) and (7) into (2), we can obtain the formula to calculate the mud's incipient motion shear stress:

$$\tau_c = \theta_m (\rho_s - \rho)gd + A_k \left(\frac{S}{S_m} \right)^n \frac{1}{d} \quad (8)$$

Because flow friction velocity $u_* = \sqrt{(\tau / \rho)}$, and a friction coefficient formula (G.Dou,1960) is been accepted, the mean velocity at the condition of critical incipient motion can be obtained as:

$$U_c = \frac{1}{\kappa} \ln \left(11 \frac{h}{k_s} \right) [\theta_m (\rho_s - \rho)gd + A_k \left(\frac{S}{S_m} \right)^n \frac{1}{d}]^{1/2} \quad (9)$$

where, κ is Karman constant with a value of 0.4, k_s is the roughness height on bed.

Formulas(8) and (9) are what we recommend to investigate the conditions of mud's incipient motion in this paper. Though our main aim for research is at the fine sediments, the formulas are applicable both to fine and coarse sediments. For later, the gravity effect term plays a main role, while for fine grains, the cohesive effect term will play a main role.

DETERMINATION OF COEFFICIENTS

Coefficients and index number contained in formulas(8) and (9) need to be determined. A_k and m can be obtained according to the experimental data of incipient velocity under the conditions of stable deposition. For mud, gravity effect term may be neglected, only the 2nd term exists in formula(9). For stable deposition, $S = S_m$, if we know the flow-sediment conditions, m and A_k can be obtained from formula(9) by try. Using the data listed in Dou G.(1960), we spot the values of A_k to d on Fig.2 and can find out $A_k = 9 \cdot 10^{-6}$ (N/m).

Similarly, according to formula (8), the relationship between $\tau_c d / A_k$ and S/S_m can be expressed on Fig.3. The grain distributions are known in these selected series of data. The stable depositing concentration S_m may be calculated according to the method advised by X.Fei. First, calculate out specific surface parameter of the mud $M = \Sigma (p_i/d_i)$, in which, p_i is the percents of grains with size d_i . Then $S_{vm} = 0.92 - 0.2 \cdot \log M$ and $S_m = \rho$, S_{vm} can be obtained. From Fig.3, may find out the index number $n = 2.35$.

As to θ_m , the Shields parameter at critical incipient motion can be determined according to

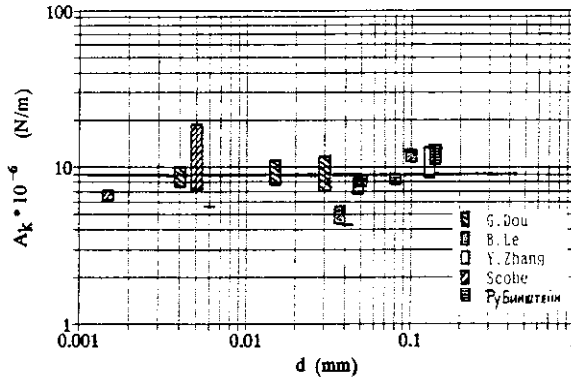


Fig. 2 The relation of A_k and d

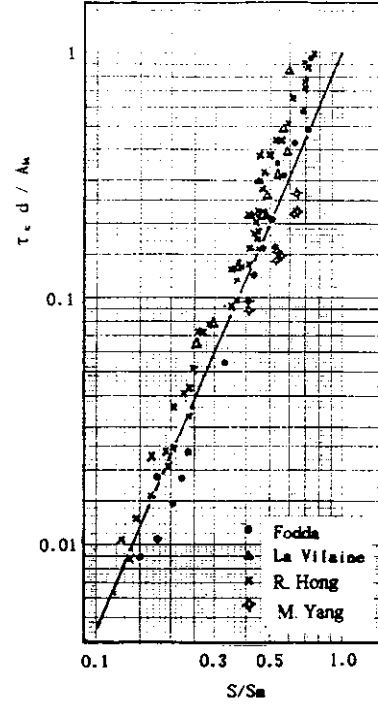


Fig. 3 The relation of $\tau_c \cdot d / A_k$ and S/S_m

Shields Diagram. The effect of this term mainly contributes to the motion of coarse sediments. It exists as a constant in many formulas, from 0.03 to 0.06. But, when fine sediments' incipient motion will be considered simultaneously, the gravity effect term still plays a considerable role, and θ_m not ought to take as constant. Here, we suggest to extend the right part of Shields Diagram according to its tendency but the abscissa of Shields Diagram is replaced by Se , a parameter only reflecting the influence of particle characteristics:

$$Se = \frac{d}{\nu} \left[\frac{\rho_s - \rho}{\rho} g d \right]^{1/2} \quad (10)$$

$$\theta_m = 0.015 Se^{0.1} \quad (11)$$

Based on the above discussions, the complete formulas of incipient motion stress τ_c and velocity U_c can be expressed as following:

$$\tau_c = \theta_m (\rho_s - \rho) g d + \frac{9 \cdot 10^{-6}}{d} \left(\frac{S}{S_m} \right)^{2.35} \quad (12)$$

$$U_c = \frac{1}{\kappa} \ln \left(11 \frac{h}{k_s} \right) \cdot \left[\theta_m (\rho_s - \rho) g d + \frac{9 \cdot 10^{-6}}{d} \left(\frac{S}{S_m} \right)^{2.35} \right]^{1/2} \quad (13)$$

VERIFICATION AND DISCUSSION

The differences of formulas (12),(13) with others commonly used are these two aspects: First, the effective gravity term, namely parameter θ_m will changes after the sediment characteristics. Second, the relative concentration of sediments S/S_m are introduced in cohesive term. As above mentioned, the mud's deposition, consolidation, incipient motion and resuspension, are intensely influenced by the characteristics of sediments and environmental water. The deposition concentration S and its density ρ' are not only the results, but also the indices of many factors' action. So they are of great importance in describing the incipient motion of mud.

By using formula(13), we obtain the relationship of U_c and d for consolidated soil, and compare it with that deduced from several other formulas (R.Zhang,1989), as shown on Fig.4. The measured data are also plotted on it. From this, we can find the formulas proposed in this paper can coincide with other commonly used formulas and measured data.

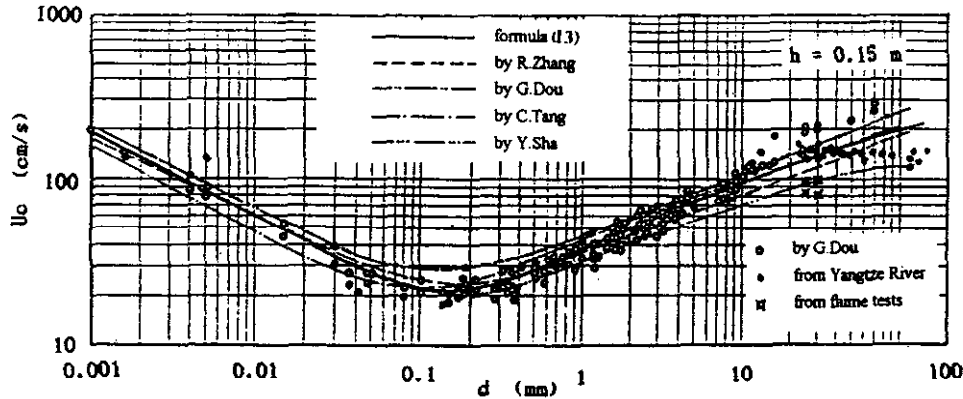


Fig. 4 Comparison of formula (13) with Others and measured data

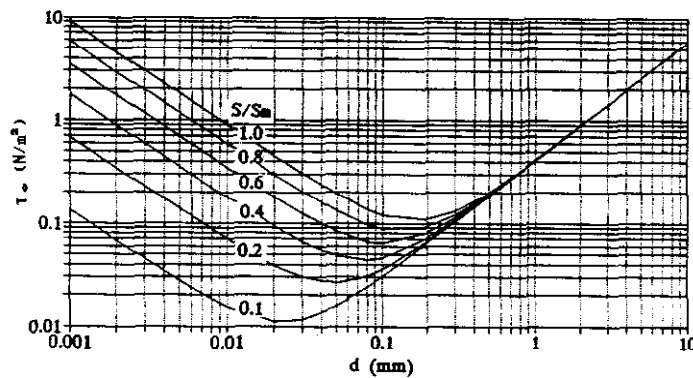


Fig. 5 The relation described by formula (12)

Additionally, formulas (12) and (13) can also reflect the variations of depositing concentration S or density ρ' . Fig.5 is the relationship of the critical incipient motion shear stress and particle size d . We can see there are different curves for different values of S when sediment is fine enough. For mud this means, the more low the deposition concentration, the more weak the critical incipient motion shear stress. Of course, this is reasonable.

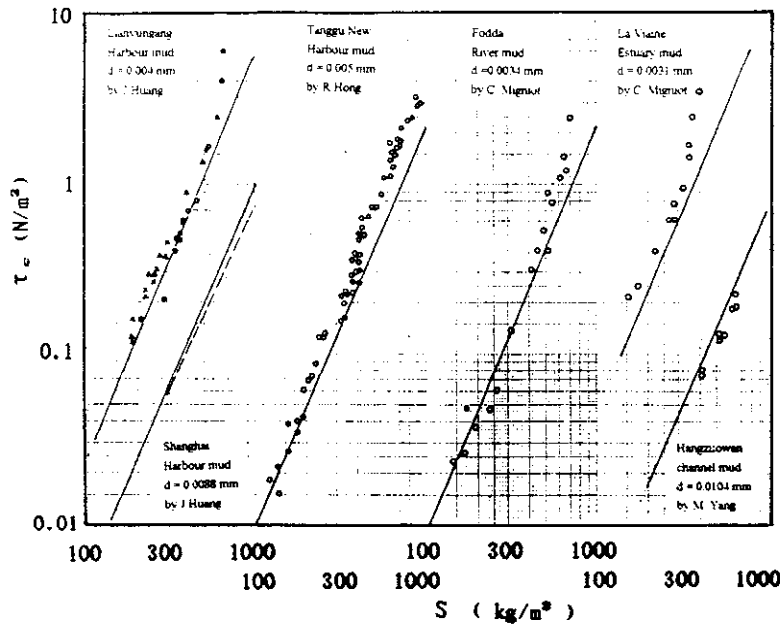


Fig. 6 Comparison of formula (12) with measured data

Some experiments finished in recent years have more taken notice of the roles of depositing concentration or density, which is a important factor influencing the threshold of mud. We collect several sets of data which compare with the formula suggested by this paper as shown on Fig.6. It indicates formula(12) may also agree with these data.

Formula (12) and (13) are based on proper theoretical bases, emphasizing the influence of sediment deposition concentration, obtained its parameters from measured data and verified by a lot of test results. These formulas can be used to predict the critical conditions of fine cohesive sediment incipient motion. They include only several common physical variables, and are very convenient to use.

ACKNOWLEDGEMENTS

This research work was supported by the Natural Sciences Foundation of China.

MITIGATION OF RESERVOIR SEDIMENTATION THROUGH WATER RESOURCES MANAGEMENT

By Jing-San Hwang, Deputy Director, Taiwan Provincial Water Conservancy Bureau, Taichung, Taiwan, R.O.C.

INTRODUCTION

Taiwan is an island located in the Western Pacific Ocean, about 36,000 Km² in size. Less than one third of this area is suitable for cultivation. It is banana shaped with high mountains running roughly in the north-south direction with many peaks exceeding 3,000 m in elevation. Consequently, the streams on the island are generally short and steep, many with a heavy sediment load. The climate is sub-tropical, with high precipitation between May and September and relatively dry during the rest of the year, except in the northern part near Taipei where light but persistent rainfall also occurs in November through February. Also, Taiwan has a long history of development and utilization of water resources. Irrigation was already an extensive government and private practice in the 17th century after a mass emigration from mainland China. Within the recent three decades of prosperous development in industry and agriculture, water resources conservation and utilization activities have been intensified. The key points of the water resources development regarding the reservoir sedimentation on this island can be divided into three aspects for discussion, hydrology, topography and geology.

Hydrology : The average annual rainfall on Taiwan is 2500 mm based on the mean value of annual rainfall records so far. It seems very abundant, but it is unevenly distributed. Seasonally speaking, 62% of annual rainfall falls in the wet season from May through October in Northern Taiwan, while 78% falls in central region, 90% in southern region and 79% in eastern region. The average annual rainfall on the whole island is 78% occurring during the so-called wet season.

The seasonal hydrological condition in a year has a severe impact on the water resources environment causing great difficulty for the development of water resources. Not only the seasonal distribution has great differences, but also there is a high variation in long term rainfall occurrence. In the northern region near Taipei, the ratio of annual rainfall in a wet year to a dry year is 2.17, while the ratio in the south near Kaohsiung is 5.69. The ratio of 1 means the average annual rainfall, and the larger the ratio, the greater the difficulty of water resources management.

Topography : Topographically speaking, 33% of the island is mountainous, higher than 1,000 meters in elevation, 38% of the total area of Taiwan belongs to the low hill

and sloping area ranging from 100 to 1,000 meters in elevation, and only 29% is called flat and suitable for cultivated agricultural usage.

According to the topographical condition, high mountains running roughly in the north-south direction with many peaks exceeding 3,000 meters in elevation means the streams on the island are generally short and steep. For reservoir development, this type of river or stream is not suitable because there are no any good pockets for storage. Consequently, the reservoir and dam system on this island is very expensive due to having to construct a very high dam to create only a very small reservoir.

Geology : Geology of Taiwan can be broadly divided into three major geological provinces; (1). Central Range, (2). Eastern Coast Range, and (3). Western foothills. The third geological Province is the most important geological province for water resources development in Taiwan, because almost all of the reservoirs, existing and proposed, are located in this province. The western foothills province is composed of Neogene clastic sediments. The rocks are mainly alternating sandstone and shale with locally interspersed limestone and tuff lenses (1).

The rocks of sandstone, shale and their alternation in the western foothills province are relatively young and soft in hardness, producing a very erodible, low bearing capacity for dam erection. The properties of erodible rocks are also troublesome causing high sediment yield in the reservoirs. The high sediment load and quick reservoir desposition in Taiwan is damaging to reservoir operation efficiency resulting in a shortened usage time.

In addition to the limitation of water resources development due to natural characteristics, rapid increase in social demand and the protection of the environment are of major concern. The most consideration is the impact of water resources development on the water and land environment. If many dams are completed, the rivers down stream of the dams will be degraded and the coast line will recede due to the reduction of sediment.

SEDIMENT YIELD AND RESERVOIR SEDIMENTATION

Sediment Yield and Reservoir Life : The higher the sediment Yield, the higher the reservoir deposition. The reservoir depletion rate due to sediment accumulation in Asian countries is very high, especially in mainland China, Taiwan and Japan. The Yellow River in northern mainland China is famous for its turbidity and high sediment content. Its average sediment load is 37.6 kg/m^3 . The average annual sediment transport rate is 0.148 to 1.08 billion metric tons between Tokoto and

Longmen, equivalent to an average annual erosion depth of 7 mm over the whole drainage area. The annual sediment yield to the Sanmen Gorge is around $1,678 \times 10^6$ tons, which means 2.43 mm of annual average depth is eroded from its entire upstream watershed.

The uplift movement of the Japan Archipelago results in rapid erosion of the mountainous area and leads to the formation of steep mountain slopes. The annual erosion rate of whole Japan Archipelago ranges from 0.1 mm to 10 mm with an average value of 3.7mm which is very close to the mean value of Asian erosion rate.

Sediment yield in the continental United states is relatively low, therefore the useful reservoir life is very long. A summary of published storage capacity depletion of reservoirs in the United States as reported by Dendy, 1978, indicating the average annual accumulation in the reservoirs is converted into an equivalent average depth eroded from the drainage basin and it ranges from 0.17 mm to 0.74 mm (2).

Under the climate condition of high temperatures and high precipitation, and the geologic condition of soft and easy erodible rocks, the erosion rate in Taiwan is, of course, extremely high, especially in the south. The erosion rate ranges from 2mm in the north to 36 mm in the south, causing the probable life of a reservoir in Taiwan ranges from 185 years to 30 years. The probable life of a reservoir depends not only on the erosion rate and sediment yield, but also on the reservoir storage capacity. The larger the reservoir capacity, the longer its probable life. Almost all of the reservoirs in Taiwan can be catalogued to be the small reservoirs with storage capacity less than 100 million cubic meters, inducing their useful life almost less than 100 years.

The Criteria of Reservoir Sedimentation : The rate of sediment accumulation is affected by the geophysical environment and human activities. Acceptable criteria of reservoir sedimentation for dam and reservoir planning are discussed briefly in the following.

In the past decades, the design and construction of dams in Taiwan was almost always taken from the America. As mentioned previously, the erosion rate and the sediment yield are incredibly different between the two countries, therefore, the criteria for reservoir design and planning in the United States are not suitable for use in Taiwan. For instance, the average annual erosion rate in Tennessee Valley is around 0.25mm, while that in southern Taiwan is about 36mm; 144 times that of Tennessee valley. Consequently, the criteria for reservoir sedimentation in Taiwan have to be somehow modified to meet the geophysical environment even though the original concept refers to the American philosophy.

In " Sedimentation Engineering " ASCE, page 587, the major American philosophy of reservoir sedimentation is described in the following quotation " Most major reservoirs today are designed to provide sufficient storage to hold a 100-yr accumulation of sediment without encroaching on the storage provided for their functional operation. In an age that has progressed from the first automobile to a landing on the moon in much less than a 100-yr span, it is possible that in time either the reservoirs of today will no longer be needed or that more effective methods of retaining their capacity will be developed". Based on the quotation two key points of its major concept can be deduced;

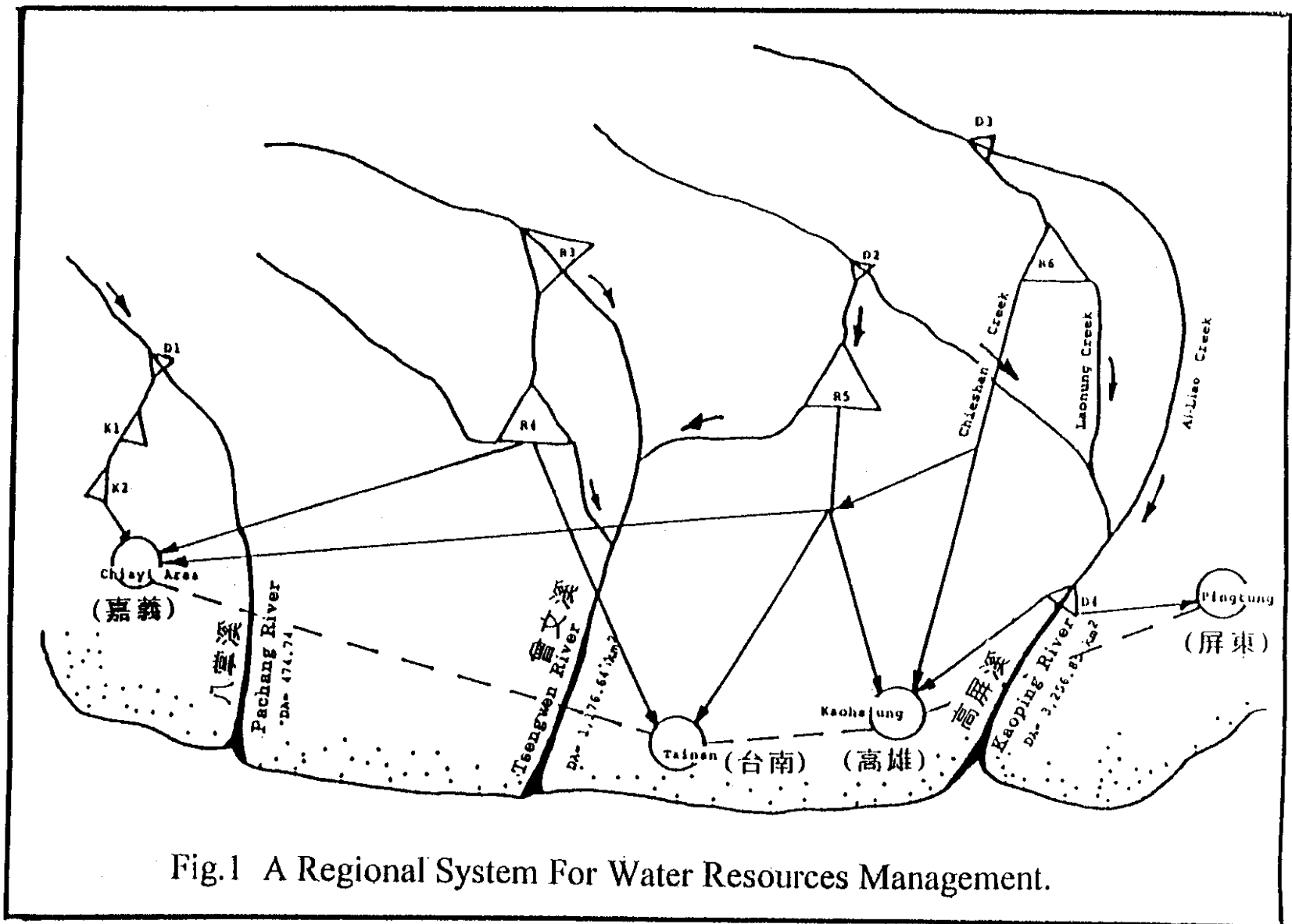
- (1) A dead storage capacity has to be provided for a 100-yr accumulation of sediment.
- (2) Waiting for someone to present a more effective method of retaining the reservoir capacity.

Looking at the above mentioned criteria of reservoir sedimentation, they are obviously not suitable for the geophysical environment of Taiwan, almost all of the reservoirs will be filled by sediment deposition in less than 100 years, even some of them in less than 50 years due to the high sediment yield. The criteria for reservoir sedimentation have to be modified to meet the circumstances of the natural environment in Taiwan. The major points for modification are as follows:

- (1) Based on the so called economical life of 50 years, the average effective life of reservoirs should be longer than 50 years. Namely, the useful life of reservoirs has to be longer than 100 years.
- (2) The decision of the dead storage capacity is only made depending upon the appropriate level of water releasing facilities.
- (3) Just waiting for practical effective methods for retaining the reservoirs capacity to be developed is not good enough. Research into the subject is necessary now.
- (4) Sediment flushing has to be one of the functions of the water releasing facilities.

For arriving at the criteria, the following procedure which has been conceived and formulated may be currently acceptable for the development of reservoirs and dam in Taiwan.

- (1) The off-stream reservoirs in Taiwan are verified as one of the most effective methods of retaining the useful reservoir capacity.
- (2) A reservoir desilting system should be included in the structures of the dam providing facilities for sediment flushing or treatment.



- (3) A reservoir after its completion should be operated in conjunction with a diversion weir which can control a great amount of water resources by means of a "run-of-the-river" operation.
- (4) The more effective use of the water resources of a region can be achieved through the optimum conjunctive use of water available in the region, avoiding the use of a reservoir as a sole water source.
- (5) The reservoir desilting measures or the treatment of silting should be one procedure in the operation of a reservoir. Namely, the arrangement for periodical sediment flushing of a reservoir should be well designed and carried out prior to the beginning of the reservoir operation.

DESILTING RESERVOIR SYSTEM

Different methods have been attempted previously by many water engineers in various places to control, reduce or remove sediment in reservoirs and lakes with varying degrees of success. These methods include (but are not restricted to)

- (1) reducing sediment inflow through the upstream area by the planting of trees and grass, soil stabilization, upland check dams, and other soil conservation practices;
- (2) dredging or mechanical remove of sediment;
- (3) a careful arrangement of the reservoir system creating a sediment by-pass water way to keep sediment from flowing into the reservoir;
- (4) flushing of sediment out of the reservoir by well planned operational reservoir flow.
- (5) reducing the necessity of reservoir development through well management of water resources for mitigation of reservoir silting problems.

Desilting of Reservoirs : Except for certain small reservoir for municipal or industrial purposes, or the clearance of an out-let area, it is generally impractical to remove any substantial quantity of silt from a reservoir after it has been deposited. The reasons for the difficulty of removing a large amount of sediment from a reservoir are the high cost and the disposal of the acquired silt. The most practical remedy lies in preventing permanent deposits, but this is only possible under certain circumstances.

The most famous example of desilting reservoir is the Sanmen Gorge Dam on the Yellow River in northern China. Sanmen Gorge Dam was built in 1960, it is a 106m high, 974m long, concrete gravity dam. After 5 years of operation, the reservoir capacity was reduced by one third due to the deposition of sediment. This problem was remedied between 1973 and 1974. Five of the turbines were removed reducing the hydropower capacity from 1200 MW to 200 MW. The penstocks of the removed power units are now

used for sediment flushing. With the flushing capacity increased from 3,080 CMS to 10,000 CMS and aided by initial dredging, the reservoir storage capacity has been stabilized since 1974 (3).

Among the reservoirs in Taiwan, one reservoir called Jensepei deals with the silting problem by adopting the modified " Spanish Method ". A flushing gallery was built through the right abutment of the dam with a horizontal tunnel of 1.5 meters diameter and a vertical tower of the same size. Flushing for desilting is arranged by emptying the reservoir between May and July and permitting natural floods to flow through. The efficiency of the flushing of Jensepei Reservoir is very high. For the 31 years from 1955 to 1986 after the flushing the average annual silting rate was 29,000 m³, about 12% of the original deposition. So far, the desilting operation of the Jensepei reservoir is still working very well maintaining a constant capacity for storage.

Unfortunately, the above mentioned desilting pattern is not universally suitable for every reservoir. Before a reservoir desilting scheme is arranged and required to be effective, a water utilization pattern should be conceived and formulated, because the reservoir desilting scheme is only effective under certain circumstances.

Mitigation of Reservoir Sedimentation Through Water Resources Management : A reservoir system for water resources development basically is not a sustainable system because it will, sooner or lesser, be filled by sediment. Consequently, if a water resources system can be formed including the reservoirs as less as possible, the silting problem also can be mitigated as minor as possible. Based on a study of silting impacts on different reservoirs in Taiwan (4) which shows us that the different water resources systems affect the unit cost of reservoir silting inducing different costs of silt treatment. The cost for reservoir silting is highest in on-stream reservoir systems, and is lowest in off-stream reservoir systems.

A combination of river intake, without any silting problems, and off-stream reservoir, with minor silting problems, to form a more effective sediment mitigation system has been performed in Taiwan for many decades. Recently, the sediment mitigation measures can be extended one step further from a single system to a basin or regional point of view to form a basin system or a regional system for mitigating the silting problems as much as possible. For instance, the major part of development in the southern area is from Chiayi in the north to Pingtung in the south. The water supply system for the future in this area is a system balanced with four diversion weirs, the Jenyi, the Chiashen, the Chioujung, and the Kaoping diversion weir, and six reservoirs, Jenyitan, Lantan, Tsengnen, Wusharetou, Nan-Hua and Meinun to supply the four major areas of Chiayi, Tainan, Kaohsiung and Pingtung (Figure 1).

The reservoirs in this regional system are mostly off-stream reservoir in conjunction with river intake systems with the exception of the Tsengwen reservoir which is on-stream. According to the operational simulations of the reservoir with both individual and in combination with each other respectively, the best sediment mitigation measures is the combination of reservoir and diversion weirs. After the combination of the whole regional system, not only the water resources demanded for this area can be satisfied, but also a rotational periodic reservoir sediment flushing pattern can be arranged for sedimentation mitigation (5).

CONCLUSIONS

Based on a study describes above, a reasonable approach to acquiring a mitigation of reservoir sedimentation would be a regional conjunctive use system including the effective control and efficient uses of flowing water and a well planned reservoir system with desilting measures taken into consideration. In addition to the efficiency of water uses can be enhanced, the sediment impacts on the system can be also mitigated as much as possible.

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SEDIMENTATION AND SOLUTIONS FOR CONEMAUGH RIVER RESERVOIR

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Abstract: Sedimentation problems in the Conemaugh River Reservoir have developed over the 40 years of its operation. These sediment problems have begun to interfere with gate operations. It was desired to model the sediment deposition that had occurred over the life of the project and model proposed alternatives for deposition rates and locations. The system is an extremely dynamic system with inflows varying from 100 cfs to 100,000 cfs in one day, with flows returning to 1,000 cfs or less within a few days. The dynamics of the system required an unsteady flow model to adequately model the flows within the reservoir and associated sediment movement but a dynamic one-dimensional sediment transport model was not available for modeling the reservoir. The hydraulic results of the one-dimensional unsteady flow model UNET were used with the sediment transport algorithms in the normally steady state sediment transport model TABS-1 (modified HEC-6). This marrying of models produced very good results in reproducing the deposition in the Conemaugh River Reservoir. The results indicated continuing sedimentation problems even after proposed dredging. A continuous sediment removal system was proposed and an installation is being planned to remove continuing sediment deposition near the dam. This sediment removal system should be effective given the fine nature of the sediment and the deposition near the dam.

INTRODUCTION

Conemaugh River Lake is a flood-control project in southwestern Pennsylvania on the Conemaugh River which is a tributary of the Kiskiminetas River and in turn the Allegheny River above Pittsburgh, Pennsylvania. The location of the project is shown in Figure 1. The reservoir is downstream from Johnstown, PA, the site of the infamous Johnstown flood of 1889 and is located in a basin of 1351 square miles. The topography is characterized by high rugged rolling hills in the lower reaches and higher, deeply dissected, mountainous areas in the upper reaches.

The Conemaugh River Lake was formed in 1952 by the closure of the Conemaugh River Dam. The normal operating pool has been gradually raised over the past 40 years from 880 to 890 feet National Geodetic Vertical Datum (NGVD) prior to the installation of the hydropower plant in the late 1980's. The normal pool elevation has been about 900 feet NGVD since that time.

Sediment Surveys of the lake performed in 1966 and 1982 indicated an accumulation of about 11,300 acre feet or 4.1% of the total volume. While the percentage of the volume is not large, the placement of the sediment is in the lower portion of the reservoir near the dam. The depth of the deposited sediment exceeds 30 feet for the lower three miles of the reservoir and is beginning to interfere with the operation of the outlet works. A survey by divers found deposition at the low level outlets as shown in Figure 2.

NUMERICAL MODELING

Two computer models were used in the modeling of the Conemaugh River Lake and its main tributaries. The model used for the hydraulics was the UNET unsteady one-dimensional model while the TABS-1 model (modified HEC-6 model) was used to calculate sedimentation within the lake. The TABS-1 model was modified to utilize the unsteady flow data from the UNET model as the basis for calculating sediment transport. The UNET model was developed by Dr. Robert Barkau and is licensed

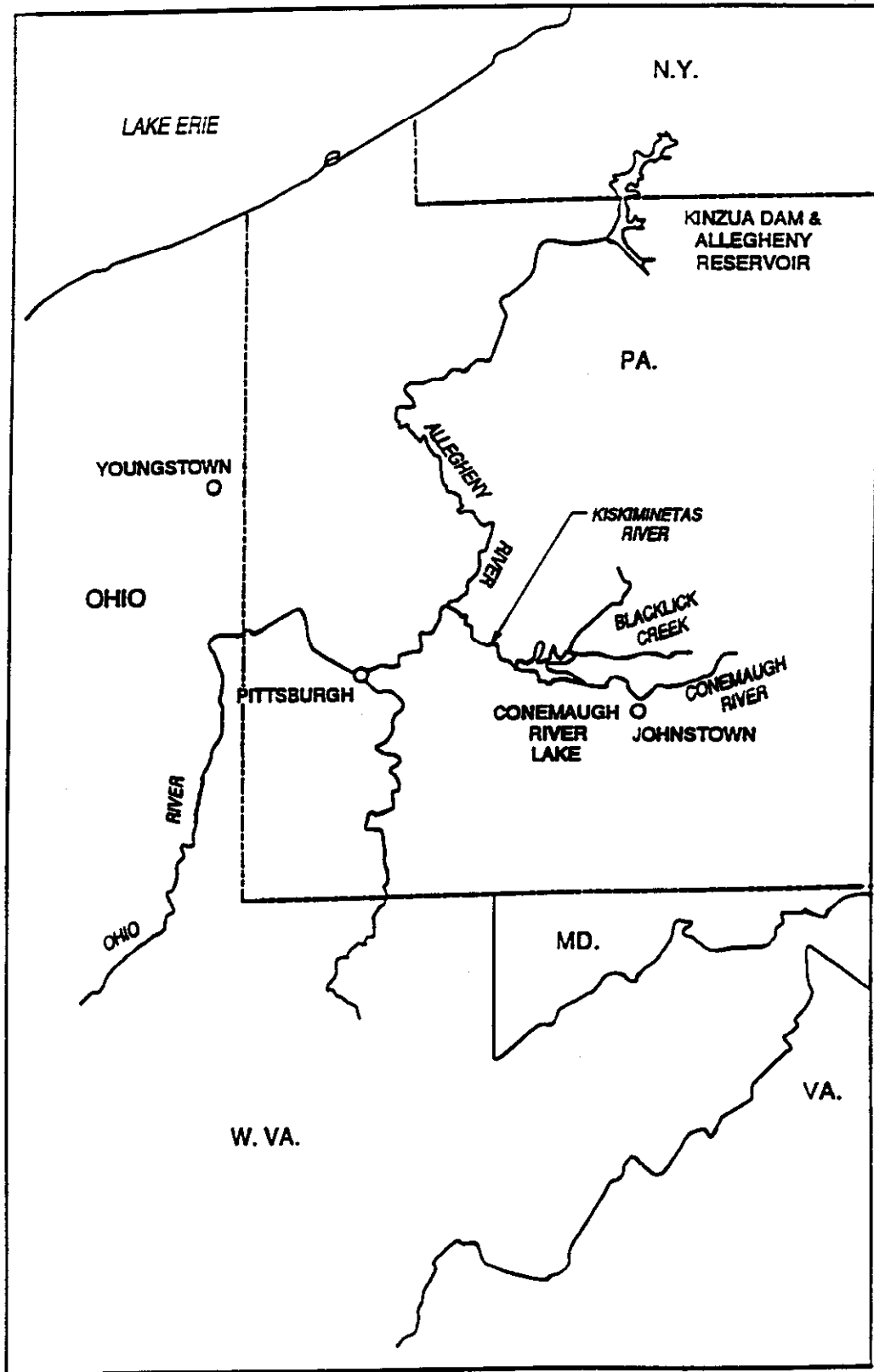


Figure 1. Vicinity map

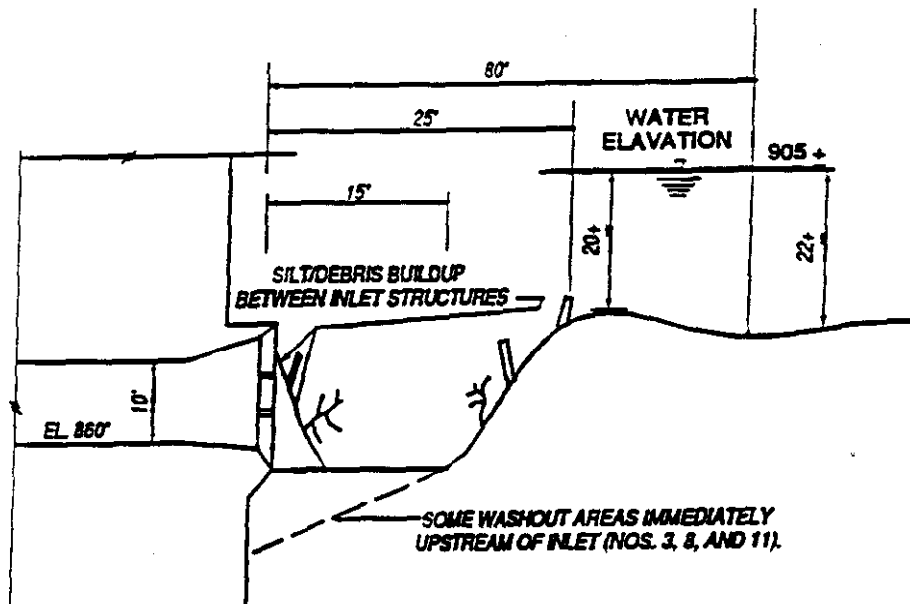


Figure 2. Schematic showing depositional pattern at dam.

for use within the Corps of Engineers (USACE/HEC 1991a). The TABS-1 model is a modified version of the HEC-6 model (USACE/HEC 1991b) which allows branching stream networks and was modified to use the UNET data in place of the steady flow calculations internal to the model.

The UNET model was adjusted using USGS and Corps supplied data. Average daily flow data from the USGS gaging stations at the inflows to the reservoir. The observed data was increased by a factor of 1.6 to account for ungaged inflow into the reservoir. The reservoir stage was used as the downstream boundary condition for the model and the model was used for a 30 year simulation. The agreement between observed reservoir outflows and the modeled outflows was, overall, very good. The flashy nature of the inflows presented some problem for the UNET model since reservoir inflows could vary from 100 cfs on one day to 100,000 the next for major storms.

The TABS-1 sediment model was adjusted to observed sediment discharge rating curves provided by the Pittsburgh District. The inflowing sediment was not analyzed for grain size distribution but the sediment surveys did include samples that were analyzed for sediment grain size and specific weight. The inflowing sediment gradation for the TABS-1 model was adjusted until the resulting deposition matched the observed grain sizes. The concentration was then adjusted to give the proper deposition depths. The sediment concentration required to match observed values was five times the observed concentration. This is in keeping with a reducing sediment concentration due to stricter laws and an improved public awareness regarding mining and other activities in the basin. The final results slightly over predicted the volume of sediment deposited between 1952 and 1966 but matched the grain size distribution observed in the reservoir sediments and observed depths of sedimentation along the thalweg.

The TABS-1 model was then run for the 35 year period of record for four alternative plans. The alternatives were: (a) no action or base test condition, (b) Plan 1, increase base flow release from 30 to 200 cfs, (c) Plan 2, dredge a channel through the reservoir with continued hydropower, and (d) Plan 2 with no hydropower diversions to note the effect of continuing hydropower diversions. All alternatives used the same reservoir operating curves. The results of calibration and modeling can be seen in Wade, et. al. 1994

MODELING CONCLUSIONS

The results of the numerical analysis indicated that the reservoir will continue to fill with sediment near the dam regardless of actions taken. The dredging plan will increase sediment storage capacity in the short term but will not lessen the current rate of sedimentation. With continued operation the sediment in the reservoir can be expected to approach the level of the permanent pool - whether that level is at 880 feet NGVD - the original pool level, 900 feet, or 910 feet. The diversion of hydropower through the power plant approximately 2 miles upstream from the dam increases the amount of sedimentation between the hydropower diversion and the main dam due to reduced flow rates in this reach.

ADOPTED SEDIMENT MANAGEMENT PLAN

The loss of flood control storage at Conemaugh Lake Dam is relatively small at less than 5% over a 40 year period. The build up of this sediment near the dam sluices and the potential for interference with the operation of the gates is of major concern. As a result of the model study and the potential for interference with gate operations, it was determined that the lake sediment management plan should focus on this area and not the entire lake. The plan that is most favored by the Pittsburgh District is a modified Waterways Experiment Station (WES) strategy. The plan will consist of dredging near the upstream face of the dam and the installation of a Sediment Evacuation Pipeline System (SEPS). Dr. Rollin Hotchkiss of the University of Nebraska was contracted by the Pittsburgh District to evaluate the use of a SEPS at this site. He concluded that the system was technically feasible but cautioned that due to the sensitive nature of bypassing sediment, considerable environmental studies may be required. The inflow and outflow sediment loads for this lake have been measured in the past and will be utilized in this analysis. The final sediment management plan will account for an existing downstream domestic water intake and would be in full compliance with all environmental permitting. The SEPS will be constructed after completion of the dredging and after monitoring indicated new sedimentation adjacent to the dam.

DREDGING

The dredging plan for the immediate area upstream of the Conemaugh Lake Dam is shown in Figures 3 and 4. The upstream edge of the level area will have an arc configuration to accommodate the SEPS thru the center of the dam. The volume of this dredging plan is estimated at 200,000 cubic yards. A water based hydraulic dredger and a clam bucket crane will be utilized to perform this excavation. To reduce outflow turbidity during this operation, the majority of lake releases will utilize the cleaner water from the hydropower plant. The dredge material will be transported 1/2 mile upstream to a disposal site below ordinary high water and within the lake property. To mitigate for lost habitat, a wetland will be constructed at this disposal site or at a nearby location.

PROPOSED SEPS SYSTEM

The installation of a SEPS system through the dam will not infringe on the overall safe operation of the structure. At this time, the SEPS design is conceptual. The major components of the proposed SEPS near the dam are: SEPS intake pipe, floating intake movement platform, intake pipe movement system, hinge connected bulkhead, mid-SEPS pipe, discharge valve, SEPS operating system, operations building, SEPS discharge pipe, and diffuser. The layout of the system is shown in Figure 5. The upstream intake pipe will consist of a 200 foot long, 2 to 3 ft diameter, perforated flexible pipe. The intake movement platform will be a barge with a hoist. The intake movement system will be a cable scheme anchored at the banks. The hinged connected bulkhead will consist of a joint for the flexible

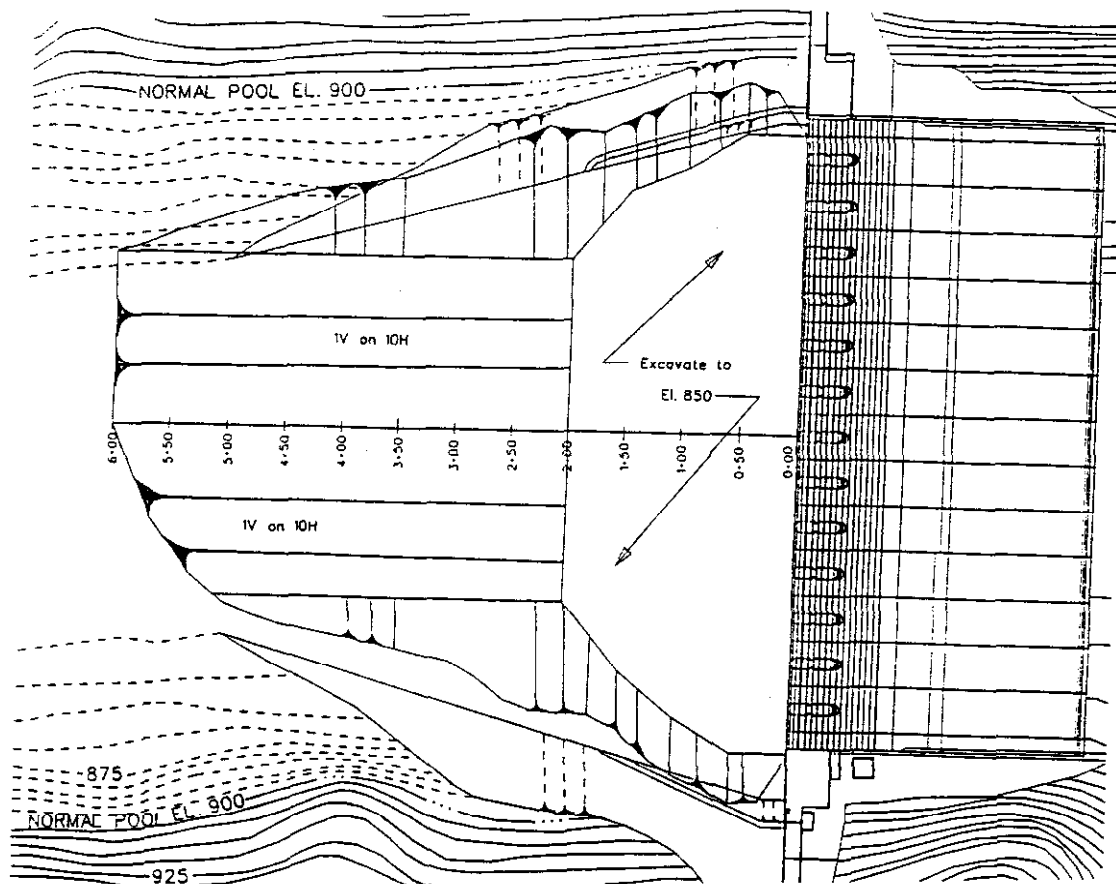


Figure 3.
Excavation Plan

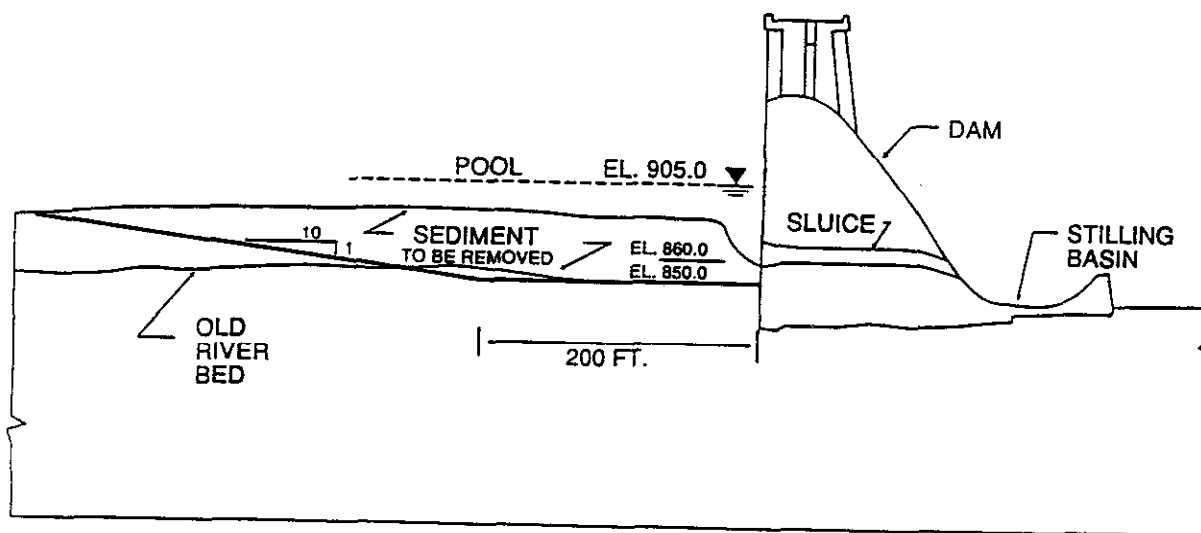


Figure 4
Section View of Dredge Plan

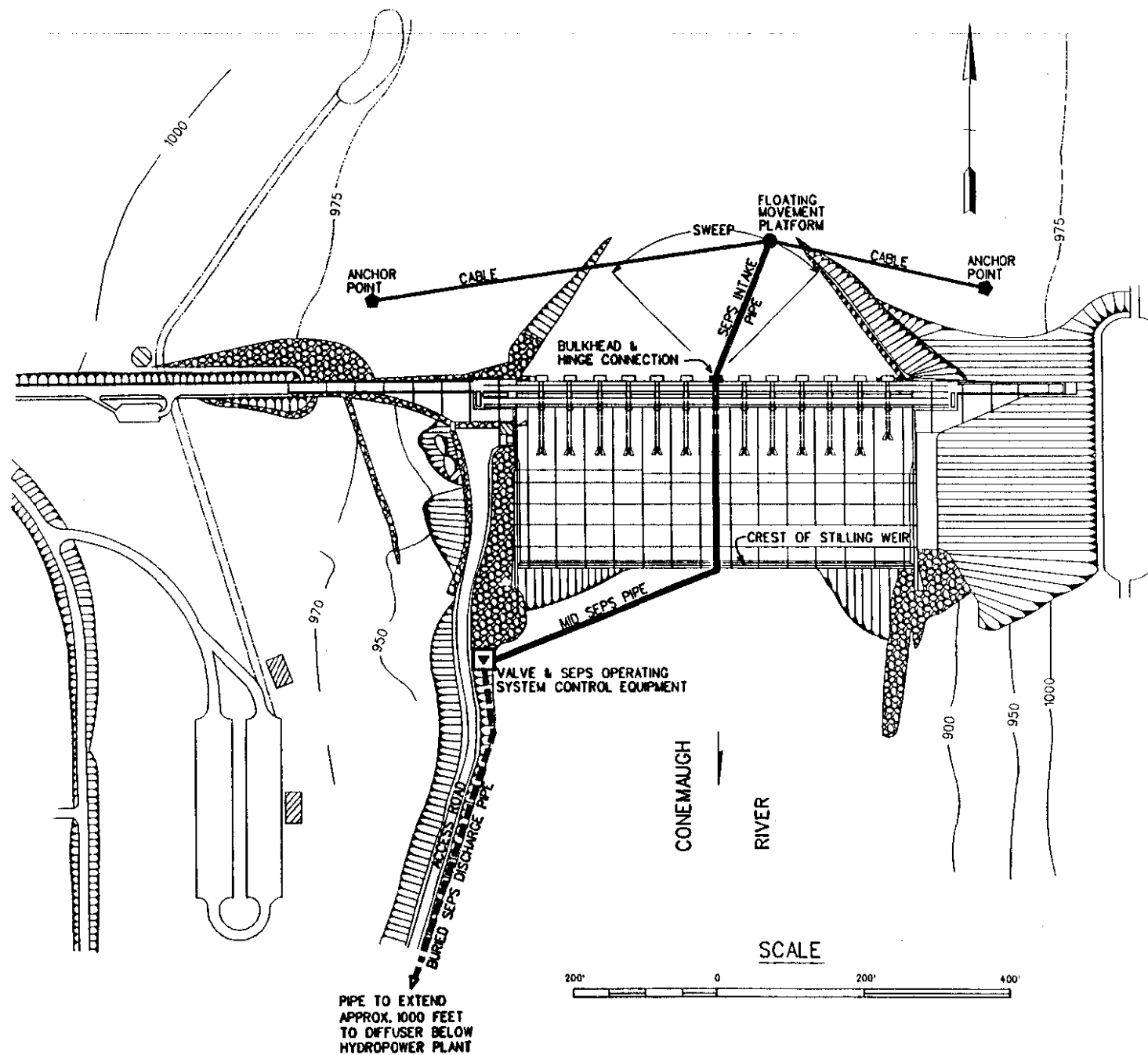


Figure 5.
Plan of SEPS Piping

intake pipe and a coupling for the solid mid-SEPS pipe. The mid SEPS pipe thru the dam will be a solid steel pipe, also 2 to 3 ft in diameter. The pipe will be securely anchored within the stilling basin. THE operations building will house the discharge valve, sediment transport monitor, operating equipment and SEPS control PC. A solid steel 2 to 3 ft diameter SEPS discharge pipe will be constructed in the right bank down to the hydropower outlet. This pipe will be buried for environmental enhancement. The diffuser will be a perforated pipe perpendicular to the stream flow and near the thalweg.

In addition to the SEPS components near the dam, four flow/turbidity monitoring stations will be established. Two stations will be installed at the existing lake inflow stations and two will be installed near the hydropower outlet as shown in Figure 6.

PROPOSED SEPS OPERATION

The two existing lake inflow gaging stations will be upgraded to monitor inflow sediment transport. The two new downstream monitoring stations will gather information concerning outflow sediment transport. These monitoring stations will transmit the information to the SEPS operations building every 10 minutes via satellite. The sediment transport within the SEPS pipe will be monitored near the valve every 10 minutes. The prime directive of the SEPS operational system numerical model will be to match the SEPS sediment transport to the hydropower release sediment transport and provide a total sediment transport within established environmental guidelines. The SEPS numerical operation model will interpret all information and decide the SEPS outflow that will provide the required balanced sediment transport within the system. The SEPS valve will regulate the required flow from the SEPS system. The anticipated discharge capacity of the SEPS will be 30 to 100 cfs. Every 10 minutes the SEPS system will interpret information from the monitoring stations and make any adjustment to the SEPS outflow. After a trial period, the optimum monitoring cycle for the SEPS will be established.

CONCLUSIONS

The numerical modeling effort confirmed that dredging will not solve the long term sedimentation problem that exists at the Conemaugh River Reservoir. Dredging will restore lost capacity and remove sediment from the area near the gates, but problems can be expected in the future unless other actions are taken to keep sediment from building up in front of the dam. The application of a SEPS at Conemaugh Lake Dam will complement the sediment management plan by assuring that the area adjacent to the dam stays relatively free from sediment. If sediment does continue to accumulate near the dam the SEPS system will reduce the frequency and amount of future dredging. By constantly monitoring the sediment into and out of the lake, the SEPS can be utilized to evacuate sediment near the dam in a manner that should be acceptable to downstream water users. This balanced sediment management plan will reduce environmental concerns and to a large degree, dredging in the future.

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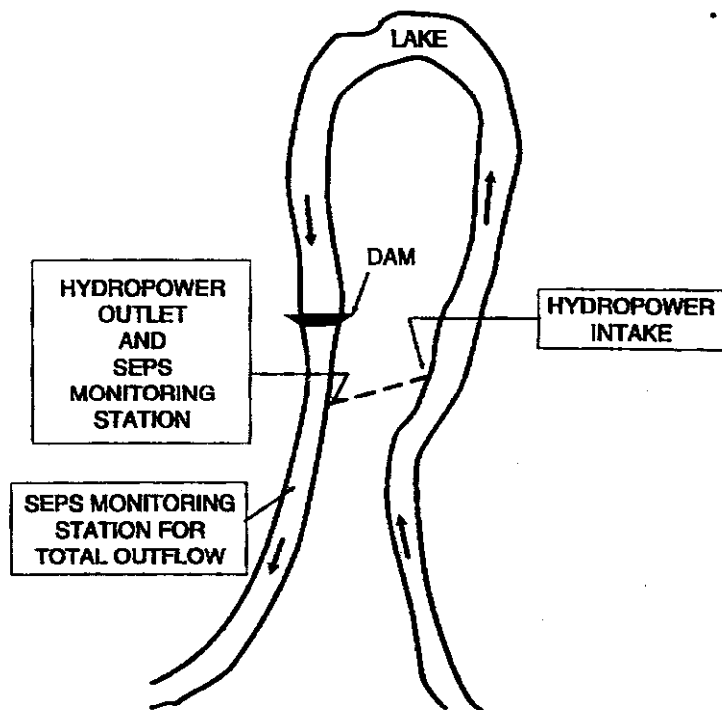


Figure 6. General Map Showing Location of SEPS Monitoring Stations, Dam and Hydropower Diversion.

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AN EXPERIMENTAL STUDY ON SCOUR FUNNEL IN FRONT OF A SEDIMENT FLUSHING OUTLET OF A RESERVOIR

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Abstract: When a reservoir is build on a sediment-laden river, a near-bottom sediment flushing outlet may be one of the most important means to exclude sediment deposited in front of the intake works. In order to make a rational design and layout of a sediment flushing structure, the understanding of the characteristics of a scour funnel is significant. A physical model experiment on scour funnel in front of a sediment flushing outlet of Zipingpu Reservoir has been conducted. On the basis of the tests data, the patterns of scour pit have been analysed, relevant conclutions are proposed.

INTRODUCTION

Worldwide reservoir storage is depleting at an increasing rate due to sedimentation. Besides losing the benefits expected from the original design such as flood control, water supply, water power, irrigation and navigation, reservoir sedimentation affects the entire river system in many aspects: raising the water surface and groundwater levels upstream, bank caving and degradation of streambed downstream, creating difficulties for water diversion and normal operation for electric power generation, altering the habitat for species both upstream and downstream.

For solving the problem of reservoir sedimentation so that reduces revervoir siltation and prolong the life of the reservoirs, different measures have been investigated and put into practice. These measures may be classified into three types: retaining (intercepting sediment in the watershed and upper reaches), releasing (delivering sediment from reservoir) and utilizing (making use of flood water and sediment as much as possible for various purposes) (Zhang and Xie, 1993). There are several ways to release sediment from reservoirs, such as releasing sediment during large flood, sediment relese by emptying the reservoir or by density current and removal of the deposits by hydraulic scour, dredge boat or slurry pump(Scheuerlein, 1987). One of the effective solution to the recovery of deposited reservoir capacity, especially for reducing coarse sediment passing through turbine sets of the hydro-power station may be the installing a deep or bottom flushing structure on the dam. In order to know the performance of the flushing device, it is necessary to determine the scope of the scour pit and its pattern. Based on the physical model tests for the design of flushing bottom outlet of Zipingpu Reservoir, the method of determination of the pattern

feature of scour pit including the length of the flat section in front of the outlet, the longitudinal and side slopes has been investigated in this paper.

SOME OF THE RELATED RESERCH RESULTS

The existing research results on scour pit in front of a flushing bottom-outlet can be grouped into three categories: theory study, experimental tests and field measurements.

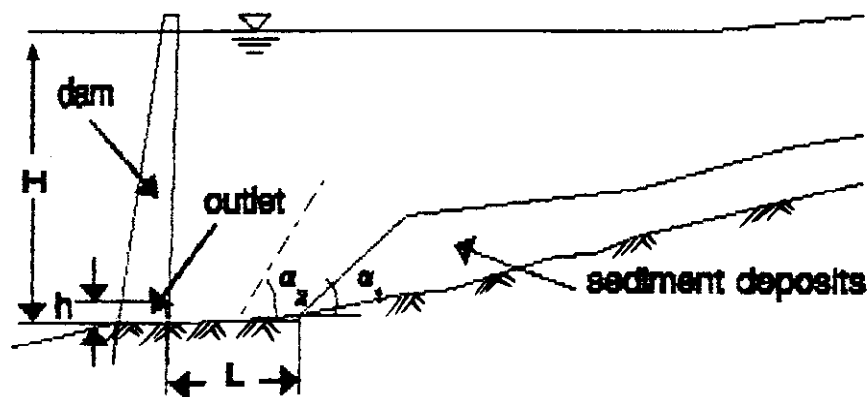


Fig.1 Side view of schematic diagram of a scour funnel

Theory study: The theory analysis is mainly to use the principle of the sink flow field and the incipient velocity of sediment to determine the length of the flat reach, L , in front of the flushing bottom-outlet and the longitudinal slope of the scour funnel, α_1 (see Fig.1). According to theory of sink flow, the distribution of velocities in front of the flushing bottom-outlet can be determined. In the area where the flow velocity larger than the incipient velocity of sediment deposited, sediment will flush out through the bottom outlet. Corresponding to a given condition of flow and sediment in front of the dam, the value L and α_1 can be determined (Lu, 1987).

Model Tests: According to the results of eleven scale hydraulic model tests (Xion, 1989) when the sediment release under a reservoir operation condition of the normal pool level, case of using the plastic sand and natural sand as the model sand, the average longitudinal slope and in angle α_1 has the range from 23.2° to 32.7° respectively. These values are very close to that of the angle of repose under water of plastic and natural sand respectively.

The side slope angle usually is steeper than that of the longitudinal one. The discrepancy will increase with the increase of the magnitude of outlet discharge and the diameter of the deposited material with a range of 4~11 percentage. (Shu and Ren, 1986)

Field measurements: The field data of slope angles of scour pit collected by different investigators are considerably small than that of the laboratory hydraulic model experiment (Zhu, 1989; You, 1988; Wan, 1986) as shown in table 1. The geometric feature of flushed

Table 1 Field data of slope angle of scour pit

Name of reservoirs	Annual sediment load ($10^8 \times m^3$)	Total storage capacity ($10^8 \times m^3$)	Slope angle of scour pit (degree)	
			α_1	α_2
Kongzhue	0.337	3.57	6	
Bikou	0.189	5.12	3.4~5.4	8~17
Qington Gorge	1.392	6.06	4~7	9~4
Fen He	0.178	7.02	9.5~11.0	13~17
YanGou Gorge	0.585	2.16	7~9	11~15

pit is significantly dependent on the reservoir water level. The so called "Scour funnel" is corresponding to the specific flushing pattern which is characterized by deep water sediment release without drawing down of reservoir water level. Most of the field data of flushed slope usually are mixture of different flushing patterns including reservoir water level draw-down even by emptying the reservoir, so they are not really representing the funnel scour but belong to the progressive erosion or retrogressive erosion or a mixture.

EXPERIMENTAL STUDY

Hydraulic model experiment of scour funnel of Zipingpu Reservoir: Zipingpu Reservoir located at the upstream of Minjiang River, a tributary of the Yangzi River in China. Its maximum height of dam is 120m, the design flood discharge is $8990m^3/s$, the normal pool level is 880m, and the installed capacity of hydro-power plant is 680MW. The annual suspended load is 8×10^6 tons, and bedload is 1.5×10^6 tons. The elevation of the intake of power plant is 800m. For the purpose of reducing sediment deposits near the dam, particularly preventing from the coarse sediment passing through the turbines and choking the trash racks, it is planned that a sediment flushing away structure will be installed beneath the entrance of the power plant. The elevation of the bottom sill of the flushing outlet will be 770m, 20 meters lower than that of the power plant. In order to judge whether or not the sediment flushing outlet can ensure the sediment free in front of the intake of power plant and prevent from the coarse sediment passing through the turbine, the hydraulic model tests for study the longitudinal and side slope angle of the scour pit have been conducted.

The scour pit experiment was carried out by making use of the comprehensive hydraulic model of Zipingpu Reservoir. The model is a undistorted model with a scale of 1:100. The experiment flow condition or operating condition of the reservoir including normal pool level (880m) and draw down to the restrict water level for flood control, the lowest water level 840m. The sediment deposit elevation in front of the dam is 845m. In order to ensure the scour similarity between model test and prototype, the diameter scope of model sand is determined according to the incipient velocity similar. The incipient velocity V_c , in prototype is determined by Shan youqing formula:

$$V_c = \left[0.43d^{3/4} + 1.1 \frac{(0.7 - \varepsilon)^4}{d} \right]^{1/2} h^{1/5} \quad (1)$$

Where d is diameter, h is water depth, ε is the porosity.

The V_c in the model is determined by the formular of Dou Gouren:

$$V_c = 0.32 \left(\ln 11 \frac{h}{K_0} \right) \left(\frac{r_s - r}{r} g d + 0.19 \frac{g h \delta + \varepsilon_k}{d} \right)^{1/2} \quad (2)$$

Where $\delta = 0.213 \times 10^{-4} \text{cm}$, $\varepsilon_k = 2.56 \text{cm} / \text{s}^2$. In case of $d \leq 0.5 \text{mm}$, $K_s = 0.5 \text{mm}$; if $d > 0.5 \text{mm}$, $K_s = d$.

Table 2 Scale for incipient velocity

Diameter of model sand $d(\text{mm})$	Water depth in model $h(\text{cm})$	Incipient velocity(cm / s)		Scale for incipient velocity λ_{vc}
		prototype V_{cp}	model V_{cm}	
0.12	5	127	16.96	7.5
0.18	10	142	18.81	7.6
0.20	50	198	24.31	8.1
0.23	100	218	27.83	7.8

To determine the diameter of model sand, taking derivation of Eq(1) and (2), and let them equal to zero, the range of particle sizes of model sand corresponding to extrema value of incipient velocity can thus be determined. Based on this procedure, the natural sand, with a diameter from 0.1 to 0.3mm, $d_{50} = 0.15 \text{mm}$ has been selected as the model sand. Its incipient velocity and corresponding scale are shown in Table 2. It indicates that the ratios of the incipient velocity between prototype and model in different water depths and sediment diameters ranged from 7.5 to 8.1, are close to the scale of incipient velocity, 10, determined ac-

cording to the Froude model law.

The experiment of scour pit includes four sets of combination comprise of two operation conditions, two deposit elevations in front of dam and two outlet flow discharges, as shown in Table 3.

Table 3 sets of run of scour pit tests

Number of sets	Operation Reservoir level (m)	deposit elevation (m)	Outlet flow discharge (m^3 / s)
1	880	845	1097, with plant intake and flushing outlet all open
2	880	845	2000, with plant intake and flushing outlet partial open
3	840	835	1097, with plant intake and flushing outlet all open
4	840	835	2000, with plant intake and flushing outlet partial open

For each run of model tests, the duration time needed for the formation of a stable scour pit is from about one hour to 6 or 7 hours depending on different operation water level of the reservoir. In order to identify the change with respect of time of sediment content as well as the ratio between the sediment contents of power plant and sediment flushing outlet, from the beginning of the scour experiment, 100ml sample of water-sand mixture was taken in every 30 seconds from the exits of power plant and sediment flushing outlet respectively. The experiments shows, during the without drawing down water level operation, at the beginning of several to fifteen minutes, large amount of deposited sediment were flushed out from reservoir, and then, the sediment content of water sample decrease rapidly. Meanwhile, the water discharged pass through power plant is clear, and the sediment content of water from sediment flushing outlet is under $0.1\text{kg} / \text{m}^3$.

In case of normal pool level operation, the scope of the flushing area is restricted to the zone close to the outlet, and a so called "funnel-shaped crater" developed around the outlet and as soon as the slope of the funnel reaches the magnitude of the angle of repose of the sediment, the excluding of sediment comes to an end. The slopes, both longitudinal and side, are rather stable and have almost the same value, that is 1:1.63, corresponding to a slope angle of 31.5° , slightly less than the angle of repose under water of the model sand. It needs point out, although the effect of the funnel scour is restricted to the zone close to the outlet, the sediment free condition in front of power plant intake maybe maintained, and it will play a very important role for preventing from the corase sand passing through

the turbine sets of the power plant.

The second stage experiment was carried out on the basis of the first stage, that means the operation water level was drawn down, the end of the backwater will move downward and causing progressive erosion. Once the water level was lowered below the topset of the deposits, retrogressive erosion will take place. The former occurs in area effected by backwater and exert an influence on excluding out the deposits at the head of the reservoir. The latter occurs near the dam and progresses rapidly towards upstream. The retrogressive erosion, through continuous back-cutting in the sediment deposits, is of high intensity and can remove a great amount of deposits from a reservoir. During the sediment scour experiment of draw-down water level, the progressive and retrogressive erosion taken place alternately, and thus made the slopes of scour pit continuously flatten, finally reach its average longitudinal slope angle of 9.5° and side slope angle of 18° , much flatter than that in the scour funnel.

Additional to the scour experiment, the measurement of angle of repose under water of model sand has also been conducted. Enough amount of model sand was slowly put in to a water container with a diameter of 60cm, after the heap of sand under water is stable, its angle of repose was measured, the average angle of repose of the model sand is 32.5° .

CONCLUSION AND REMARK

There are two distinct sediment flushing patterns in reservoir. The so called funnel scour occurs only in case of deep water and bottom outlet condition, corresponding to the normal pool level operation in a deep, large reservoir. To control reservoir sedimentation is still a challenge to civil engineers in planning, design and management, especially for the hydropower intake design. Although the effect of the funnel scour is restricted to the zone close to the sediment flushing structure, it has very important role in preventing from coarse sediment passing through the turbine sets and choking the trash racks. In order to make a rational design and layout of a sediment flushing structure, the understanding of the geometric and hydrodynamic feature of a scour funnel is significant.

Reliable determining the geometric characters of a scour funnel involves many factors including the hydraulic conditions in front of bottom outlet (water depth, flow discharge, velocity, etc), the properties of deposits in front of the dam (sediment properties such as r_s , r_i , mineral composition and feature, viscosity, consolidation, angle of repose under water and so on), and the operation conditions of reservoir. Many related problems need further study.

ACKNOWLEDGEMENTS

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PREDICTION OF SEDIMENT DISTRIBUTION IN A DRY RESERVOIR: A STOCHASTIC MODELING APPROACH

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Abstract: The paper presents a stochastic modeling approach that was used to predict distribution of deposited sediment in a dry flood control reservoir. The major modeling issues are simulation of the distribution of deposited sediment under non-uniform, unsteady flow conditions, and modeling of uncertainty related to the rate of occurrence and magnitudes of future floods. The need to simulate the former and estimate the latter were demanded by the anticipated unsteady flow characteristics in dry flood control reservoirs. The major project requirements pertaining to sedimentation were estimates of probable sediment distribution and its variability as a function of time and space. The latter were required by the environmental impact statement for estimating the likelihood of natural re-establishment of vegetation between flood events.

INTRODUCTION

The town of Ladysmith, located on the banks of the Klip River in the province of Natal, South Africa (Figure 1), was flooded 27 times over the last 102 years. Recent flood events caused major damage to commercial and residential property, resulting in demands for flood protection. The recommended project entails a dry flood control reservoir upstream of the town. The high sediment yield in the catchment gave rise to concerns pertaining to unsightly deposits of sediment, exposed between flood events, and associated nuisance related to windblown sand. The unsteady, non-uniform flow conditions that will prevail in the reservoir during flood events is expected to result in unique distributions of deposited sediment. Known techniques for predicting distribution of deposited sediment (for a summary see e.g. Annandale, 1987) could therefore not be used. A modeling approach with the abilities to simulate unsteady, non-uniform flow and uncertainties associated with the rate of occurrence and magnitude of future flood events was used to predict sediment distribution. Modeling of uncertainty was required to determine the probability distribution of deposited sediment as functions of time and space.

PROJECT DESCRIPTION

Dam and Location: The proposed flood control project will be located upstream of the town of Ladysmith at the confluence of the Klip and Sand Rivers (Figure 1). The volume of the reservoir basin will be 207 million cubic metres. The dam (Figure 2), known as Mount Pleasant Dam, will be constructed of rollcrete to a height of approximately 25m and an orifice at the lowest point of the dam of 2,54m high by 5,11m wide. The latter will always remain open. The sizing of the dam and orifice are tailored to attenuate incoming floods with recurrence intervals of 100 years to discharges equivalent to 10 year recurrence interval floods downstream of the dam.

Hydrology: The average annual rainfall is 962mm. The catchments of the Sand and Klip Rivers drain the eastern slopes of the Drakensberg mountain range, with approximate equal sizes of 760 km² and 800 km² respectively. River slopes are steep in the upper reaches, reducing significantly in the lower reaches to approximately 0.6% in the vicinity of the proposed dam. Vegetation is classified as Highland Sourveld and Dohne Sourveld in the upper catchment reaches, whereas the vegetation in the lower catchment is classified as Southern Tall Grassveld. The soil types are dominated by Fersiallitic and Montmorillonitic clays.

Estimates of the number of floods in any one year and their magnitudes are required by the modeling procedure. Probability distributions for these variables were therefore determined by analyzing the data collected at a stream gage at the proposed location of the dam. A flood was defined as any discharge exceeding 170 m³/s, the free flow discharge capacity of the orifice in the dam. By analyzing the number of floods in excess of this discharge, it was determined that a Poisson probability distribution can be used to represent the number of floods that will occur in any year. the mean occurrence rate is 3,8 (i.e. approximately 4 floods per year). It was furthermore determined that the peaks associated with these floods can be described by a Log-Normal probability distribution.

Sediment Yield: An estimate of the mean annual sediment yield was achieved by making use of a sediment yield map (Rooseboom, 1975), resurvey data of the existing lake at Windsor Dam (upstream of the proposed site of Mount Pleasant Dam, in the Klip River) and by Bootstrapping (Efron, 1979 and Annandale, 1988) of daily sediment concentration samples. It was concluded that the sediment yield map underestimates sediment yield, but that the resurvey data of the lake at Windsor Dam and the Bootstrapping results correlated well. The unit sediment yield was determined to be 315 t/km²/year, for a total sediment discharge at Mount Pleasant Dam of approximately 500,000 t/year.

STOCHASTIC MODELING

Overview: The stochastic modeling method that was used for simulating sediment deposition upstream of Mount Pleasant Dam (Annandale, 1990) consists of five phases (Figure 3). Phase I entails preparation of data and models, and simulation of typical distributions of deposited sediment for a range of selected flood hydrographs. Phase II represents the core of the stochastic modeling procedure, whereas Phase III consists of empirical estimates of the volume of sediment that is expected to deposit in the reservoir over its lifetime. Phase IV validates the findings, and Phase V entails preparation of the output for presentation.

Phase I - Input data preparation and modeling of single events: Phase I consists of activities required to determine the geometry and hydraulic characteristics of the reservoir basin, preparation of representative flood hydrographs for selected recurrence intervals, determination of sediment characteristics, development of a computational model to simulate sediment deposition under unsteady, non-uniform flow conditions, and preparation of a library of typical sediment deposition patterns resulting from selected single event floods.

The reservoir geometry was determined from survey data, whereas hydraulic characteristics, such as roughness, and sediment characteristics were determined from field observations and grading analysis. The flood hydrograph shapes were prepared by making use of unit hydrograph methods presented in HRU 1/72 (Hydrological Research Unit, 1972), for 1, 2, 3, 4, 5, 10, 20, 50 and 100 year recurrence intervals. Each of these hydrograph shapes were deemed to represent the inter-recurrence interval ranges with the 100 year hydrograph shape used to represent floods equal to or greater than the 100 year flood.

A computer model that can simulate unsteady, non-uniform flow (Benade *et al.*, 1990) was used to simulate sediment transport by means of an uncoupled solution procedure. The computational model is based on the de Saint-Venant equations and a sediment continuity equation. These equations were discretized by making use of a four-point, implicit Preissman scheme (Abbott, 1979) and solved by means of a double sweep method (Liggett and Cunge, 1975). The sediment transport equations that were used to calculate sediment discharge were selected from the theories of Engelund and Hansen (1967), Ackers and White (1972) and Yang (1972). The assumption was made that these equations can be used to simulate sediment transport under unsteady, non-uniform flow conditions.

The stochastic modeling procedure uses the principle of superposition to determine the development of sediment deposition patterns over the lifetime of the reservoir. For this purpose a library of sediment deposition patterns associated with input hydrographs with recurrence intervals of 1, 2, 3, 4, 5, 10, 20, 50 and 100 years were developed by making use of the computational model.

Phase II - Stochastic modeling of sediment deposition: Figure 3 indicates that the stochastic modeling procedure entails simulating sediment deposition over 50 lifetimes (L) of 50 years (Y) each. Estimation of sediment deposition in any one year commences with the determination of the number of floods (N), randomly selected from the Poisson probability distribution for that particular year. The recurrence interval of each flood (R) is then determined by random selection from the Log-Normal probability distribution, and the appropriate sediment distribution for recurrence interval R subsequently selected from the library of single event simulation results. The selected sediment deposition pattern is superimposed on previously selected patterns.

At the end of each year the software determines whether the sediment deposition information must be stored for further analysis. If the year variable (Y) has a value of 10, 20, 30, 40 or 50, the sediment deposition information for the period up to this time event is stored in an output file. Storage of data on these time intervals allow estimates of

probable sediment distribution as a function of time and space. After simulation of 50 years, the whole process is repeated for the next lifetime (L), until 50 lifetimes have been simulated.

When the simulation of sediment deposition over 50 lifetimes of 50 years each is complete, the mean and standard deviation of the cross section sediment area and depth are stored for output at each cross section of the reservoir basin for periods of 10, 20, 30, 40 and 50 years.

Phase III - Empirical estimation of volume of deposited sediment: The known inadequacies of current sediment transport theories and the other assumptions necessitated validation of the findings of the simulation procedure. This was done in Phase IV by comparing the simulated volume of deposited sediment with an empirical estimate of sediment deposition for Mount Pleasant Dam and reservoir. The comparison required an independent, site-specific estimate of the volume of sediment that was expected to deposit in the reservoir. The empirical estimate of the expected volume of deposited sediment was made by first estimating the expected sediment yield from the catchment, whereafter the trap efficiency of the reservoir and finally the expected volume of sediment was estimated. The method to empirically estimate sediment yield is briefly described in the section of this paper dealing with sediment yield, whereas the trap efficiency was estimated by comparing simulated in- and outflow sediment hydrographs for Mount Pleasant Dam and reservoir. The expected volume of deposited sediment was calculated by applying the trap efficiency to the estimated sediment yield.

Phase IV - Validation: The validation process commenced by comparing the simulated volume of deposited sediment and the independent estimate made in Phase III. The independent calculation made in the latter phase is an estimate of the mean volume of sediment that is expected to deposit in the reservoir, therefore requiring an estimate of the mean volume of the simulated deposited sediment for comparison. The two volumes differed, and required an adjustment of the simulated volume of deposited sediment. This was done by ratio-ing while maintaining the relative distribution as simulated. The justification for the latter was found in a sensitivity analysis conducted by alternate use of the three sediment transport equations. The finding from the sensitivity analysis was that the relative distribution of sediment remained essentially the same in spite of the fact that the volumes of simulated deposited sediment differed.

Phase V - Presentation of results: The results were presented on drawings showing the mean distribution of sediment plus or minus one standard deviation in the longitudinal and transverse directions relative to the flow direction in the reservoir basin. This information, allowing for the uncertainty related to the number and magnitude of future floods, was presented for 10, 20, 30, 40 and 50 year durations and allowed botanists to evaluate the odds of success of re-establishment of vegetation. An example of the predicted distribution of deposited sediment in the longitudinal direction, showing the mean and variability, after ten years of operation is shown in Figure 4.

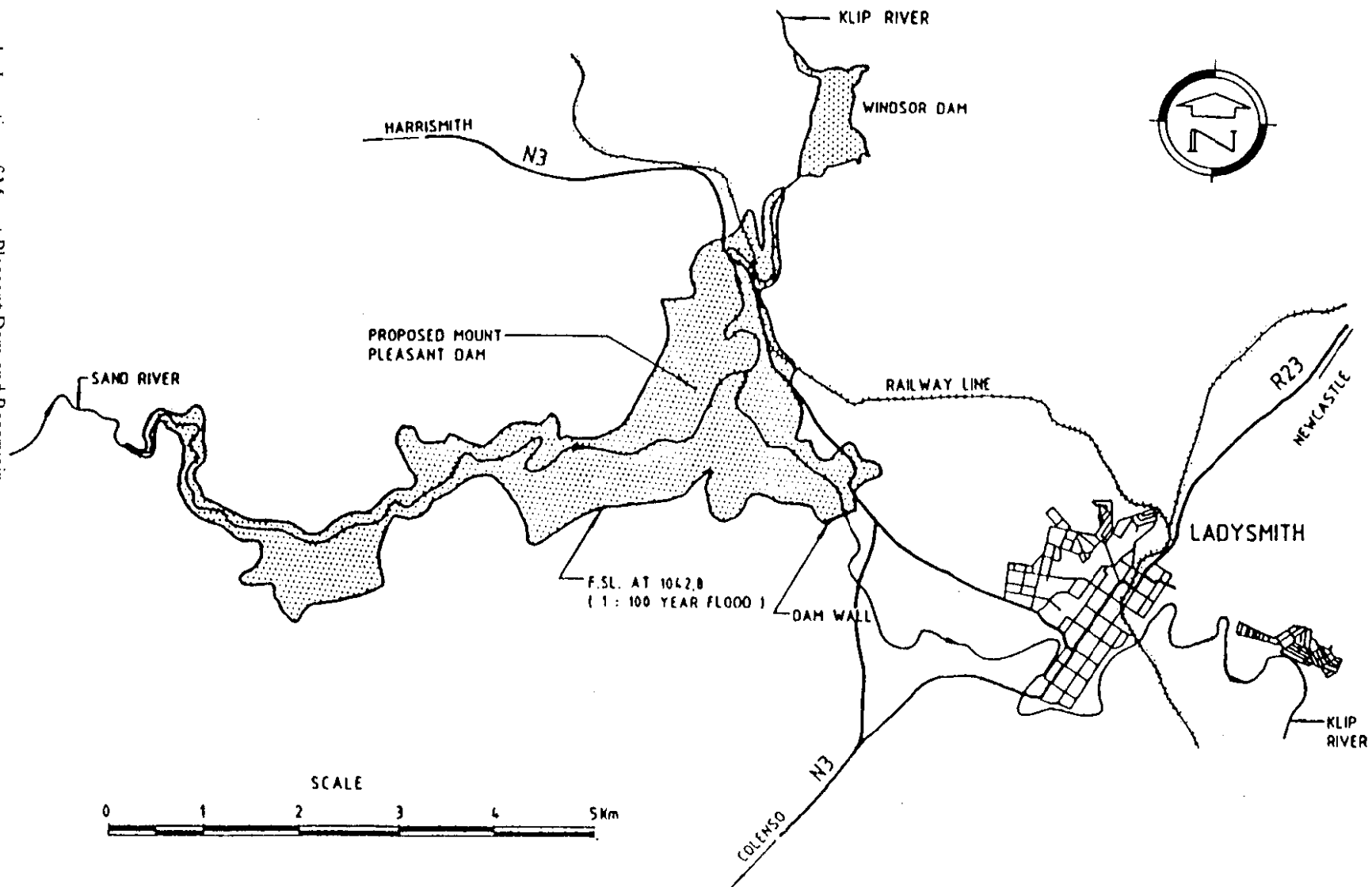
SUMMARY

The impact of unsteady flow and the uncertainty related the number of future floods and their magnitudes on the distribution of deposited sediment in dry flood control reservoirs were accounted for in the procedure presented in this paper. Unsteady, non-uniform flow conditions that prevail in dry flood control reservoirs have an impact on the distribution of deposited sediment. This impact was assessed by assuming that the sediment transport equations of Yang (1972), Engelund and Hansen (1967) and Ackers and White (1972) could be coupled with an unsteady, non-uniform flow model to simulate the distribution of deposited sediment. The uncertainty pertaining to the number of future floods and their magnitudes was modeled by making use of a stochastic modeling procedure. The procedure randomly generates the number of floods and their magnitudes on an annual timestep and simulates sediment deposition for each of these floods by repeating the process for 50 lifetimes of 50 years each. The information thus generated is statistically analyzed to provide estimates of mean sediment distribution plus or minus one standard deviation.

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Figure 1: Location of Mount Pleasant Dam and Reservoir



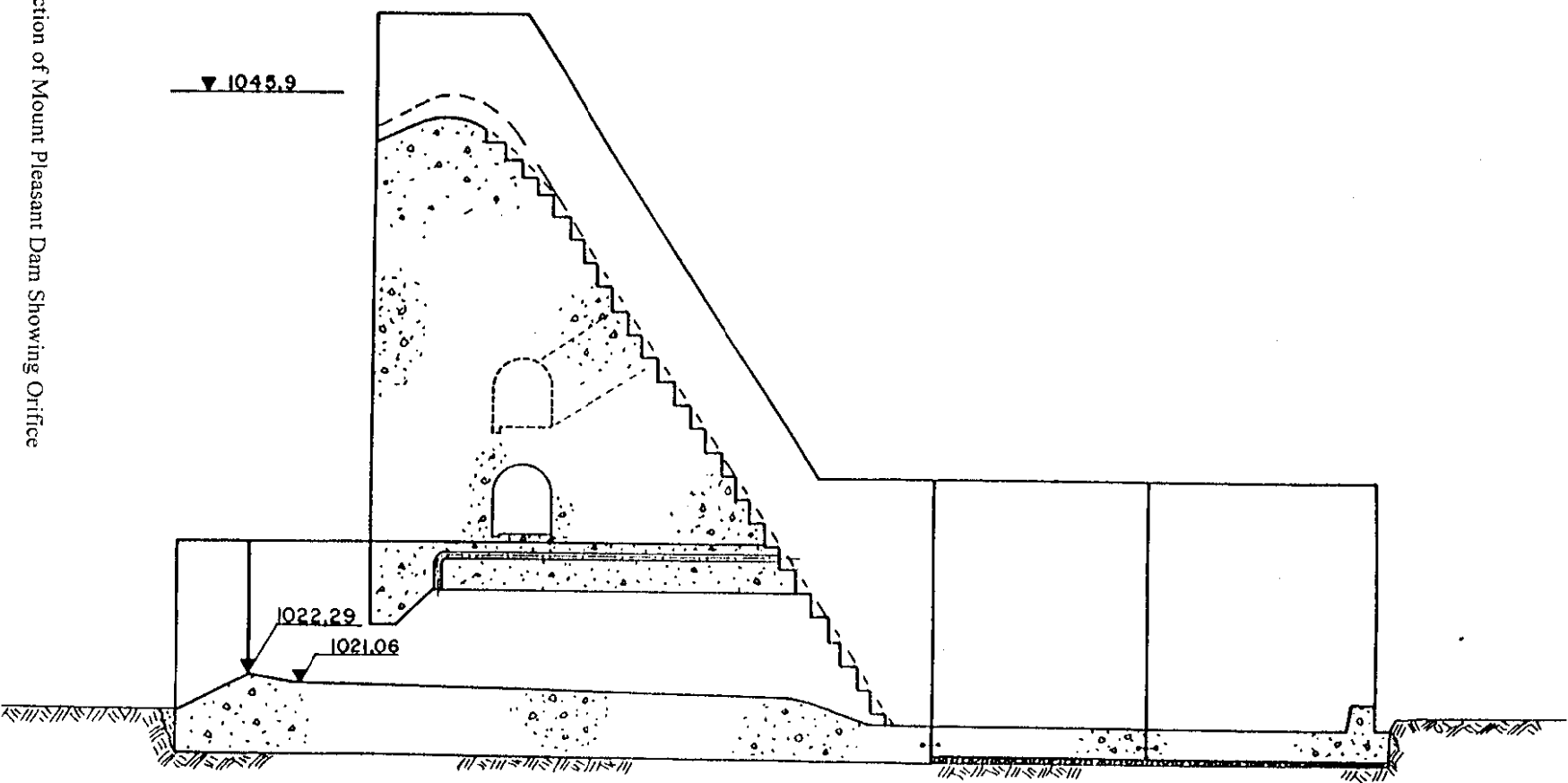


Figure 2: Section of Mount Pleasant Dam Showing Orifice

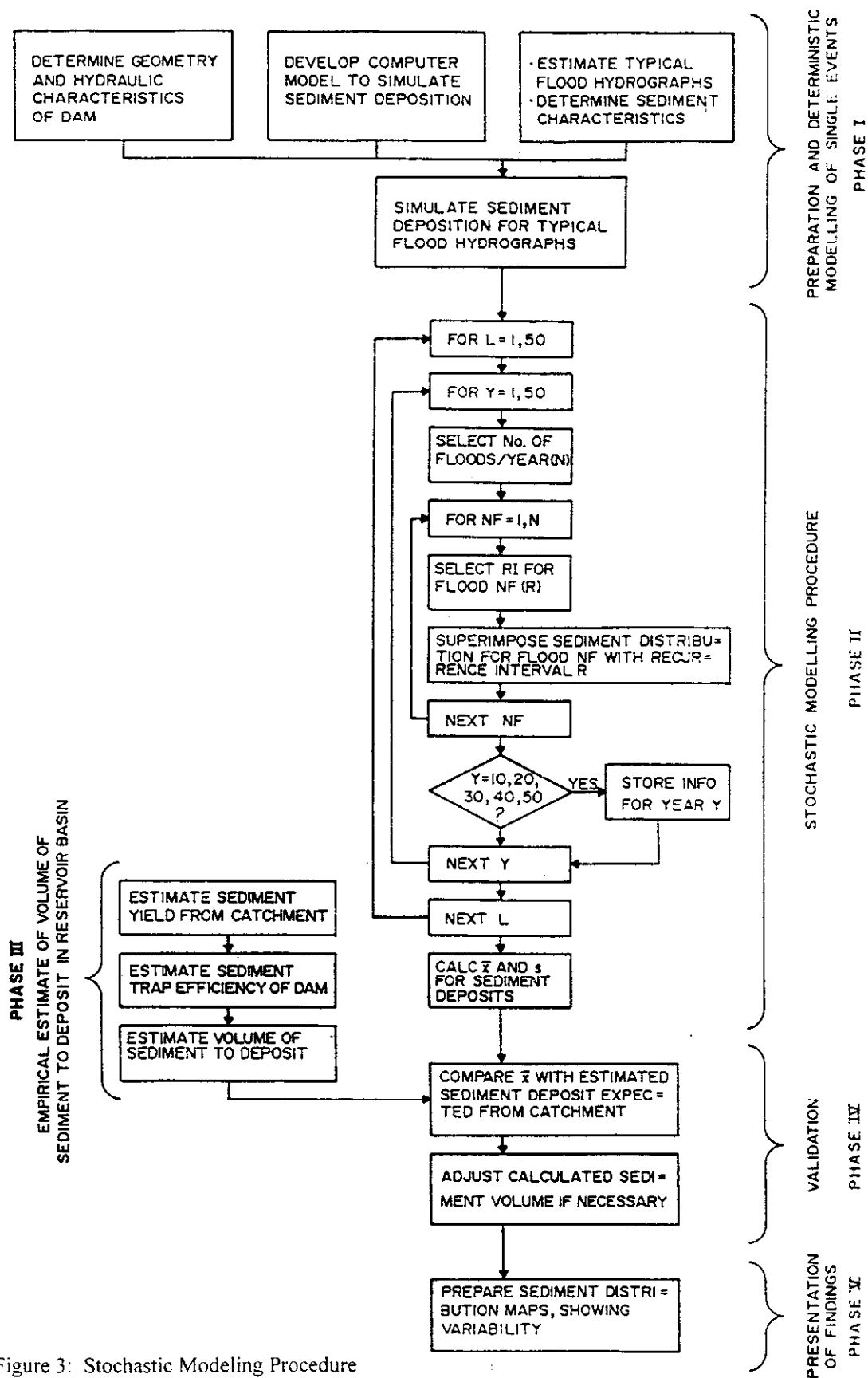


Figure 3: Stochastic Modeling Procedure

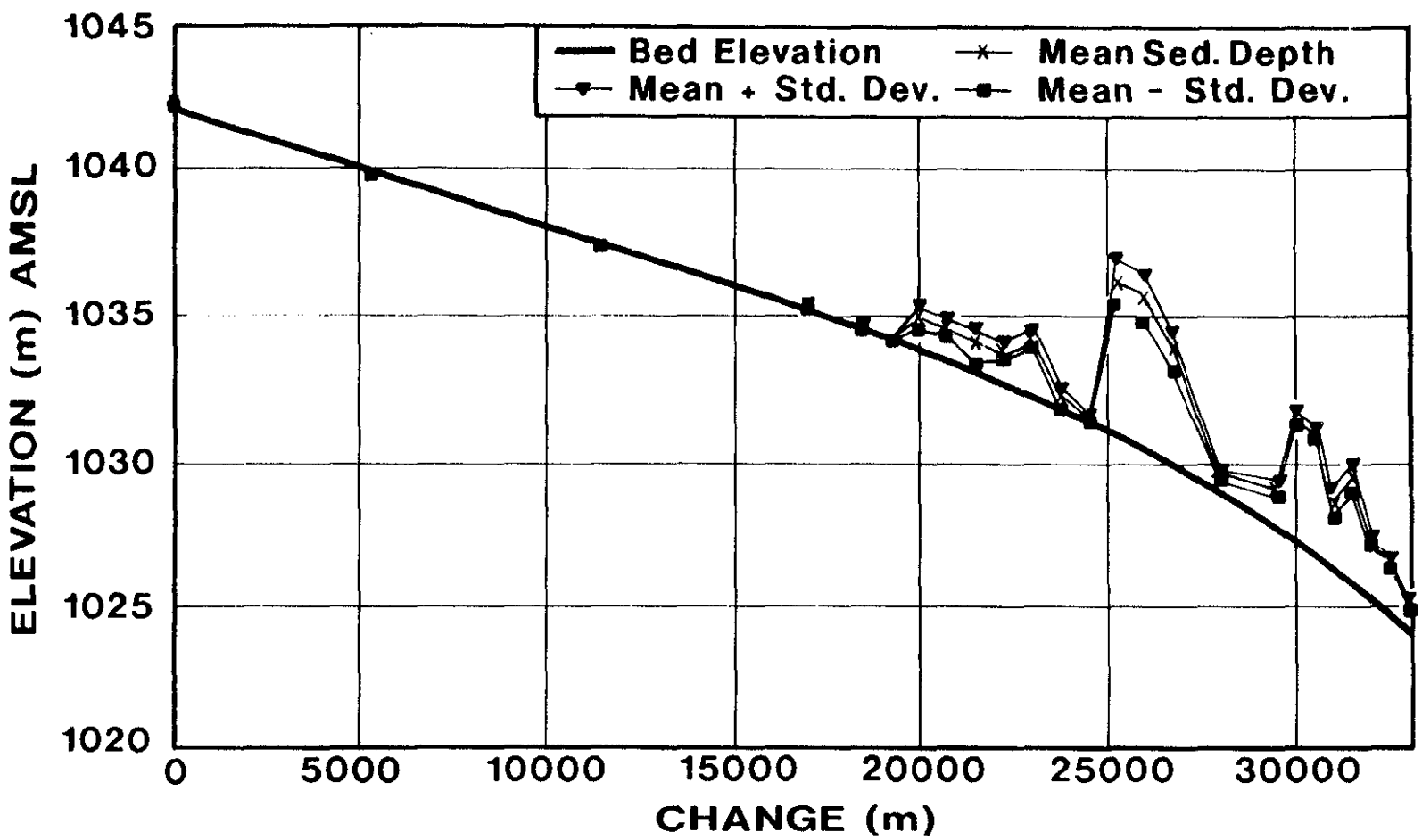


Figure 4: Example of Simulated Distribution of Deposited Sediment After 10 Years on a Normalized River Bed Elevation For Clarity

RESERVOIR EROSION AND SEDIMENTATION FOR MODEL CALIBRATION

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Abstract: In order to apply a mathematical model to a river or reservoir, test and calibration are critical steps to establish the applicability of the model. The FLUVIAL-12 model was calibrated using data from the North Fork Feather River covering Cresta and Rock Creek Reservoirs for the erosion and siltation processes which occurred during the February-March 1986 flood. The objective of calibration was to assess the applicability of the model and to select an appropriate sediment transport formula for the study.

The selection of a sand and gravel transport formula is usually handicapped by the lack of accurate site-specific sediment transport data. In this approach, the sediment transport formula was selected based on their applicabilities in simulating stream channel changes. It is the working hypothesis that a sediment formula suitable for mathematical application should generate stream channel changes that can be substantiated by measurements. In this study, three sediment transport formulae were tested. Based on the simulated results for the reservoirs and the river channel, the Yang formula was selected for this study.

Simulated and measured changes in cross-sectional profiles show that such changes may be in channel bed or in overbank areas, or both. It should be very clear that scour or fill at a cross section is by no means uniformly distributed across the channel width. Scour of the bed may be accompanied by scour or fill of the overbank area, or vice versa. The bed topography in a curved channel is also affected by the channel curvature. Such complex adjustments in channel morphology directly affects the hydraulics of flow and sediment transport. *It is therefore emphasized that fluvial simulation should be based on an erodible-boundary model instead of an erodible-bed model.*

INTRODUCTION

A general problem facing reservoirs is the accumulation of sediment. For certain reservoirs, siltation has already damaged certain functions, such as water storage, power generation, flood control, etc. Any solution for reservoir sedimentation problems must be evaluated before its implementation. The evaluation may be based on physical modeling or mathematical modeling, or both. While there are many developed mathematical models, the validity of most models are not verified based on field data. In order to apply a model to a river or reservoir, calibration of the model is the first phase of the project. The objective of calibration is to assess the applicability of the model and to select an appropriate sediment transport formula for the study.

Cresta and Rock Creek Reservoirs (see Fig. 1) on the North Fork Feather River (NFFR) in northern California underwent siltation that has affected powerhouse operation in recent years. Preliminary plans have been made by the Pacific Gas & Electric Company (PG&E) to modify Cresta and Rock Creek Dams to allow drawdown of the reservoir level for sediment-pass-through (SPT) operations during floods. A numerical modeling study has been made to evaluate the feasibility of maintaining sediment equilibrium of the reservoirs. This paper presents the test and calibration of the FLUVIAL-12 model (Chang, 1988) for the river and reservoir system. The FLUVIAL-12 model has been formulated and developed since 1972 for water and sediment routing in natural and man-made channels. The combined effects of flow hydraulics, sediment transport, and river channel changes are simulated for a given flow period. While this model is for erodible channels, physical constraints, such as bank protection, grade-control structures and bedrock outcroppings may also be specified. River channel changes simulated by FLUVIAL-12

include: (1) channel-bed scour and fill, (2) width variation, and (3) changes in bed topography induced by the curvature effect. These inter-related changes are coupled in the model for each time step. Computations are based on finite difference approximations to energy and mass conservation that are representative of open channel flow.

CALIBRATION OF FLUVIAL-12 NUMERICAL MODEL

Data Base for Test and Calibration of Model - Field data generally are required for test and calibration of a model, including the channel configuration before and after the changes, a flow record, sediment records, and sediment characteristics. Test and calibration study for the FLUVIAL-12 model was made using data from the North Fork Feather River covering Rock Creek and Cresta Reservoirs, for the erosion and siltation processes during the February-March 1986 flood. The data base for the study includes the hydrograph, bed-material characteristic, and cross-sectional data that are described below separately.

The hydrograph for the February-March, 1986 flood is shown in Fig. 2. This flood is estimated to have a return period of 80 years. During the high flow period, the drum gates at the two reservoirs were lowered to allow the flood flow to pass through the spillway. The powerhouses were shut-down with no flow passing through the penstocks.



Fig. 1. Cresta Reservoir (left) and Rock Creek Reservoir (right)

Sediment size distributions obtained in previous studies (Bechtel, 1989; PG&E, 1990) were incorporated into the data set. Bed materials in the reservoirs are generally in the sand-size range; those in the river channel are gravel and boulders. Coarse sediments, mostly gravel, can be found in the upper half of the Rock Creek Reservoir.

Bathymetric surveys of Cresta Reservoir and Rock Creek Reservoir were made before the flood in May, 1984 and after the flood in April, 1986. Since the major flood was preceded and followed by low flows, most channel changes occurred during the flood. Forty-nine cross sections in the river channel were selected and surveyed by PG&E for the study. In order to obtain a detailed depiction of the river channel changes in the reservoirs, additional cross sections were selected. Cross-sectional profiles for these

sections were obtained from the 1984 bathymetric survey of the reservoirs.

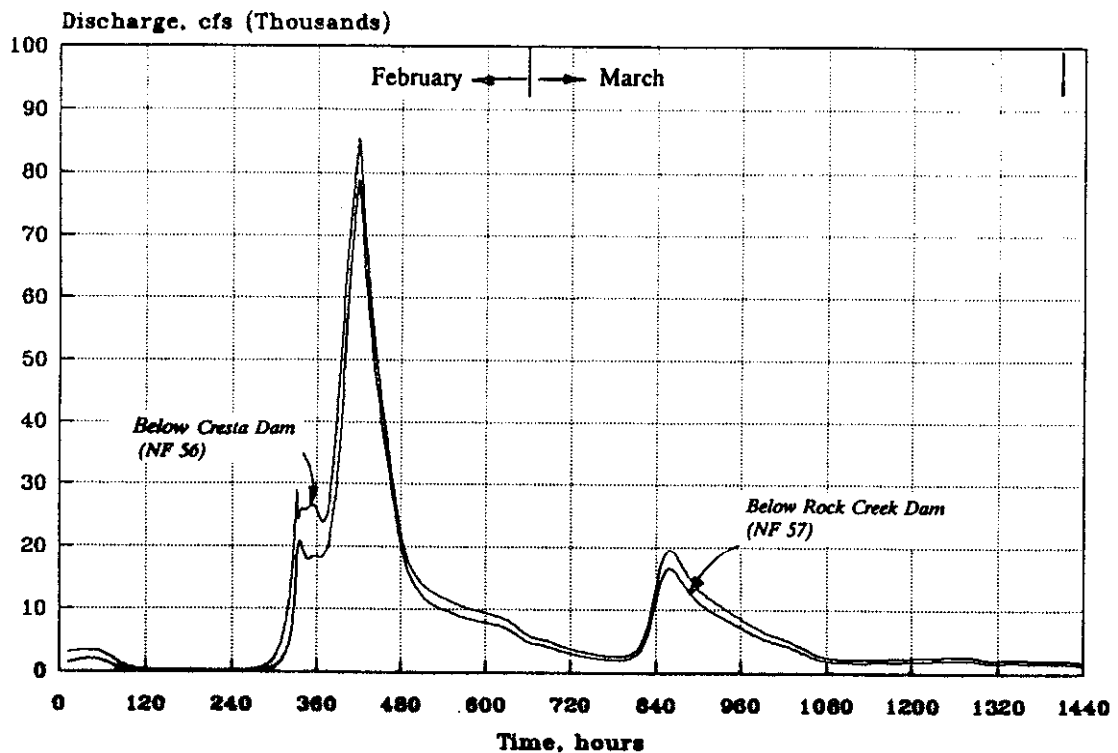


Fig. 2. Hydrographs for February-March 1986 flood

Selection of Sediment Transport Formula: A sediment transport formula is required in mathematical modeling of an alluvial stream. The selection of a sand and gravel transport formula is usually handicapped by the lack of accurate site-specific transport data to substantiate the computed transport rates. In a stream, such as the Feather River, sediment transport measurements may only be made during floods when there is substantial movement of the bed material. In addition, the accuracy of gravel transport data is limited by existing sampling methods. In view of these difficulties, an alternate method for selecting a transport formula for application to the specific stream was used for this study. This method is based on the measured changes in stream morphology instead of site-specific transport data. This method does not substitute for measured transport data, but it provides a basis useful for evaluating the applicabilities of sediment transport formulae. In the approach, several transport formulae were tested based on their applicabilities in simulating stream channel changes. It is the working hypothesis that a sediment formula suitable for mathematical application should generate stream channel changes that can be substantiated by measurements.

Stream channel changes in the Feather River during the 1986 flood are noted to have the following features: (1) channel-bed scour in Rock Creek Reservoir, and (2) deposition in Cresta Reservoir. These changes were significant and thus useful for assessing the predictability of each sediment transport formula.

Several sediment transport formulae have been developed for stream channels with gravel as the principal bed material. For this case, the following formulae were evaluated separately to test the appropriateness of FLUVIAL-12 for the river: Meyer-Peter Muller (MPM) formula (1948), Yang formula (1984), and Parker formula (1990). Among these, the MPM formula is a formula widely used for gravel-bed streams.

The Parker formula is primarily for gravel transport. The Yang formula includes a component on sand transport and another component on gravel transport. MPM and Parker formulae estimate sediment transport moving as bed load, where sediment moves by rolling, saltation (bouncing), or sliding. In contrast, the sediment load estimated by the Yang formula is the bed-material load, which includes particles movement as bed load and particles moving in suspension.

Sediment Delivery Through Rock Creek Reservoir: The range of Rock Creek Reservoir is from Rock Creek Dam at river mile 33.5 to river mile 35, above which the flow is beyond the backwater influence of the dam. Deposition of coarse sediments has turned the upper half of the reservoir to a riverine situation. During the 1986 flood, there was major sediment removal from Rock Creek Reservoir, 546,000 cubic yards based on the bathymetric survey. If the void ratio of 0.4 is used for the deposited sediment, this volume is equivalent to 731,000 tons. The portion of coarse sediment (sand and gravel) is about 90 % or 660,000 tons. Upstream of the reservoir, changes in the stream channel were limited.

Sediment delivery is the cumulative amount of sediment having been delivered passing a specific stream section during a specified period of time. The simulated spatial variations of sediment delivery based on the MPM, Parker and Yang formulae are shown in Figs. 3, 4 and 5, respectively. The simulated sand and gravel deliveries based on the respective formulae were compared with the observed patterns of scour and deposition. The amount of sediment deposition or removal within a stream reach is the difference in cumulative delivery from one stream station to the other. For the total delivery curve shown in Fig. 3 based on the MPM formula, the simulated sediment removal from Rock Creek Reservoir is about 180,000 tons. This delivery curve also shows minor deposition in the stream channel above the reservoir. The delivery based on the Parker formula shown in Fig. 4 indicates sediment removal of about 1 million tons from the reservoir. From the total delivery curve based on the Yang formula shown in Fig. 5, the simulated sediment removal is about 700,000 tons. This result is consistent with the actual observations.

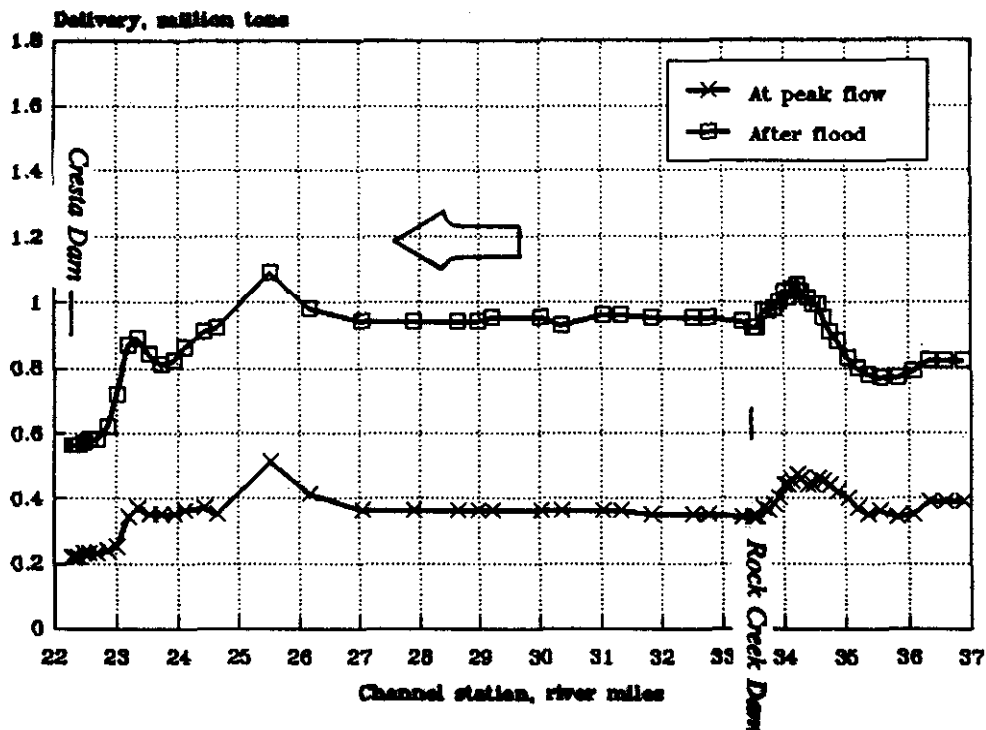


Fig. 3. Simulated spatial variations in sediment delivery based on the MPM formula

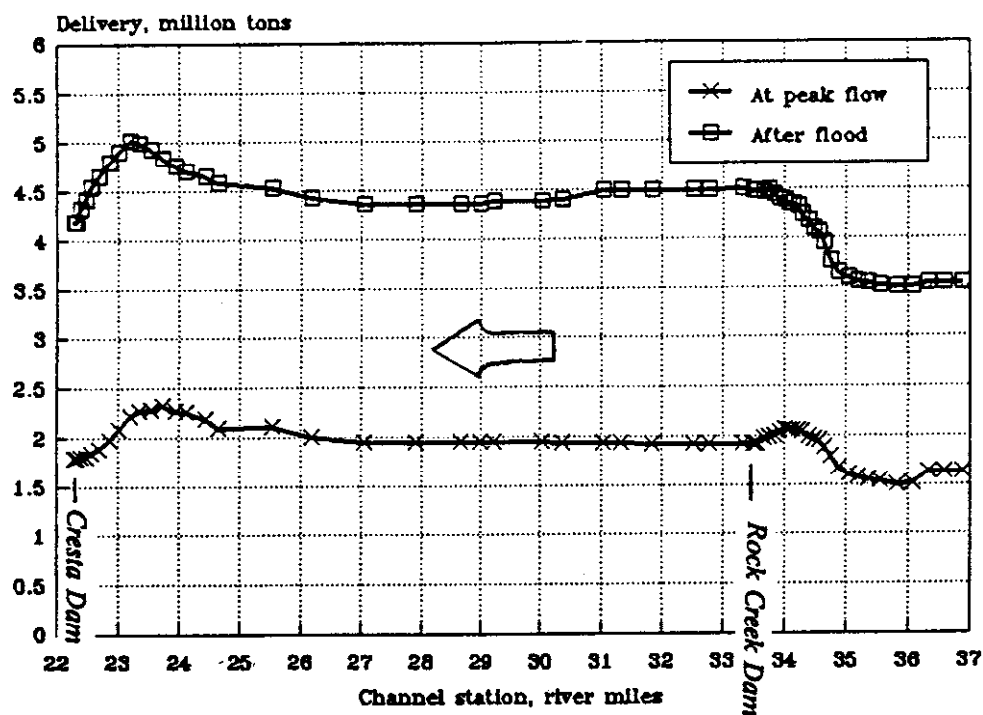


Fig. 4. Simulated spatial variations in sediment delivery based on the Parker formula

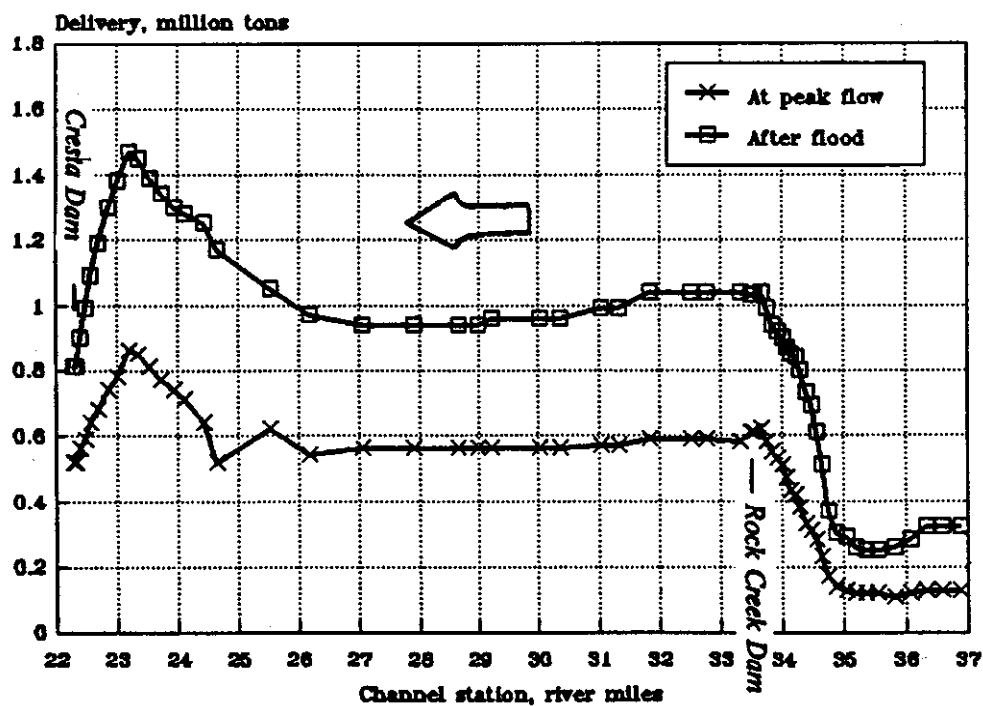


Fig. 5. Simulated spatial variations in sediment delivery based on the Yang formula

Yang, C. T., 1984, Unit Stream Power Equation for Gravel, *J. Hydraul. Eng.*, ASCE, 110(HY12), pp. 1783-1798.

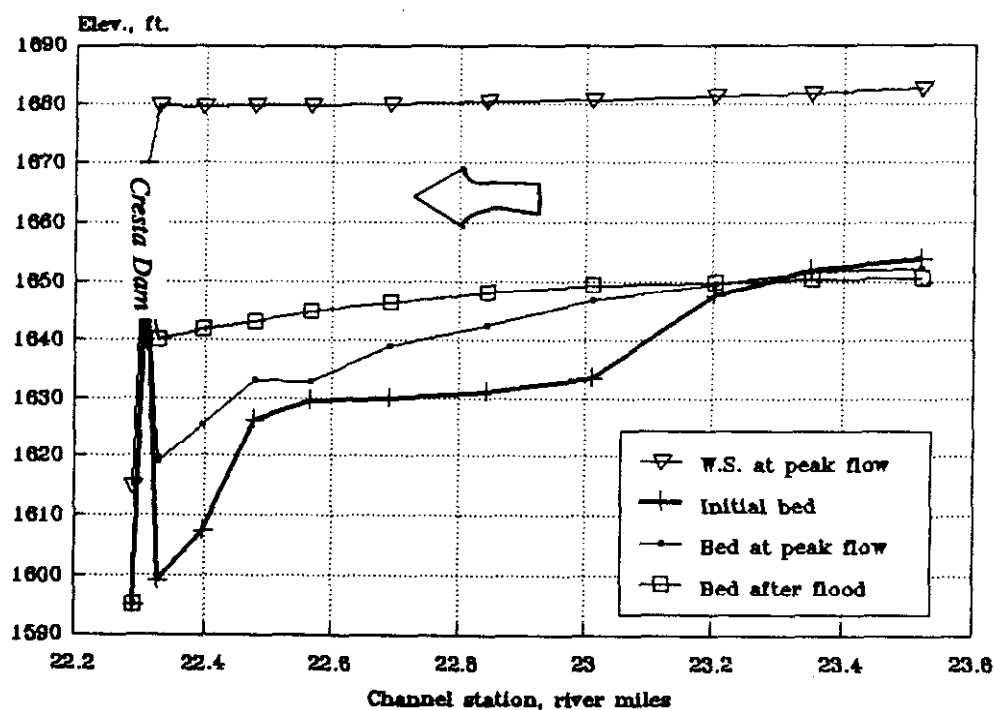


Fig. 6. Simulated changes in longitudinal profiles for Cresta Reservoir

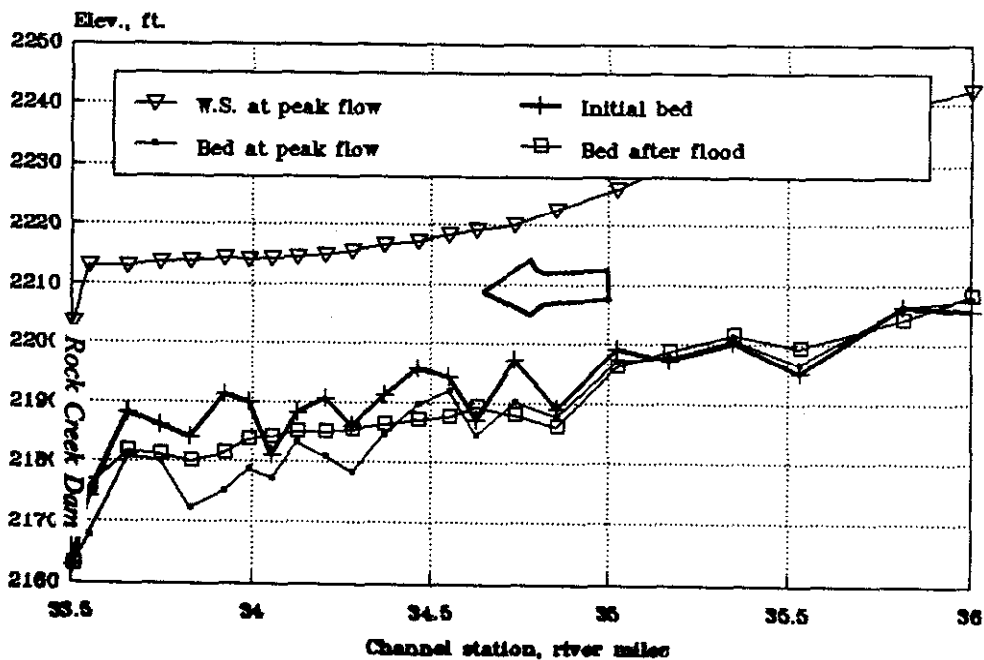


Fig. 7. Simulated changes in longitudinal profiles for Rock Creek Reservoir

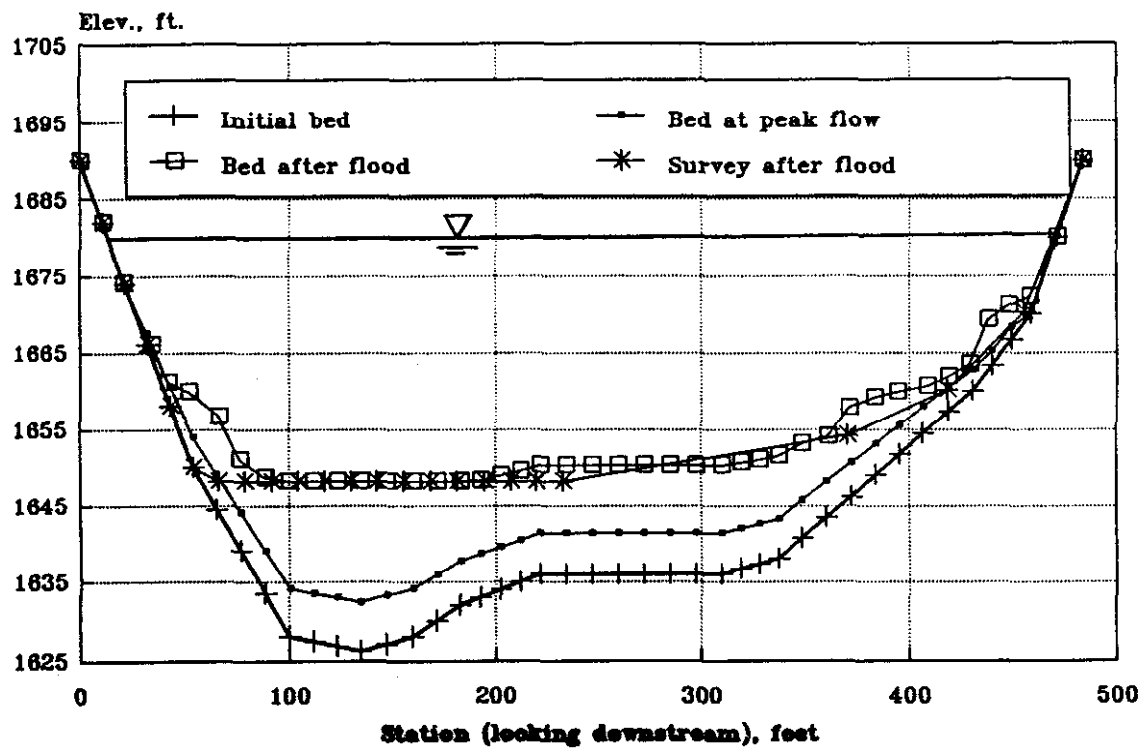


Fig. 8. Simulated and measured cross-sectional changes at Section 22.49, Cresta Reservoir

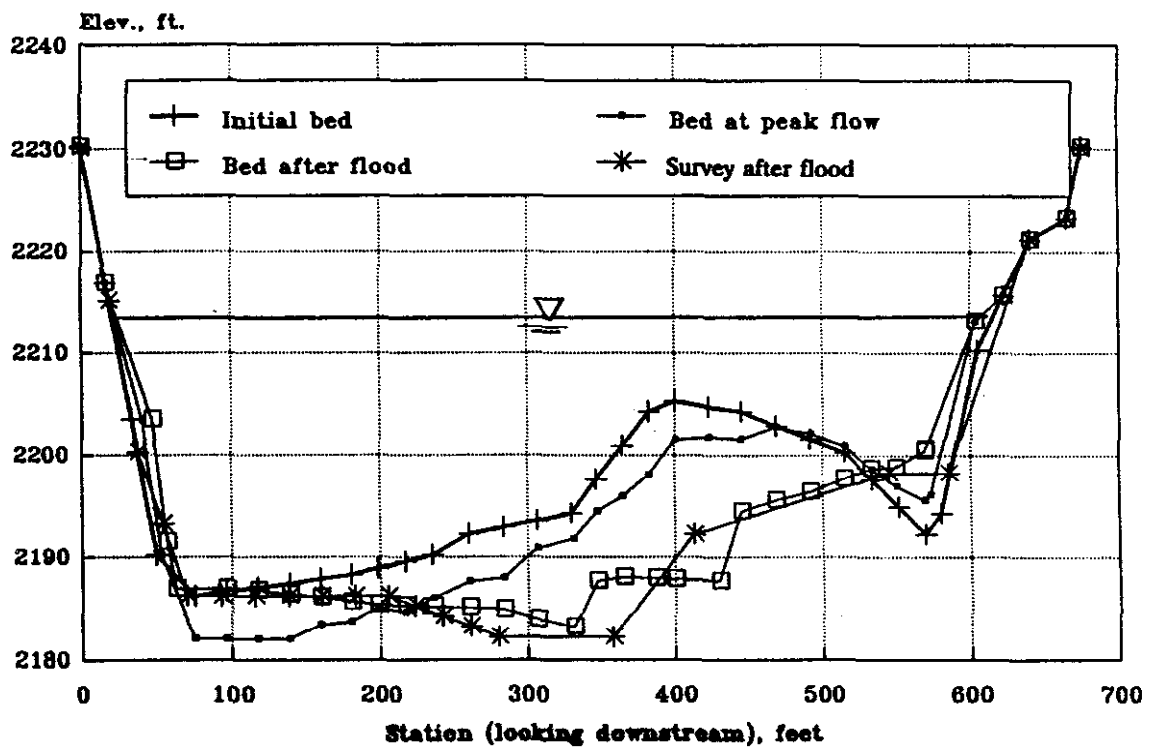


Fig. 9. Simulated and measured cross-sectional changes at Section 33.73, Rock Creek Reservoir

Sediment Delivery Through Cresta Reservoir: During the 1986 flood, changes in Cresta Reservoir were characterized by deposition in the downstream portion within one mile of the dam. The amount of deposition was estimated from survey data to be 700,000 tons of coarse sediment. There was also noticeable erosion in the reservoir above river mile 23.25, related to the drawdown effect when the drum gates were lowered. With the drum gates lowered, the delta at the reservoir entrance experienced higher flow velocity and erosion. The erosion in the delta was measured to be about 247,000 cubic yards (330,000 tons).

The simulated amount of deposition in the reservoir may be obtained directly from the delivery curve based on the drop in delivery from river mile 23.23 to Cresta Dam at river mile 22.3. This value is 320,000 tons based on the MPM formula (see Fig. 3); 900,000 tons based on the Parker formula (see Fig. 4) and 670,000 tons based on the Yang formula (see Fig. 5).

Based on the simulation results for the reservoirs, the Yang formula was found to be the most applicable. This is related to the fact that the Yang formula is unique for being applicable to both sand-bed and gravel-bed streams. The NFFR is a sand-bed river (in the reservoirs) as well as a boulder/cobble-bed river. The MPM and Parker formulae are primarily for gravel-bed streams.

SIMULATED CHANGES IN RIVER/RESERVOIR SYSTEM

With the Yang formula selected for the study, simulated changes in the river/reservoir system are presented as changes in longitudinal and cross-sectional profiles, as shown in Figs. 6 through 9. These changes should reflect the spatial variations in sediment delivery. In each figure for the cross-sectional profile, the surveyed cross section should be compared with the simulated after the flood.

The simulated patterns of scour and fill at these cross sections are also used to demonstrate the complex channel geometry adjustments during floods. In the case of deposition, fill of the reservoir floor tends to build up the reservoir bed level in horizontal layers but the fill is by no means uniform across the channel width. The fill patterns for Sections 22.49 (Fig. 8) depict that the thalweg received greater fill than do the overbank areas. For those sections showing erosional changes, the scour pattern at a cross section is not uniform as exemplified in Fig. 9; they are affected by the geometries of adjacent channel reaches and channel curvature.

The depositional and erosional changes as simulated are consistent with the survey. For this reason, the FLUVIAL-12 model, with calibration made for the Feather River, has been established as a predicative tool for the river and the intended SPT operations.

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NOTES

SALT MOVEMENT THROUGH SEDIMENT RETENTION DAMS IN MANCOS SHALE-DERIVED SOILS

By

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Abstract: Sediment retention dams constructed on Mancos Shale-derived soils in the Cisco Desert of eastern Utah are intended to control salinity loading to the Colorado River. In 1994, soils and sediments in and adjacent to three of these retention dams were analyzed for soluble mineral content (SMC) to determine the dams' effectiveness. Soils and sediments sampled upstream of the dams, within the sediment basins, within the dams, and immediately downstream of the dams indicated limited effectiveness of the structures for controlling salinity in those areas. The sediment basins behind the retention dams are collecting sediments and salts; however, high concentrations of salts downstream of the structures reveal leaching of salts from the sediments through the dams. The retention dam that showed the least increase in salt concentration in downstream soils was filled to capacity with sediment three years after construction and does not allow runoff to pond in the sediment basin. The lack of ponding appears to limit leaching of salts through the retention dam sediments. Retention dams without some type of impervious liner are not recommended for salt control on Mancos Shale-derived soils.

INTRODUCTION

Attempts to control salinity in the Colorado River by reducing sediment and salt yields from public lands predate the Colorado River Basin Salinity Control Act of 1974. Mancos Shale is widely recognized as the largest major source of salinity in the Upper Colorado River Basin (Laronne, 1977) and has been the focus of salinity control efforts on public lands. Sediment retention dams have been used extensively for salt control in Mancos Shale-derived soils, however, reports available since the 1970's have questioned their effectiveness. Laronne (1977), analyzed soluble mineral content (SMC) data from soil samples collected from in and around 2 stock ponds at Leach Creek, Colorado and concluded that; "even artificially retained sediments lose much of their soluble minerals through leaching." Investigations by the Bureau of Land Management (BLM) (1978), indicate that; "retention dams constructed in highly erosive Mancos Shale soils are ineffective in storing salt due to leaching." Johnson (1982), recommended that; "existing sediment retention structures must be examined in order to determine their effectiveness in retaining salts."

In July 1994 a study was initiated to determine the salt retaining effectiveness of three retention dams constructed on Mancos Shale-derived soils in the Cisco Desert of east-central Utah. The retention dams have trapped over 25,700 tons of sediment since their construction in 1985 (USDOI, BLM, 1995, unpublished data), however, efflorescence and high electrical conductivity (EC) readings in the channels downstream of 2 of the 3 dams indicate unusually high concentrations of salts. Soil samples were collected from in and adjacent to the three retention

dams and analyzed for SMC in an effort to determine if salts were leaching from the retention dams.

This paper will describe the results of analyses of SMC in over 200 soil samples representing native soils and sediments collected from in and adjacent to three sediment retention dams. The SMC results will be used to determine the effectiveness of the three retention dams in retaining salts. A recommendation will be made regarding the benefit of retention dams used for salt control on Mancos Shale-derived soils.

DESCRIPTION OF STUDY AREA

The study area consists of three adjacent watersheds located approximately 5 miles northeast of Thompson, Utah, within the Bootlegger Wash East Fork (BWEF) watershed, a tributary to Sagers Wash which is a tributary to the Colorado River. The watersheds lie along the south-facing toe of the Book Cliffs and from west to east are designated as S10, S11, and S12 (Figure 1).

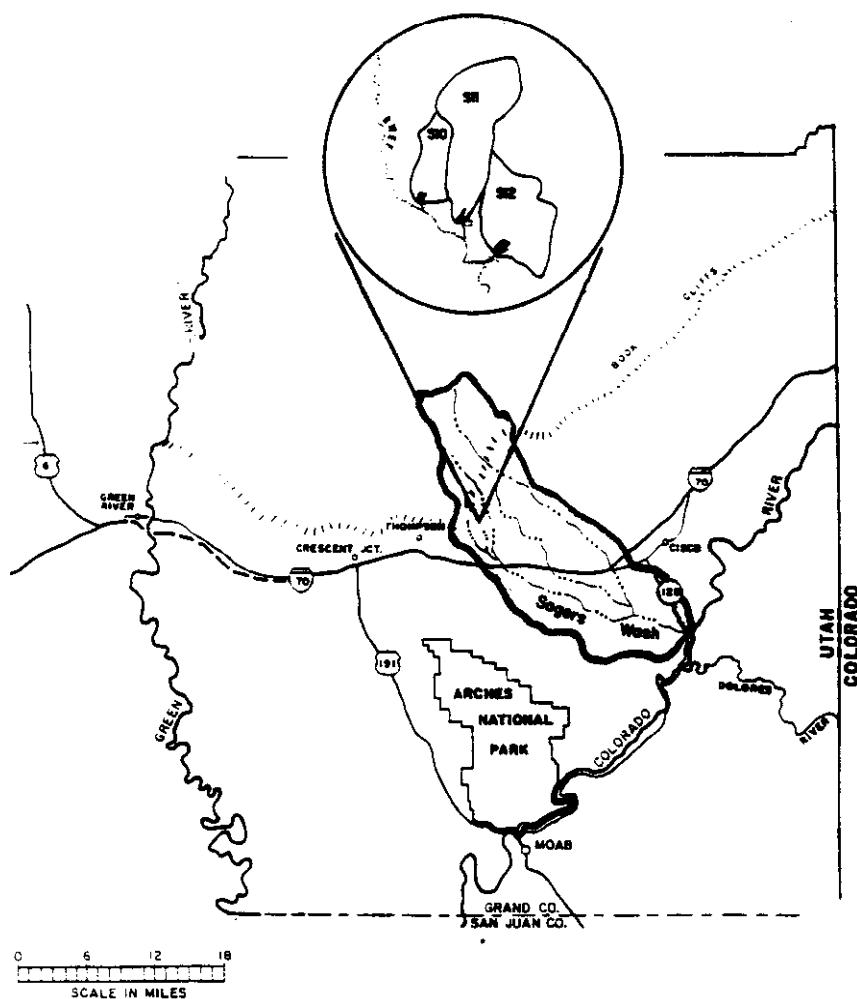


Figure 1.—Location of study area.

Watersheds S10 and S11 originate on the steep Mesaverde sandstone escarpment of the lower Book Cliffs and from there traverse Mancos Shale uplands. The watershed areas are 46 and 130 acres respectively and elevation ranges from 5880 feet to 5150 feet above sea level. Average slope is 9% and 40% respectively. Twenty-two percent of S10 and thirty-eight percent of S11 are classified as a bouldery, silty, clay loam and badland complex soils. Fifty percent of S10 and thirty-nine percent of S11 are classified as fine sandy loam (sandstone and conglomerate derived), silty clay loam (marine shale derived), and gravelly sandy loam (shale and sandstone derived) soils. Watershed S12 lies entirely within the Mancos Shale uplands and has a watershed area of 100 acres. Elevation ranges from 5260 feet to 5120 feet above sea level and the average slope is 8%. Soils are classified primarily as a bouldery, silty, clay loam and badland complex.

Surface soil organic matter content is less than one percent and water erosion hazard is severe for most soils in all three watersheds (Hansen, 1989). Vegetative cover in all three watersheds is sparse with the badlands having essentially no vegetation. The most abundant species include saltbush (*Atriplex* spp.), galleta (*Hilaria jamesii*), and salina wildrye (*Elymus salinus*).

Annual precipitation at Thompson, Utah is 9 inches per year (Ashcroft et al., 1992). A climate station installed one-half mile west of S10 in 1990 recorded an average annual precipitation of 12.6 inches for the period covering 1992, 1993, and 1994 (USDOI, BLM, 1995, unpublished data). The greatest precipitation occurs during August, September, and October in the form of high intensity, short duration, convective thunderstorms that produce high peak flows in the ephemeral washes that drain the study area.

The study area is grazed by sheep and cattle from November through June.

METHODS

Soil samples were collected using a 2.75 inch diameter soil auger and a 3 inch putty knife and stored individually in one-gallon plastic bags. Native soils upstream of each retention dam were sampled from a depth of 0 to 2 inches. Retention dam sediment basin sediments and retention dam soils were sampled from depths of 0 to 2 inches, 2 to 6 inches, 6 inches to 1 foot, 1 foot to 2 feet and every foot thereafter until contact was made with undisturbed native soil. Samples were collected in the stream channel at the downstream toe of each retention dam and, in the stream channel downstream of each retention dam directly upstream of the confluence with BWEF from depths of 0 to 2 inches, 2 to 6 inches, and 6 inches to 1 foot. Samples were collected from depths of 0 to 2 inches in the main channel of BWEF (Figure 2).

Native soils in the three watersheds were intensively divided into 4 groups; 1) Chipeta (clay), 2) badland, 3) pediment, and 4) alluvium, using Hansen's 1989 order 3 soil survey, and Johnson's 1982 landform classification. Percentages of each watershed occupied by each soil group were determined from digitized soils maps that were prepared in the field (Table 1), and samples were collected from each soil group.

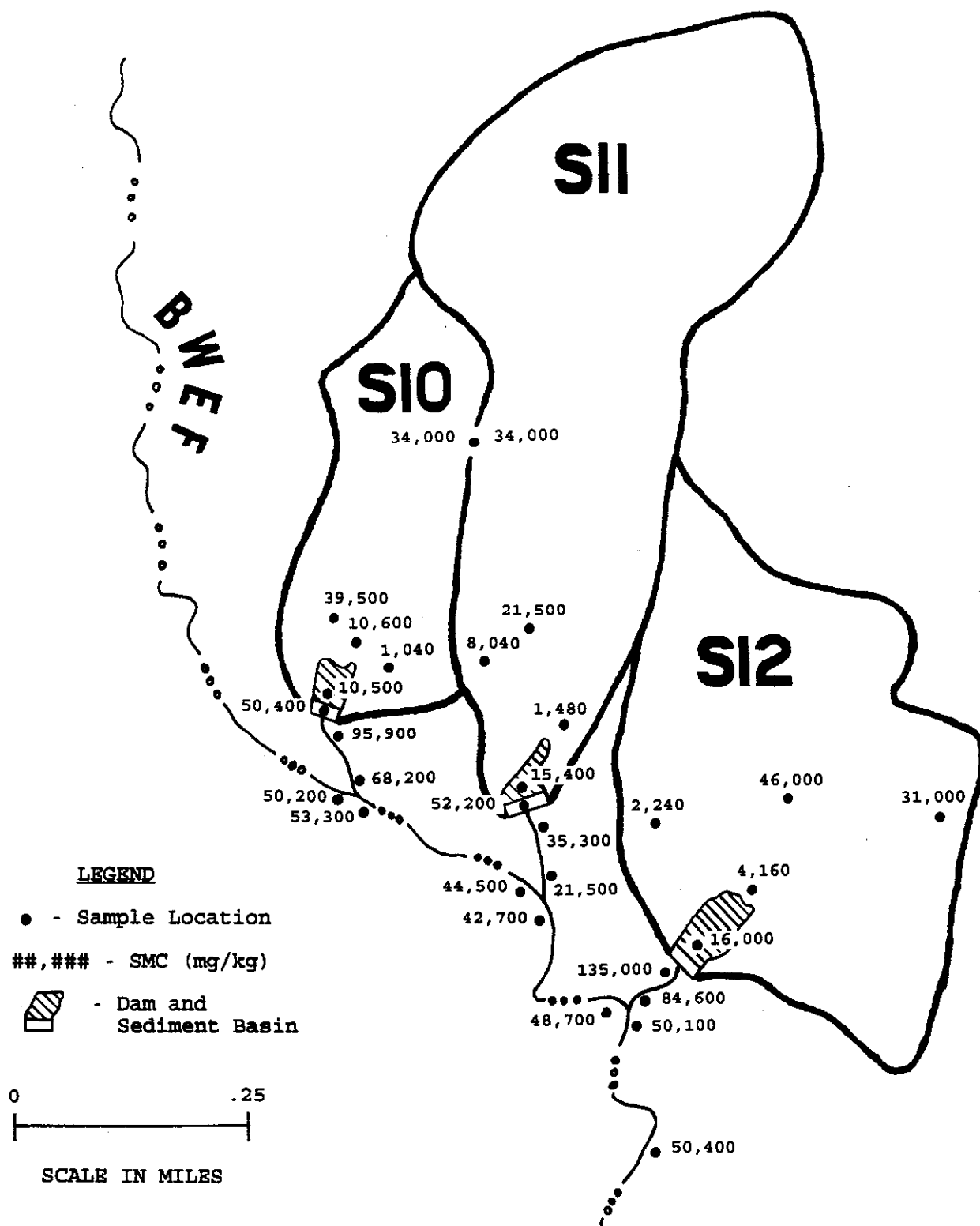


Figure 2.--Locations of soil samples and soluble mineral content (SMC) (mg/kg) for samples collected from 0 to 2 inches depth, and mean weighted SMC (mg/kg) for retention dam sediment basin sediments and retention dam soils in watersheds S10, S11, and S12 and Bootlegger Wash East Fork (BWEF).

Table 1.--Summary of the percentages of S10, S11, and S12 occupied by Chipeta, badland, pediment, and alluvium native soil groups, and soluble mineral content (SMC) of native soil samples.

Native Soil Group	S10 % of Area	S11 % of Area	S12 % of Area	S10 Native Soil SMC (mg/kg)	S11 Native Soil SMC (mg/kg)	S12 Native Soil SMC (mg/kg)	Native Soil Group Mean SMC (mg/kg)	Native Soil Group Mean SMC (%)
Chipeta	44	30	53	39,500	21,500	46,000	35,700	3.6
Badland	22	12	20	34,000	34,000	31,000	33,000	3.3
Pediment	34	58	27	1,040	1,480	2,240	1,590	.16
Alluvium	<1	<1	<1	10,600	8,040	4,160	7,600	.76
TOTAL	100	100	100					

Samples were collected from five individual soil pits in each sediment basin. The five pits were laid out by locating pit #1 in the most likely location of the deepest point in the sediment basin and locating the remaining four pits 25 feet from pit #1 in the directions of the four main compass bearings. Samples were collected from the retention dams in S10 and S11 at a location that would intercept the thalweg of the former channel. Attempts to auger soil pits in the retention dam of S12 were unsuccessful due to a rock ledge that was encountered at a depth of 5 to 6 feet in 3 locations along the dam. Samples were collected from the stream channel at the downstream toe of each retention dam by laying out a cross section perpendicular to the channel which included samples from soils at the top of the stream banks, midway down the streambanks, and in the thalweg of the stream channel.

Soil samples were analyzed by Energy Laboratories, Inc., Casper, Wyoming, using a modified version of the protocol used by Laronne (1977). Soil/deionized water mixtures containing a solid:liquid ratio of 1:20 were tumbled at 30 revolutions per minute for 24 hours. Following the 24 hour extraction period the fluid was extracted from each sample using vacuum filtration and total dissolved solids (TDS) and EC determinations were performed using Environmental Protection Agency (EPA) Methods 160.1 and 120.1 respectively (U.S. EPA, 1979). Duplicate samples of 10% of the total number of samples were analyzed for quality assurance. Regression analysis of soil samples and quality assurance duplicates resulted in an R squared of .99 indicating excellent laboratory analysis repeatability. Copies of the data file containing all analyses results are available from the Bureau of Land Management, Moab District Office, P.O. Box 970, Moab, Utah, 84532.

RESULTS AND DISCUSSION

One hundred and eighty-five soil samples and 19 duplicates were analyzed for SMC. The mean SMC's of native soils collected at a depth of 0 to 2 inches from Chipeta, badland, pediment, and alluvium soil groups are; 35,700 mg/kg, 33,000 mg/kg, 1,590 mg/kg, and 7,600 mg/kg respectively (Table 1). Chipeta and badland soils show a SMC approximately 20 times higher than pediment soils and 4 to 5 times higher than alluvium.

The mean weighted SMC's for the sediments in the retention dam sediment basins of S10, S11, and S12 are 10,500 mg/kg, 15,400 mg/kg, and 16,000 mg/kg respectively (Table 2). Watersheds S10 and S12 have 66% and 73% respectively of their areas occupied by highly saline, highly erosive Chipeta and badland soils and their retention dam basin sediments could be expected to have higher SMC's than those found if all salts were being retained (Table 1). It is unlikely that a significant amount of salt has been discharged through the spillways of S10 and S12 since almost 100% of the runoff events are retained in the sediment basins. Watershed S11 has approximately 58% of its area occupied by non-saline pediment soils that occur primarily on slopes greater than 40% and are therefore susceptible to higher rates of erosion than the pediment soils found in S10 and S12. A high percentage of pediment soils in the sediment basin sediments of S11 would be expected to reduce the SMC relative to S10 and S12. The SMC of the sediment basin sediments in S11 is also influenced by the fact that all runoff events since 1988 have passed through the sediment basin and spillway of S11 transporting salts that would otherwise be deposited in the sediment basin.

The mean weighted SMC for soils in the retention dams of S10 and S11 are; 50,400 mg/kg and 52,200 mg/kg respectively (Table 2). In the retention dam of S10, SMC peaks of 65,200 mg/kg and 64,100 mg/kg occurred at the elevations of the surface of the sediments and the bottom of the sediment basin respectively, indicating possible flow paths for leaching salts. In the retention dam of S11 a SMC peak of 60,200 mg/kg occurred at an elevation approximately 4 feet below the surface of the sediments indicating a possible flow path for leaching salts.

The SMC's of alluvium collected at a depth of 0 to 2 inches in the channel at the downstream toe of the retention dams in S10, S11, and S12 are 95,900 mg/kg, 35,300 mg/kg, and 135,000 mg/kg respectively (Table 2). The SMC's found in S10 and S12, which are 2 times and 3 times respectively the SMC of the most saline native soil or BWEF alluvium (mean SMC of 48,600 mg/kg), indicate unusual concentration of salts. The relatively low SMC in S11 may indicate that 1) the SMC of basin sediments is naturally low, 2) salts are bound up in the retention dam and sediments, 3) the sediment basin is well sealed, and/or 4) the lack of ponding in the sediment basin is prohibiting the apparent leaching seen in S10 and S12.

The SMC's of alluvium collected at a depth of 0 to 2 inches in the stream channel downstream of the retention dams directly upstream of the confluence with BWEF in S10, S11, and S12 are 68,200 mg/kg, 21,500 mg/kg, and 84,600 mg/kg respectively, indicating that salts are moving into the main channel of BWEF from S10 and S12 in greater concentration than salts are moving in the main channel of BWEF from upstream of the study area. The SMC of alluvium in S11, which is the same as the SMC for native Chipeta soils in S11, indicates no unusual concentration of salts moving into the main channel of BWEF from S11.

The SMC of alluvium collected at a depth of 0 to 2 inches in the main channel of BWEF upstream of the confluence with S10 and downstream of the confluence with S12 are 50,200 mg/kg and 50,100 mg/kg respectively (Table 2). The mean SMC for 7 alluvium samples collected in BWEF from a point upstream of the confluence with S10 to a point downstream of the confluence with S12 is 48,600 mg/kg. Comparison of the SMC of samples collected in the main channel of BWEF upstream of the study area and downstream of the study area indicates no significant increase or decrease in SMC as a result of the retention dams constructed in S10, S11, and S12.

Table 2.--Soluble mineral content (SMC), in mg/kg and (%), of soils collected from a depth of 0 to 2 inches at locations starting with native soil groups in the headwaters of S10, S11, and S12 and progressing downstream to the main channel of Bootlegger Wash East Fork (BWEF).

Watershed ID and Native Soil Group	Native Soil Group SMC mg/kg (%)	Retention Dam Sediment Basin Mean Weighted SMC mg/kg (%)	Retention Dam Mean Weighted SMC mg/kg (%)	Downstream Toe of Retention Dam SMC mg/kg (%)	Downstream of Retention Dam, Upstream of BWEF SMC mg/kg (%)	BWEF Upstream of S10, S11, and S12 SMC mg/kg (%)	BWEF Downstream of S10, S11, and S12 SMC mg/kg (%)
S10		10,500 (1.0)	50,400 (5.0)	95,900 (9.6)	68,200 (6.8)	50,200 (5.0)	53,300 (5.3)
Chipeta	39,500 (4.0)						
Badland	34,000 (3.4)						
Pediment	1,040 (0.1)						
Alluvium	10,600 (1.1)						
S11		15,400 (1.5)	62,200 (5.2)	35,300 (3.5)	21,500 (2.2)	44,500 (4.4)	42,700 (4.3)
Chipeta	21,500 (2.2)						
Badland	34,000 (3.4)						
Pediment	1,480 (0.2)						
Alluvium	8,040 (0.8)						
S12		16,000 (1.6)	n/a	135,000 (13.5)	84,600 (8.5)	48,700 (4.9)	50,100 (5.0) 50,400 (5.0)
Chipeta	48,000 (4.8)						
Badland	31,000 (3.1)						
Pediment	2,240 (0.2)						
Alluvium	4,160 (0.4)						

CONCLUSIONS

Three sediment retention dams constructed for salt control in watersheds S10, S11, and S12 of the BWEF watershed have trapped more than 25,700 tons of sediment since 1985. Analysis of SMC in over 200 soil samples collected from in and adjacent to the three retention dams reveals that: 1) the mean SMC of native Chipeta, badland, pediment, and alluvium soils collected from a depth of 0 to 2 inches is 3.6%, 3.3%, .16%, and .76% respectively, 2) the mean weighted SMC of sediment basin sediments in S10, S11, and S12 is 1.0%, 1.5%, and 1.6% respectively, 3) the mean weighted SMC of soils in the retention dams of S10 and S11 is 5.0% and 5.2% respectively, and 4) the SMC of channel alluvium collected from a depth of 0 to 2 inches at the downstream toe of the retention dams in S10, S11, and S12 is 9.6%, 3.5%, and 13.5% respectively, indicating that leaching of salts from sediment basin sediments is occurring in S10 and S12. The sediment basin in S11 was filled to capacity with sediment by 1988 and has not allowed runoff water to pond since then. The apparent limited leaching in S11 is most likely due to the lack of ponding. Comparison of the SMC of samples collected in the main channel of BWEF upstream of the study area and downstream of the study area indicates no significant increase or decrease in SMC as a result of the retention dams constructed in S10, S11, and S12 (Table 2). Retention dams without some type of impervious liner are not recommended for salt control on Mancos Shale-derived soils.

ACKNOWLEDGMENTS

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