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SECTION 1

DATA AND ITS MANAGEMENT

SEDIMENT MANAGEMENT ON THE MISSISSIPPI

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ABSTRACT

The Mississippi River is the fourth largest drainage basin in the world, has a mean average discharge of 600,000 cfs, and carries in excess of 200,000,000 tons per year of suspended sediment. Managing the downstream movement of this volume of water and sediment in such a way that contributes to the project purposes of flood control and navigation is the real challenge. The science of River Engineering is made difficult by the number and complication of the parameters involved when attempting to define this movement by mathematical terms and physical formula. For this reason, it is very important that the actual river responses which incorporate all parameters be analyzed and that empirical relationships based on proven theory be developed for use in design. This paper uses this approach to develop two reach specific design curves for designing stone dike contraction structures based on the same basic concepts. The first curve is for the Mississippi River and Tributaries 9' draft project (Cairo, Illinois, to Baton Rouge, Louisiana, reach) and relates the width of the main channel to the conveyance ($Ad^{2/3}$) allowed outside of the main channel. The second curve is for the Baton Rouge to Gulf project (Mile 181 to Baton Rouge Reach) and relates to highest point in the navigation channel crossing to the conveyance allowed outside of the main channel. Development of these curves gives the engineer a mathematical way of computing required dike height and length to ensure economical project development.

INTRODUCTION

Purpose and Scope

This report presents empirical relationships between channel conveyance and width or depth which are being used to design stone dikes to efficiently move water and sediment down the Mississippi River in a manner compatible with project purposes. Two design curves using the same basic concepts will be presented. The first curve is being used on the Mississippi River and Tributaries (MR&T) project (9' draft), and the second on the Baton Rouge to the Gulf project (40' increasing to 45' draft). The design curves are river reach specific; however, the concepts are valid to both applications and similar relationships can be developed for any alluvial river system.

Mississippi River General

The Mississippi River, which drains 41% of the continental United States, is the 4th largest drainage basin in the world, has a mean annual discharge of 600,000 cfs, and carries in excess of 200,000,000 tons per year of sediment in suspension past the latitude of Old River, Louisiana. In addition to the suspended load, it is not unusual to observe 5 to 20-foot sand waves moving along the channel bottom. Sand waves as high as 40 feet have been noted. Managing this sediment movement in a way that compliments development of the system for flood control and navigation is the real challenge.

Need for Empirical Study

The science of River Engineering is made difficult by the number and complications of the parameters involved when attempting to define the movement of water and sediment with mathematical terms and physical formula. Physical model studies give useful design guidance, and good progress is being made in developing improved two- and three-dimension mathematical models. However, physical models are very expensive; and the varying physical parameters effecting the movement of water and sediment downstream along different geometric alignments through various soils with innumerable combinations of hydrographs make this a very difficult problem to define with precise mathematics. For these reasons, when designing river control works, it is imperative that the river itself be analyzed and empirical relationships developed for use in design. It should be noted that the results observed on the river do in fact incorporate all variables to an infinite degree. These empirical relationships represent valid engineering theory and can be explained using classical hydraulic formulas and observed river responses. As already noted, the specific empirical relationships developed for the Mississippi River are not directly transferable to other systems; however, the concepts and relationships can be used to develop similar data for use in design of other projects.

CONVEYANCE

Definition

For the purpose of this analysis conveyance will be defined as $Ad^{2/3}$ below a flowline equal to the Low Water Reference Plane (LWRP) +25' to +30' (depending upon reach location) where A is the area of the section or subsection and d is the depth. LWRP+25' to +30' was selected as approximately a bankfull elevation which represents a discharge with the most dominant channel shaping characteristics. This selection is reinforced by previous conveyance studies by Anding (1970), which showed consistency in conveyance between bendways and crossings for this discharge and sediment studies by Biedenharn (1987) which show that a preponderance of the total sediment is transported by bankfull or below stages. The term "$Ad^{2/3}$" is easily derived from Manning's flow formula which is classically written as:

$$V = \frac{1.486}{n} R^{2/3} S^{1/2}$$

V = Velocity
n = roughness
R = Hydraulic Radius
S = Slope

By substituting into and adjusting this formula for large river sections it is typically written as:

$$Q = \frac{1.486}{n} Ad^{2/3} S^{1/2}$$

Q = Discharge
A = Area
d = Depth

For our analysis the slope can be considered constant and the roughness is essentially the same for all subsections between the top bank control. Therefore, Q is essentially proportional to $Ad^{2/3}$ (conveyance).

Varying Discharge - Conveyance Consistency

The above definition shows that for a constant discharge (water and sediment) the conveyance would equalize for all sections. However, discharge is never constant on an alluvial river system and at any instantaneous point in time each section is scouring or filling subject to previous experienced and ongoing hydrographs. Figure 1 (Anding 1970) depicts this continuous scour and fill. This figure plots average sediment discharge against water discharge for several meandering (bendways) and straight (crossing) reaches on the Mississippi River. This figure shows that for a water discharge of 1,000,000 cfs, the average meandering reach transports approximately twice as much sediment as the average straight reach, indicating scouring in the bendway and filling in the crossing. The exact opposite is true for a discharge of 300,000 cfs.

This data has also been confirmed by actual field surveys taken during high water on the Mississippi River which shows bendways scouring as much as 60 feet during the high flow and then refilling to their original elevation as low water approached. Comparable magnitude of fill at crossings during high flow and later scour during the falling river stages have been recorded. This continuous scour/fill relationship is why the measured total conveyance for a given discharge is not equal at all individual sections along any given reach at one point in time. Simply stated the conveyance at each section is attempting to equalize; however, the scouring or filling never has time to adjust to conditions as imposed by the previously experienced and the continually changing hydrographs. Even though this variation occurs at individual sections, studies of dredging, non-dredging, sinuous, and straight reaches over a period of time spanning 24 years of record show a very consistent mean reach conveyance for all reaches over time as shown in Figure 2 (less than 15% deviation).

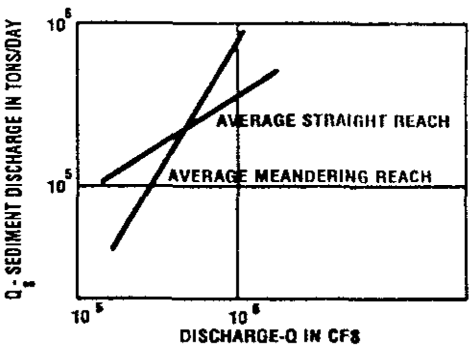


Figure 1
Sediment/Water Discharge

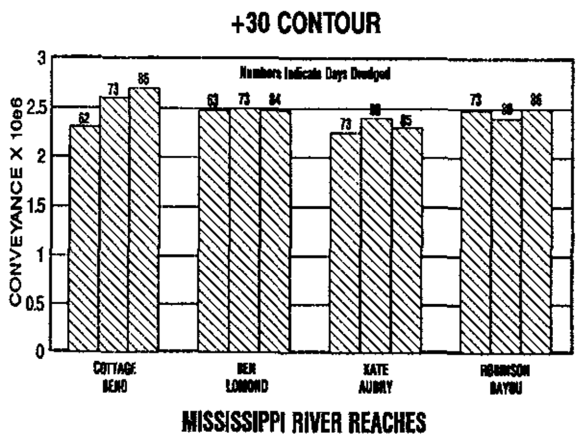


Figure 2
Total Channel Conveyance

This consistency shows that Q is essentially proportioned to conveyance considering mean reach conveyance as related to mean discharge and supports the concept that if given time to equalize for a given flow, all sections would become proportional. Field observation also shows that the preponderance of the perpetual scouring and filling at individual sections tends to occur in the main channel areas and that the fringe areas of the channel tend to be less dynamic. By analyzing these fringe areas (outside a predetermined main channel width) and recognizing that the mean conveyance for the mean discharge remaining essentially constant, an empirical relationship can be developed to show how much conveyance can be allowed in these areas and still insure that the fill cycle for any given section does not exceed the required elevation in the navigation channel to insure maintenance free navigation.

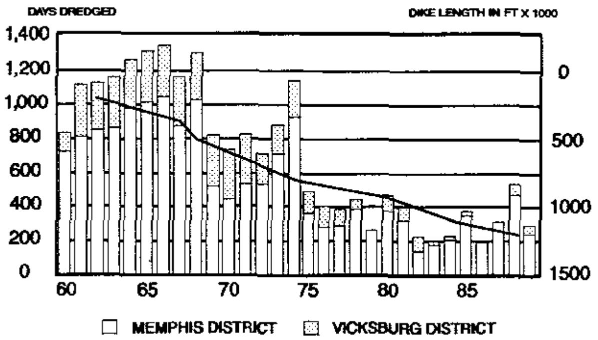
MR&T DESIGN CURVE

General

The first example of successfully using this conveyance approach in the format shown is on the Channel Improvement Feature of the MR&T project, which provides for stabilizing the Mississippi River from Cairo, Illinois, to the Head of Passes, Louisiana, along a satisfactory alignment to protect the flood control system and provide dependable, economical navigation. One of the major components for construction of this feature are stone dikes which are typically used in crossings and straight reaches to control channel width and alignment to reduce or prevent periodic maintenance dredging. Least cost analysis of dredging problem areas show that it is almost always cost effective to prevent the maintenance dredging with dike construction. The effectiveness of this feature is demonstrated by an analysis of dredging and dike construction date which shows a direct relationship between the length of dike constructed and the nuumber of days dredged per year (see Figure 3). As dike construction increased, dredging decreased proportionately. Historically, most of the work on this feature was to control the overall general channel alignment. However, in recent years as the dike program approached 70% completion, additional refinement in design was needed to more directly address areas which continued to have persistent dredging problems. The best data available to develop this refined design procedure was believed to be the river itself. There were numerous reaches where extensive dredging was required until dikes were constructed and now never required maintenance dredging along with reaches with dikes where dredge persisted. As a result, the subsequent design curve was developed.

Section Control and Channel Layout

The engineer has only three ways of controlling the navigation channel depth without dredging. The first way is through overall alignment of the main channel. Under ideal conditions with the proper alignment, sinuosity adequate depth can be maintained by stabilizing the banklines with revetments and no or only minimal dike construction. However, for obvious reasons, the ideal alignment cannot always be maintained and in these instances, the only other two controls available is the width of the main channel and the height of the dikes used to control this width. By controlling these two parameters, the conveyance outside of the main channel can be limited to the extent required to ensure a 9-foot navigable depth over the highest point in the 300-foot navigation channel as shown on Figure 4. To develop this empirical relationship, a total of 65 cross-sections out of 42 separate reaches were analyzed. Thirty-one of these reaches contained dikes and required no maintenance dredging, while 11 contained dikes but still required dredging.



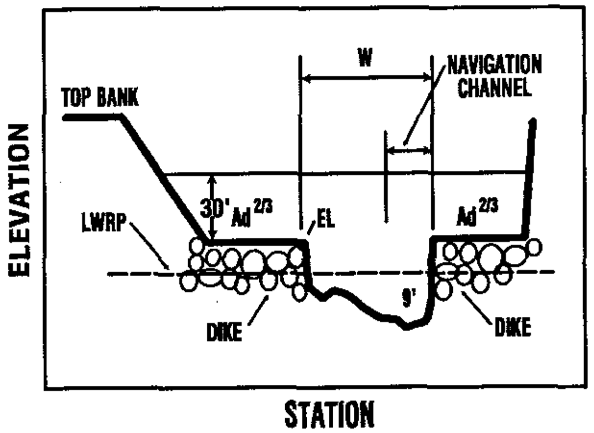


Figure 3
Dredging/Dike Construction

Figure 4
Typical Section

Depth/Conveyance

Using the 65 cross-sections discussed above, the conveyance ($Ad^{2/3}$) outside of the main channel above the top of dikes and below an elevation of LWRP+30' (approximately bankfull stage) was computed. This conveyance was then plotted against the width of the main channel as shown on Figure 5. Sections located where maintenance dredging is required were

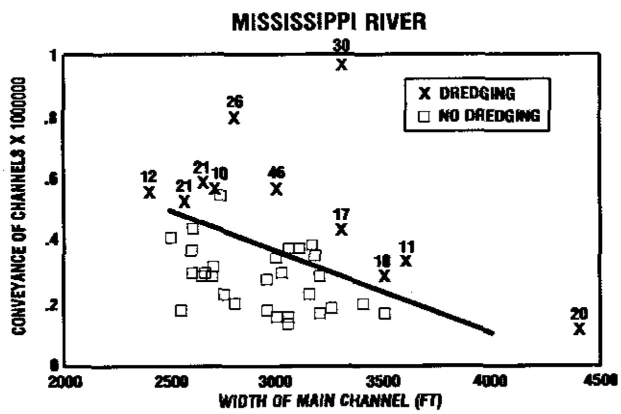


Figure 5
MR&T Design Curve

plotted with X's and those where no maintenance is required are plotted as squares. By comparing the plots, it becomes obvious that two distinct groupings emerge with the areas where maintenance dredging is required having considerably more conveyance outside the main channel for a given main channel width. The line of separation between these data becomes a design line whereby one can determine the conveyance which can be allowed outside the main channel for a given main channel width. For example, for a channel width of 3,000', a conveyance of 380,000 can be allowed outside of the main channel before maintenance dredging would be expected. Using this line, the elevation of the top of stone in the dikes can be determined to appropriately control conveyance.

BATON ROUGE TO GULF DESIGN CURVE

General

The second example of using this conveyance approach is on the Baton Rouge to Gulf project. This project provides a 500' wide with 40' draft channel, which is now being deepened to 45'. The curve developed for the MR&T project is not applicable for designs in the reach; however, the design concepts are still valid. Instead of using width between dikes (no dikes previously constructed in this reach), the width was established and conveyance was plotted against depth. The idea is to determine how the conveyance must be reduced in order to gain specific depth.

Section Control and Channel Layout

The same basic controls are available for this project as were available for the MR&T project. For example, by establishing the main channel width and dike height the conveyance outside of the main channel can be controlled to the extent required to insure navigable depth over the highest point in the 500-foot navigation channels. To develop this empirical relationship between this outside conveyance and available navigation depth 17 crossings were selected and analyzed. Nine of these crossings required no maintenance dredging for the 40 or 45-foot project. On the comprehensive survey of the crossings a 2,000 foot main channel and the 500-foot navigation channel was defined as shown on Figure 6. The 500-foot wide navigation channel is established by law and the 2,000-foot

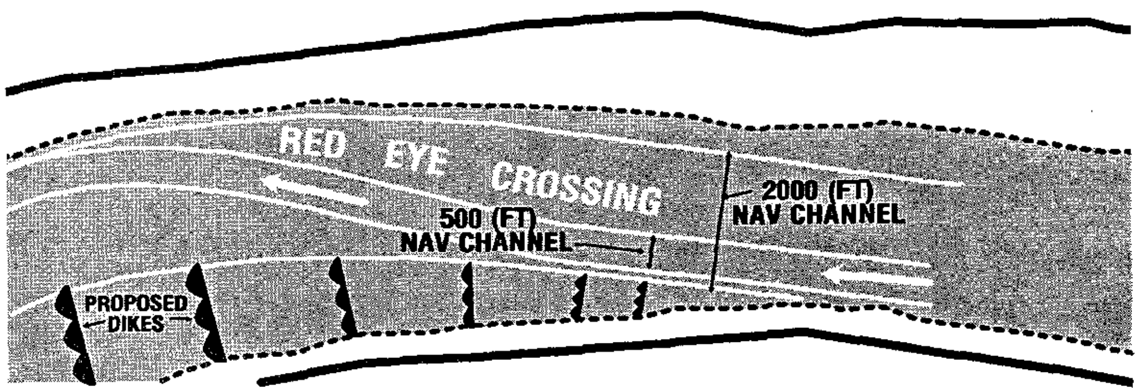


Figure 6
45' Channel Plan

main channel width was selected as being representative of other existing top bank control crossings where no maintenance dredging has been required for the 40-foot project and would not be expected for a 45 to 55 foot project.

Depth/Conveyance

Using the layouts for the 17 crossings discussed above a typical section generally through the highest point for the crossing in the 500-foot navigation channel was selected. From this section the conveyance ($Ad^{2/3}$) outside of the main channel below an elevation of LWRP+25' (approximately topbank) as previously defined was computed. This conveyance was then plotted against the highest point in the crossing taken from the most recent comprehensive survey within the defined 500-foot navigation channel as shown on Figure 7. Sites which have or are expected to have maintenance dredging are shown as solid squares and sites where no maintenance dredging has occurred or is expected to occur are shown as open squares.

A statistical analysis using least squares was then used to develop the heavy line which represents the average data for the 17 points. However, for the purpose of design, average values should not be used since for this condition depth would be unavailable for 50 percent of the locations. Therefore, a band was developed which encompasses a preponderance of the data and the safe side of the bend was selected as the design curve. For example, if a 40-foot deep navigation channel is desired, the conveyance outside of the main channel must be no more than approximately 400,000. Likewise, if a 45-foot deep navigation channel is desired the conveyance outside of the main channel must be no more then

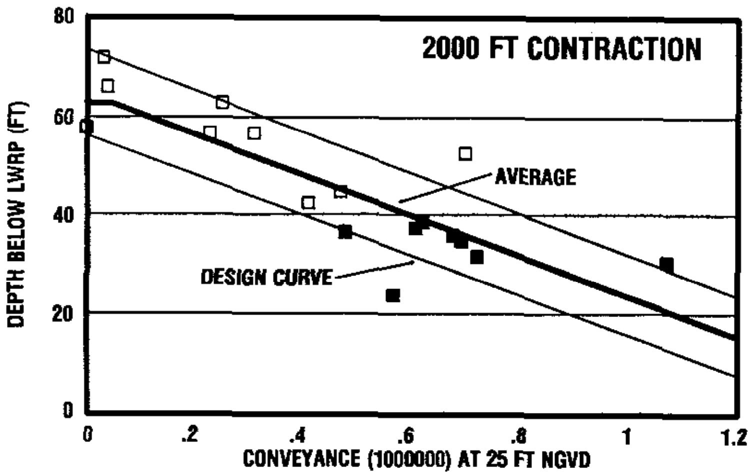


Figure 7
Baton Rouge to Gulf Design Curve

approximately 300,000. As an additional check for consistency of data, it is interesting to note that by using the design curve for a 40 foot required depth all of the sites which require maintenance dredging fell to the right of the line, indicating too much conveyance outside of the main channel. The same analysis using the average data line shows 4 sites on each side of the line, confirming the 50 percent condition previously discussed for the average conditions. With the development of this curve, stone dikes can be located in plan at a problem crossing as shown in Figure 6 and the top of stone elevation computed to obtain the desired conveyance over the dike.

SUMMARY

This paper presents some of the problems associated with developing design formula and criteria for moving large volumes of water and sediment downstream in a manner consistent with project purposes. The importance of analyzing actual river responses which incorporate all variables is stressed. Two empirically developed design curves which are currently being used on the Mississippi River are presented. These curves give the designer a way to mathematically compute dike height and length. As previously noted, these design curves are reach specific; however, the concepts and relationships developed can be used to develop similar design curves for other alluvial river systems.

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A MANAGEMENT STRATEGY FOR SEDIMENT STATIONS

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ABSTRACT

The Water Resources Branch of Environment Canada is implementing a Station Management and Information System (SMIS) for its sediment monitoring activities. This management strategy is designed to improve documentation of objectives and decisions, to assure that correct amounts of data and correct types are being collected and to increase staff commitment at all levels. The system being implemented links station objectives, annual data review required to set field instructions, and an array of data analysis strategies.

This management strategy presents a major implementation challenge in providing training, designing forms, developing software, testing prototypes and convincing staff to establish the correct procedures and utilize the approach. Where successfully implemented, this strategy has brought improved order, more effective sampling designs, improved staff commitment and an increasing base of interpreted data.

A further benefit of this strategy will be the ability to manage the sediment program as a network. Knowledge of why and how the network is functioning, and of the value of its output will enable management to respond quickly and proactively to new demands. In the rapidly evolving need for new environmental monitoring approaches, such as ability will be an assessment.

INTRODUCTION

The Water Resources Branch of Environment Canada has the federal responsibility for monitoring fluvial sediment transport. Its traditional approach to this responsibility has been to operate sediment data collection as an adjunct to the hydrometric program. Typically, the active sediment 'network' has been between 1/10 to 1/15th the size of the hydrometric network.

Operational planning for sediment monitoring is framed around ongoing hydrometric activities. Sediment data are collected only at hydrometric sites and by the hydrometric technicians. While this approach has permitted sediment work to build upon the logistical framework of the larger program, it has resulted in a number of problems as well.

During a national review of the Branch's sediment program numerous problems identified were: missing or unclear station objectives; station records with either too much or too little data; incomplete records of decisions; non-objective decision making; limited staff commitment at all levels; little sensitivity of sampling design to site conditions; and, virtually no interpretation of data. While some of these problems arose from the sediment program's close, but secondary, association with the hydrometric program, others related to the objective to collect endless sediment records and to approach each project need in this same manner.

At a time when data collection activities face major challenges such as, resource restraint, increasing demand for more and even new data types, and a rapidly increasing demand for information, these concerns had to be quickly and effectively addressed.

STATION MANAGEMENT STRATEGY

Design Considerations

In designing a solution to these concerns certain criteria were established: (1) a sytematic approach was required to link activities from objective setting through the field activities to the data analyses and decision making on sampling design and station life; (2) procedures had to be short, readily understood and as standard as possible; (3) forms had to be easily updated; (4) all decisions relating to sampling had to be recorded; (5) clear instructions had to be provided to field staff; and, (6) the design had to complement existing Branch files and procedures.

Station Management and Information System (SMIS)

The resulting station management strategy provides a comprehensive framework for the sediment activities and its information content (whether decisions or data analyses). This strategy (SMIS) is composed of several elements and is directly linked to the Branch's normal work planning cycle, its Quality Assurance Program and the array of files (e.g. correspondence) which support both the hydrometric and sediment programs. The SMIS links sediment activities to its parent hydrometric program and the inventory activities of the Branch hydrology program.

The elements of the SMIS are laid out in Figure 1. Briefly these are:

- Hydrometric Station Profiles which provide information on hydrometric program objectives, users, main station highlights.

- Sediment Station Profiles which provide similar information as above but for the sediment aspects of the hydrometric station only.

- Station Management Plans (SMP) which are an annual technical review of the results of the field program against the station objectives. Decisions are recorded and field instructions prepared.

- Sediment Station Analysis reports are prepared after the SMP process indicates termination of the station is appropriate or when the data need to be fully analyzed for an immediate application.

- Basin/River Analysis reports are prepared when there is an interest in sediment transport through a river basin.

- Network Plans and Program Overviews are to be prepared for either a network or portion thereof. The SMP provides much of the basic information on existing and discontinued stations for such regional exercises.

The profiles provide a basic inventory which is updated either as objectives change or significant events occur. The station management plans are the key

SMIS element and are discussed in detail below. Various data analyses reports have been completed, for example: for single stations on the Highwood River in Alberta (Day and Spitzer, 1984) and the South Saskatchewan River in Saskatchewan (HARDY BBT, 1989); for basins such as the Saskatchewan (Ashmore, 1986) and the Milk River (Spitzer 1987); and for regional networks such as in Manitoba (Yuzyk and Penner, 1988).

Station Management Plans (SMP)

SMP forms the core of the network management strategy. The annual data review and assessment process permits the Branch to keep close track of each sediment station. This element is best suited for our miscellaneous sampling programs where the Branch collects samples over a period of years to sufficiently cover the range of annual and seasonal flow characteristics. Generally, depending upon the complexity of the transport characteristics and the representativity of the period of record to the long flow record, 30-60 samples will be sufficient. The SMP process also assists in maintaining existing long-term data records by focusing sampling attention on data gaps and on extreme events.

The basis of the SMP is the establishment of an acceptable rating relationship between suspended-sediment concentration and water discharge. The annual review process focuses field activities on extending or filling in gaps in the relationship, in much the same manner as the stage-discharge curves are developed. To evaluate representativity of the concentration and particle size data, these samples are checked against flow (annual and seasonal series) in order to ensure good coverage.

The SMP 'file' is composed of one page of objectives and station descriptive information, a second page containing the annual summary of the field program (each new year's page is added to the file), a historical summary page which sets the overall context for the SMP and identifies record gaps, an instruction page for field sampling (a copy is given to the field technicians) which contains room for an evaluation of success in delivering the instructed sampling, and a series of annually updated tables and graphs required to make the appropriate assessment.

The SMP is supported by a number of simple graphics including: concentration-discharge relationships; flow-duration curves; particle size data for suspended and bed sediments; discharge hydrographs; and flow frequencies. Simple tabular records are also kept.

The process was designed to be managed by the Branch's Regional Engineer (who directly supervises the hydrometric technicians) using the input of the field technicians. In this way the technicians are familiar with the purpose of the sampling, are able to provide input based upon their site knowledge, and are part of the planning and decision making process.

The SMP process, in following these simple procedures, provides a first level of data interpretation, which can then be expanded for various reports.

Furthermore, this process provides technical staff with an opportunity to participate in sampling strategy design. This involvement aids in developing a sense of ownership. It also requires a greater understanding of river behaviour and sediment transport. This knowledge in turn, will make technicians more effective in recognizing the significant of site conditions.

IMPLEMENTATION ASPECTS

In actuality the SMIS evolved from a series of separate initiatives as the Branch sought to address its concerns. First, station analysis reports were prepared for several key long-term data sets ($\geq$20 years). These studies were undertaken either by professional staff or contractors. Second, station objectives and details were documented on the profiles.

The SMP process was built on our experiences from the first two steps. The annual data review which forms the basis of the SMP, in fact, was developed as part of the single station analysis. Implementation of the SMP process required considerable effort. Standard forms and graphs had to be developed. Prototypes had to be developed and tested. Training on the SMP process and on sediment transport had to be designed for both engineers and technicians - formal packages are now being developed. Also custom-designed computer software had to be developed for the graphics and for computing sediment loadings using rating curves.

For the SMP to be accepted by the technicians they had to be made comfortable with a completely new process, involving data analysis and sampling design. Training is very important when implementing such a new process which requires staff to think more aggressively and to be more involved with the program management process. Hands on training approaches have proven to be the most successful. Emphasis on involving technicians remains a continuing objective in making the SMP process successful. Bringing their knowledge of site conditions into sampling design decisions has greatly improved station management.

BENEFITS AND SUMMARY

The implementation of the SMIS is giving the Branch an incrementally strengthening to its control on station activities and information output. Field sampling is now better targeted hence saving effort or at least ensuring that correct sampling is being done. There is also a growing base of interpreted data to meet today's diverse needs. Tight control of objective setting and documentation of changes in objectives is now becoming routine. In reality however, it is proving necessary to constantly reinforce the need for this management strategy. Implementing such a change during a period of restraint has proven to be especially difficult. At the same time, however, the SMIS is particularly valuable during restraint as it forces managers to question program objectives and to make program management more accountable.

An improved awareness of the sediment program, in terms of its potential contributions and its management needs, is a major gain from this strategy. An attitude change in both managers and staff has arisen from this new awareness, and the program has benefited accordingly. The technical staff, for example, have developed a new sense of expectation and control. This new level of responsibility is proving to be a good motivator.

This strategy also offers the Branch an opportunity to manage its sediment data collection activities as a network. The new control on operations, and the knowledge of what the data can tell managers about the status of the network and about sediment movement in rivers, provide the basis for good decision making. The developing concern for environmental monitoring in particular, is challenging the Branch to develop more flexible responses, to increase and to adapt to activities more quickly and without new resources. The ability to 'flex' a network, and to appreciate the consequences, will be a definite asset.

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FIGURE 1 STATION MANAGEMENT AND INFORMATION SYSTEM

ELEMENT		
1) Profiles	(a) hydrometric	(a) Information
	(b) sediment	(b) Information
2) Management Plan (SMP)	Station #1 · Station #2 · Station #3 · Station #4	Evaluation Planning Quality Control
3) Technical Analyses and Summaries	(a) Single Station Analyses	(a) Analysis and Interpretation for Decisions and Summary
	(b) Basin/River Analysis	(b) Analysis and Interpretation for Decisions and Summary
4) Assessment and Planning	Network Plans and Program Overview	Overview Assessments and Planning

SEDIMENT MONITORING IN THE UNITED STATES

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ABSTRACT

Sediment monitoring and other data-collection activities in the United States during the past 100 years have provided an extensive, but disordered, data base. Until recently, fluvial-sediment programs of the U.S. Geological Survey (USGS) have been limited to the physical characteristics of sediment and its movement. Present concerns about environmental contamination and global change, however, are causing increasing awareness of fluvial sediment as a transport medium for contaminants and as a possible indicator of global-climate change.

A program of sediment monitoring is proposed to enhance the utility of USGS networks, and to provide informaton to meet objectives of a sediment network. The program consists of: (1) sediment monitoring at a subset of selected USGS water-quality-network stations, (2) secondary or supplementary sediment monitoring at stations having specific or unique objectives, and (3) use of existing data sets to increase the value of the sediment-monitoring effort. The proposed program is not a sediment network, but could be the basis for a network if funding permits future increases in the effort.

INTRODUCTION

Sediment-monitoring activities in the United States are in transition. Data collected in the past were used primarily to assess the effect of sediment discharge on the works of humans in the river environment. Today, sediment data are being used for an increasing number of purposes. A variety of scientists, unfamiliar with sediment transport, rely on sediment data to define transport rates of various contaminants sorbed on sediment particles. This increased use of sediment data comes at a time when budget constraints have severely curtailed the collection of sediment data, particularly on a national scale.

The purpose of this paper is to identify the roles that a National sediment network might have--the desired role, which is based on scientific and engineering considerations, and the actual role, which is affected by funding and personnel constraints. The focus is on a national perspective rather than on local areas or regions where specific studies might have specific objectives for the collection of sediment data. This paper examines sediment monitoring and hydrologic networks rather than individual data-collection stations or operational concerns of sediment stations or a network.

The program for the collection of basic sediment records by the U.S. Geological Survey (USGS) commonly has considered local or specific data needs rather than stressing regional or areal variation in sediment-discharge characteristics through time. In contrast, a monitoring effort is, by definition, one that emphasizes observation in time, generally with the purpose of regulation or control of those operations for which the data are being collected. Hydrologic networks, by emphasizing spatial characteristics, are systematic linkings of component sampling stations, through common methods and objectives, into a program that addresses large-scale water-resource problems. Most networks are designed to distinguish temporal as well as spatial variations, and thus include monitoring. Because a sediment network might be a group of stations at which sediment is monitored and managed as a unit, a sediment network ostensibly provides more information than do the individual sampling stations.

"The mission of the U.S. Geological Survey is to assess the quantity and quality of the earth resources of the Nation and to provide information that will assist resource managers and policy makers at the Federal, the State, and the local levels in making sound decisions. Assessment of water-quality conditions and trends is an important part of this overall mission" (Hirsch and others, 1988).

The above passage shows that a role of the USGS is to assess the quality of the Nation's water resource, including the characteristics of fluvial sediment and its movement. The actual role of sediment monitoring in the United States, however, is constrained by funding and personnel limitations, and by evolving, but possibly still insufficient, recognition that sediment data are required to characterize fully the quality of streamflow. Consideration is given, therefore, to how meaningful sediment monitoring might be accomplished with limited resources.

SUMMARY OF SEDIMENT MONITORING IN THE UNITED STATES BY THE USGS

Fluvial-sediment data, mostly for monitoring purposes, are available for numerous stations in the United States. Reasons for collecting these data during the last 100 years have varied considerably, as have the periods represented by the data and the frequency of sampling at the various stations. Thus, the sediment data base is extensive but disordered. Because costs associated with the collection and analysis of daily suspended-sediment samples are large relative to the costs associated with the collection of some other types of hydrologic data, few stream sites in the United States continue to be sampled for sediment on a daily basis.

Previous Sediment-Monitoring Operations

The first systematic sediment-monitoring program in the United States was begun by the USGS in 1889 at sites on the Rio Grande at Embudo, New Mexico, and El Paso, Texas (Glysson, 1989). This experimental work led to the application of sediment monitoring in 1925 of the Colorado River at Grand Canyon, Arizona. Other sampling sites for suspended sediment were established in the Colorado River basin during the following 15 years to aid reservoir-construction activities. A cooperative program between the USGS and the U.S. Soil Erosion Service (now the U.S. Soil Conservation Service) to measure sediment yields in small agricultural basins was begun in 1934. During the next 13 years, other sediment-monitoring programs initiated by the USGS included a total-load study in mountain streams of Idaho, a comprehensive study of sediment transport in the Missouri River basin, and a study of sediment discharges in the Washita River basin of Oklahoma (Love, 1948). After the end of World War II, the number of daily suspended-sediment stations operated by the USGS increased rapidly, reaching a peak of 360 in 1982 (Glysson, 1989); by October 1988, the number had decreased to 126.

A sediment network for the United States was planned by the Federal Interagency River Basin Committee, Subcommittee on Sedimentation, in 1953. The proposed network included daily sampling stations for suspended sediment to generalize sediment yields nationwide. The objectives of the network were limited to identifying physical characteristics of fluvial sediment and its transport to obtain information pertinent to watershed-treatment measures, reservoir design, stream-channel dynamics, and navigation in large waterways (Swenson, 1963). Of the 221 proposed index stations (later increased to 241), 81 were already active; 52 were operated by the USGS and the remaining 29 by the U.S. Army Corps of Engineers (Swenson, 1963). At no time was funding provided to the Subcommittee to begin operation at the other proposed index stations. Rather, decreased funding resulted in 3 fewer active stations by 1963, and only 14 stations are actively operated at present (1990) by the USGS. No further attempt to design and operate a sediment network of national scope has been made since 1953.

Current Sediment-Monitoring Operations

The collection of daily and periodic suspended-sediment data from numerous stations throughout the United States by the USGS is funded through the USGS cooperative program and by other Federal agencies; these stations are subject to being discontinued at any time. These stations are operated for a variety of local, regional, and national purposes, but they are not included in a national network. Because the USGS funds the remaining 14 active daily stations in the national program mentioned above, it is less likely that this funding will be discontinued. These stations, however, were not selected with objectives of a national network. Thus, these stations are unevenly distributed through the country, have not been assessed for representativeness, and do not constitute a national network.

Bedload in most streams of the United States is a small percentage of the total sediment load, but in some streams of the western United States bedload may be one-half or more of the total load (W.W. Emmett, USGS, oral commun., 1990). Funding through the national program, however, is presently unavailable for the collection of bedload data at any site in the United States.

At present, the USGS operates several water-quality networks and is expanding the effort through a program of National Water Quality Assessment (NAWQA). Suspended-sediment samples have been collected routinely from 4 to 12 times per year at stations in the National Stream-Quality Accounting Network (NASQAN) and the Hydrologic Benchmark Network (HBMN). These two USGS hydrologic networks were designed to: (1) assess trends in water quality of major streams of the country and to document the movement of contaminants from the continental United States (NASQAN) (Ficke and Hawkinson, 1975), and (2) understand and document changes in hydrologic characteristics with time in relatively small, unaltered basins (HBMN) (Cobb and Biesecker, 1971). The NASQAN consists of 411 active stations and the HBMN has 58 active stations. The quarterly to monthly sampling schedule tends to emphasize nonflood periods of streamflow. Therefore, insufficient data are collected for the development of flood-based sediment-transport curves or contaminant loads sorbed on sediment. In their present form, therefore, the NASQAN and the HBMN provide limited sediment data, but should not be considered sediment networks.

Proposed Sediment-Monitoring Operations

It is proposed that ultimately a continental-scale monitoring effort or sediment network be considered that is operated cooperatively by the North American nations, principally the United States and Canada. Monitoring or a network could identify the sediment characteristics of North American river systems and help define chemical loads due to sorbed contaminants. The proposed objectives of the program might include: (1) determining sediment sizes and loads of the water resource; (2) determining generalized continental-scale sediment yields, thereby aiding the definition of chemical loads due to sorbed contaminants; (3) preserving the results of onsite measurements and data collection for scientific studies, including the documentation of the effects of basin characteristics on sediment movement and storage; (4) identifing trends or threshold effects due to imposed and natural changes, especially climate change, in watershed character; and (5) measuring the transport of sediment into estuaries or other water bodies of national or international significance. The sizes of watersheds sampled and the frequencies of sampling should be consistent with desired sensitivity and those objectives that appear most important in an area.

Each objective entails different sampling requirements. The length of data collection may vary from a short period, such as several years, to decades. Defining the sediment characteristics at a station might require several years or more of sampling, but the identification of a trend might require decades of data collection. Additionally, there is an interaction between specific objectives and the natural variability of sediment transport at a station in determining the number of samples needed in a given period of time. Defining the general sediment characteristics at a station might require only periodic samples, whereas defining trends for a highly variable system might require daily sampling with additional sampling during periods of stormflow.

It is not at all clear that fixed stations operated for a given period of time are the only sampling mechanism available to meet the above objectives. For example, understanding the transport of sediment through a river reach might benefit by using Lagrangian techniques (as examples see Jobson, 1987; Schoellhamer, 1988) in which a sampling site is moved downstream to assess repeatedly a streamflow parcel.

The objectives of a national sediment program need to include considerations of water quality. The potential importance of definitive sediment monitoring to water-quality studies is demonstrated by consideration of streamflow contaminants having large soil-water distribution coefficients (Table 1). Using β-chlordane as an example (and assuming equilibrium with an organic-matter sediment load of 4.1 percent), the concentration of β-chlordane sorbed on the suspended sediment is about 10,000 times greater than the concentration of β-chlordane dissolved in the water. If the average suspended-sediment concentration of the stream is 1,000 milligrams per liter, the sediment is about 0.1 percent of the water-sediment mixture. Because the sorbed concentration of β-chlordane is 10,000 times greater than is the dissolved concentration, 10 times more β-chlordane is transported on sediment than in solution. It is emphasized that dilution effects and variations in the concentration and type of organic matter in the suspended sediment can affect this calculation (C.T. Chiou, USGS, oral commun., 1990). Nevertheless, it is apparent that failure to account for sorption on sediment might result in as much as a 90-percent underestimation of the

Table 1--Selected soil-water distribution coefficients

Ion	Coefficient[a]	Contaminent	Coefficient[b]
Fe	3×10^5	2,4,4' - PCB	9.8×10^2 [c]
Be	1×10^5	2,5,2' - PCB	1.0×10^4 [d]
Mn	2×10^3 to 4×10^6	p, p' - DDE	4.1×10^4 [d]
Ba	2×10^1 to 1×10^4	β-chlordane	1.0×10^4 [d]
Th	1×10^6	DDT	7.4×10^4 [e]
Zn	3×10^3 to 1×10^4	Methoxychlor	3.7×10^3 [f]

[a] Coefficients from Nyffeler and others, (1984).
[b] Based on organic-material content of sediment of 4.1 percent.
[c] Modified from Chiou and others (1983).
[d] Modified from Oliver and Charlton (1984).
[e] Modified from Pierce and others (1974).
[f] Modified from Karickhoff and others (1979).

fluvial transport of β-chlordane. Similar calculations can be made for the other ions and contaminants listed in Table 1.

Only recently has it been recognized that sediment monitoring might be especially helpful in identifying the effects of global-climate change (Committee on Earth Sciences 1989; Osterkamp and others, 1990). Evidence is mounting that an alteration of global climate might result from the discharge of gases to the atmosphere, and that possibility might lead to changes in surficial processes that are recognizable before climate change is detectable. Earth scientists and managers have long recognized cause and effect among geologic, atmospheric, and hydrologic variables, and a similar awareness is becoming more pronounced in the political arena, where decision-makers need to have reliable data pertaining to effects before reforms concerning anthropogenic causes can be addressed. To gain a workable knowledge of possible responses to global-climate change, fundamental hydrologic information, including fluvial-sediment loads in selected streams, is of major importance.

Sediment information is among those proxy data that have been identified by the Committee on Earth Sciences (1989, p. 10) as descriptors documenting "...the rapid and slow global changes that occurred leading up to and following the extremes of..." Pleistocene glaciations. The consequences of climate change are pertinent to all land areas, but the opportunity to discriminate the effects of change might be greatest in small drainage basins in arid lands and polar areas (Committee on Earth Sciences, 1989). Small drainage basins generally have the advantage of having less variability in climate, biota, and geomorphic features than do larger basins. Climatic controls are generally more dominant in arid and polar areas than in wetter or warmer areas where water available for transport of fluvial sediment is not a limiting factor. The hydrologic responses, even to minor climatic variations, are usually more specific and more prompt in arid lands and periglacial areas than elsewhere. Few streams in arid and semiarid areas of the United States are gaged for streamflow or monitored for sediment discharge, but it is these areas that are prone to the most intense rainfall-runoff floods ever measured in the United States (Costa, 1987). Thus, if climate change is indeed occurring, sediment monitoring in small drainage basins in the arid and semiarid areas of the United States and in high-latitude areas of Canada and Alaska might prove quite beneficial in detecting the climate change.

The above problems need considerable research to identify their importance in meeting network objectives. Under present conditions, however, it is assumed that even modest increases in funding for collection of basic sediment records are unlikely in the short term. Development of a comprehensive sediment network, such as that proposed by the Subcommittee on Sedimentation in 1953, but modified or expanded to include sampling stations and sites in small drainage basins in arid and polar areas, is somewhat unrealistic under prevailing conditions. Hence, decisions concerning future sediment-program activities need to balance the advantages of meeting network or monitoring objectives against limitations in funding. Beyond the objectives previously advanced is the obligation of the USGS to maintain a sediment data base of sufficient quality to meet its responsibilities of monitoring nonpoint-source pollution. A possibility for accomplishing this objective is to use an approach that relies, in part, on data collected for purposes other than maintaining a network.

Swenson (1963) classified water-resource networks into three categories: (1) general water-quality networks, (2) special networks, and (3) support networks. Although based on a different definition for network as used here, this classification might help in developing a sediment-monitoring scheme. The NASQAN and the HBMN are examples of Swenson's general networks--those that apply broadly to the planning, development, operation, and surveillance of water resources. Secondary, or special, networks range in scope from regional to worldwide and address specific goals, such as identification of temporal changes in geomorphic processes and vegetation, variation of acid deposition, or the recognition of possible changes in erosion, fluvial-sediment transport, and storage of sediment due to global warming. Ancillary (support) networks and data bases (1) provide supporting data for a general or secondary network, (2) provide data for a limited-scope objective, or (3) augment the data base of a network although the purpose for sampling is different.

In the absence of a defined sediment network, it is proposed that sediment monitoring be organized in a manner similar to that recognized by Swenson (1963) for water-quality networks. This approach helps minimize the money and effort expended to collect sediment data, can be designed to conform to the previously proposed objectives for a sediment network, and could significantly enhance the utility and credibility of in-place water-quality networks. Dependent on available funding, most monitoring would occur at "general" sampling stations, which would be a subset of stations in the NASQAN and the HBMN; stations included in the sediment subset would be selected to provide geographic, physiographic, and basin-size representativeness consistent with sediment-monitoring objectives as well as the objectives of the water-quality networks. Sediment samples would be collected at frequencies sufficient to meet the sediment-monitoring objectives of the stations.

Remaining resources would be used for "secondary" sampling sites. Secondary monitoring would be in support of or supplementary to the general monitoring, could include sampling stations having specific objectives, would have sampling lengths and frequencies dependent on the intent for the data, and would not be restricted to existing sampling stations of water-quality networks. The overall purpose of the secondary monitoring would be to augument the general monitoring program, regardless of the period required to strengthen the overall data base. As used here, "secondary" refers mostly to secondary funding priorities or terms of sampling. Relative to data from the higher priority general-sampling stations, however, data from secondary stations would be evaluated largely in the same manner, without distinction.

The third component of the sediment-monitoring approach, virtually cost free, would be to incorporate existing data from any validated data base into the evaluations resulting from the current monitoring activity. Obviously, selection of sampling stations for both general and secondary monitoring would be influenced by the quality of this ancillary data base within a given area of interest.

Of critical importance to the development of a sediment-monitoring program or a sediment network is a plan to regulate the activities. Effective management must define sampling stations and objectives, specifically (1) identify candidate stations, including those with records from existing or previous data bases and hydrologic networks; and (2) develop a research and analysis effort, using available and accumulating data-base information, to define future needs for data and sampling-scheme modification. Included in developing a research and analysis effort could be an assessment of the methods used to calculate sediment discharge, identification of sediment-data needs for prevailing flow ranges, and identification of seasonal and annual variations of transport. If possible, data analysis needs to relate sediment transport to changes in land use and bottomland morphology, and to the transport of sorbed contaminants. Data analysis also needs to be used to identify trends. Because a well designed sampling program provides the ability to monitor changes in sediment transport through time, this temporal coverage can describe averages and variabilities, and assessment of human effects on the river system.

The three-component approach to sediment monitoring proposed here could fulfill the five previously identified objectives at little or no increased cost. Monitoring to detect trends indicative of global-climate change might offer the greatest challenge to the proposed program, however, possibly necessitating the collection of various sediment, geomorphic, and hydrologic data. To be indicative of global-climate change, these data need to be sensitive to minor changes in streamflow and sediment discharge, and need to be collected from environmentally sensitive areas having minimal natural climatic and hydrologic variability. Frequent sampling for decades might be necessary to detect trends in sediment discharge resulting from possible global warming.

CONCLUSIONS

Despite an extensive sediment data base accumulated since 1889, changing needs and changing priorities for sediment information have forced sediment-monitoring activities in the United States into a period of transition. Presently, the use of sediment data is shifting from a tradition of measuring the physical character of sediment and its transport to one of identifying chemical loads and trends suggestive of cause and effect. To help affect this transition, changes are required in sampling design that will lead to systematic sediment monitoring, if not a sediment network.

The approach proposed here is to use general and secondary monitoring, enhanced by previously collected data. This approach, however, cannot completely satisfy the proposed objectives for a sediment network; at best, the approach satisfies the needs for transition into a period of changed requirements for sediment information. Under prevailing budget constraints, the approach offers a reasonable alternative to a sediment network while providing essential sediment data for water-quality networks. Perhaps of equal importance, the approach proposed here provides a structure of sediment monitoring from which a network can be developed.

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SEDIMENT MONITORING IN CANADA

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ABSTRACT

Sediment monitoring activities in Canada are evolving to meet an extended agenda. While continuing to address the traditional client needs for water resource applications, this program must now be redesigned to meet these needs more efficiently and to address the growing needs of environmental applications. In a climate of fiscal restraint, growth is difficult. A national program evaluation identified a number of problems which are now being addressed through data interpretation, improved operational management procedures, modifications in network design, better communications and new products to clients. While progress is slow, sufficient strategies, examples and knowledge now exist to successfully drive the evolution of this program.

INTRODUCTION

Sediment monitoring activities in Canada are in transition. As with other federal data collection programs, Environment Canada's sediment monitoring program is evolving to meet new challenges. The most important one is the increasing demand for understanding the significance of fluvial sediments in environmental quality issues such as contaminant transport. A new client group is emerging to deal with this concern and Environment Canada itself now has taken a role in reporting on the health of aquatic systems.

However, as the sediment monitoring program evolves to meet this new challenge it must continue to address its traditional client base in water resource engineering. This group, is itself, demanding more and better service. For example, these clients recognize that simply monitoring transport at selected sites does not provide sufficient answers for all projects. In many cases it is necessary to be concerned about the sources of particular particle sizes, the interaction of transported material and bed forms, and the erosion and deposition patterns along a river system. Also, there are many regions of Canada where little, if nothing is known about fluvial sediments.

The purpose of this paper is to describe the steps taken to 'modernize' the sediment monitoring program of Environment Canada, and to consider its future. The focus presented is a national one. However, success in implementing these modernizing initiatives has proven to be quite variable across the country as regional managers respond according to local needs and priorities.

TRADITIONAL PROGRAM

The Water Survey of Canada's sediment monitoring program originated as an adjunct to their more extensive hydrometric data collection program. It was modelled on the USGS program, using the same equipment, field procedures and computational methods. Stations were established either to provide data for specific engineering projects or to collect long-term data sets for trend analysis. The program began in the early 1960's in central Canada and gradually developed until today there are approximately 250 active stations and 600 discontinued ones. The focus of the initial program, and indeed up to the early 1980's, was the collection of detailed, long-term records of suspended sediment. Output from the program was primarily suspended sediment data (daily concentrations and loads) with some limited bed-material and bed-load data. While the program steadily developed from the 1960's, by the end of next decade it was stagnating as Regional program managers began to seriously question its usefulness.

PROGRAM EVALUATION

Problem Identification

In response to managers' concern for the usefulness of a sediment monitoring program an evaluation project was initiated. It's first task was to identify problems. The key ones were: while successfully responding to standard engineering applications, these data collection activities were ignoring a wide range of environmental applications; limited knowledge of and expertise for assessing the nature and extent of sediment problems in Canada; lack of rigorous procedures for deciding upon station programs and their future; need to complement site specific sediment monitoring data with studies of sediment sources, bedload measurements and morphologic data; and little if any interpretive work existed to guide decision making and to extract information from the more than 800 sites (active and discontinued). After 20 years little was known about suspended sediment transport characteristics in Canada.

Responses

In order to address these problems a series of actions were initiated. There were three key ones. First, a systematic approach to analyzing and interpreting data was developed. This included software development and report strategies for single and multiple stations. Second, a series of contract reports were commissioned to document regional needs for sediment data and information (Church et al., 1985; Conservation Management Systems, 1986; HYDROTECH INC., 1985; Northwest Hydraulic Consultants Ltd., 1985; Washburn and Gillis Associates Ltd., 1985). These reports also contained client survey results, evaluation of current activities and recommendations for improving the program. Third, Regional managers were supported through improved communications and training to their staff.

Program Improvements

Significant improvements have been made in eight program areas. Briefly, these are:

1. Data interpretation is now becoming the basis for operational decisions on station objectives. A growing series of analysis reports is developing. These analyses have permitted program managers, for example, to terminate long-term stations where little new information can be gained, to reactivate stations where insufficient data exists to adequately describe the sediment transport characteristics, to provide clients with interpreted data for single and multiple stations and with generalized characteristics on basin and regional scales. Spitzer and Day (1991) describe the success of this effort in Alberta.

2. Communications with clients is improving primarily through the use of sediment workshops (e.g. Yuzyk, 1987). Brochures and pamphlets are under development. Also, a special report series has been developed and is systematically distributed.

3. Operational management is improving through the implementation of a systematic management and information system. This approach provides documentation of objectives, records of decisions, and a repeatable process for evaluating the data and targeting field sampling programs. A more complete description is given by Herrington et al. (1991).

4. Organizational commitment has been improved through implemention of a national action plan designed to guide the changes in the program, and by special task force exercises (e.g. to investigate linkages between operational and research activities).

5. Diversification of the program is occurring, for example, by initiating a hydraulic and morphologic activity which systematically addresses the need for more information on river behaviour (Northwest Hydraulic Consultants Ltd., 1986). More studies are being added such as McLean and Church's (1986) re-examination of Fraser River (British Columbia) sediment data, and Kellerhals Engineering Services Ltd.'s (1988) study of the morphologic effects of a major river diversion in northern Manitoba.

6. Network character is being rapidly modified. The early emphasis on long-term data sets is now being replaced by a more flexible approach using so-called miscellaneous stations where fewer data are collected for much shorter periods of time. Analyses of long-term data sets have indicated little improvement in information content after about 10 years - depending on the representativity of conditions (e.g. Day 1988). A detailed account of the successful network evolution in Ontario is given by Smith (1991).

7. New products have been developed. These include reformatted annual data publications which now provide all basic as well as computed daily data. A new reference index publication was designed to provide clients with more details on the stations. Also, a special report series was developed to provide a recognized, systematic outlet for interpretive efforts.

8. Linkages with water quality programs are under development. As suspended sediments, in particular, play such an important role in the transport and fate of contaminants, developing a working relationship with Environment Canada's Water Quality Branch is very important. Various approaches have been taken, such as a management report identifying needs (Blachford and Day, 1988), sampling intercomparison studies (Lapointe et al., 1989), cooperative workshops and short-term personnel assignments or exchanges.

These major improvements are supplemented by a range of other efforts which include evaluating the performance of standard field samplers (Lapointe, 1987) and by continued effort to integrate sediment work with the ongoing hydrometric and hydrologic activities of the Water Resources Branch. Reaction of Regional managers has been mixed. With the limited resources available during the federal downsizing programs there is little opportunity to add new expertise, to reassign staff or to find contract funds to undertake analyses.

Progress is made where it can be. However, on a national basis the sediment monitoring program now has the strategies, knowledge and examples required to move it into modern times.

FUTURE DIRECTIONS

What will the future be? Certainly the eight areas of improvement already discussed will continue to be the key areas for effort. Data interpretation remains a priority, not only for its role in annual operational management, but because so much data remains uninterpreted. The new environmental clients prefer interpreted data, the Department expects data programs to contribute to environmental impact assessments and audits, and basically we cannot manage what we do not understand. More emphasis needs to be placed on producing basin (Ashmore and Day, 1988) and regional syntheses (e.g. Dickinson and Green, 1988 and Church et al. 1989).

While the program will continue to be influenced by the standard engineering design objectives, powerful new objectives now exist. The need to respond to issues - primarily environmental quality ones - is starting to shape the network. For example, Ontario's rapid expansion of its' miscellaneous network is primarily in response to the International Joint Commission's interest in documenting sediment-associated contaminant loadings into the Great Lakes (Smith, 1991). This same issue is forcing a partnership with water quality monitoring across Canada, which while still embryonic, will shape many decisions relating to site location, sampling strategies and data types.

The sediment monitoring network in Canada is expected to develop along these strategies:

1. Baseline monitoring where basic types and limited amounts of sediment data (bed, bank, transported) are collected. The miscellaneous sampling strategy is appropriate to meet these needs. Over time the spatial coverage in Canada will improve. This approach will require more planning and evaluation efforts but in return will provide basic data for most engineering and environmental planning requirements. These data will also permit more successful regional and basin analyses to be completed.

2. Project monitoring where special data sets will be collected for specific engineering projects.

3. Integrated monitoring where sediment data collection is linked to, for example, water quality and aquatic ecosystem programs. While the specifics of this strategy are still under development, it is obvious that to meet these needs a system-scale approach is required to understand the source, transfer, fate and effects of sediments in river basins. Sediment data collection will have to be coordinated throughout the basin (sampling strategies, record length), supported by studies such as deposition and re-entrainment, and linked to the environmental variables of concern. This strategy will be very demanding in terms of technical expertise and operational management commitment.

SUMMARY

Sediment monitoring activities of Environment Canada, as in the US (Osterkamp and Parker, 1991) and in New Zealand (Hicks, 1989), have experienced a growth period in the 1960's, followed by stagnation in the next decade. The reasons for this stagnation include resource restrictions, low client demand and a narrow program focus. The steps taken in Canada to correct this problem include more contact with and sensitivity to clients, the introduction of operational management procedures, extensive data interpretation, a change in network style and diversification to provide different data.

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