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A PILOT FOR LONG-TERM MONITORING OF RESOURCES ON THE COLORADO RIVER IN THE GRAND CANYON USING GEOGRAPHIC INFORMATION SYSTEMS

December 1995

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Bureau of Reclamation
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Through the GCES (Glen Canyon Environmental Studies), the Bureau of Reclamation, in cooperation with several other agencies, has been working to determine environmental impacts of Glen Canyon Dam operations on the resources of the Colorado River in the Grand Canyon. A long-term monitoring program has been applied as the optimal methodology to analyze the effects on natural and cultural resources caused by fluctuating flows.

A GIS (Geographic Information System) data base developed to assess the impacts of variable flow rate on Grand Canyon resources serves as an integral component of the GCES. Long-term program objectives have been established through a pilot study at a single monitoring site by defining: data that are available and practical for use in the GCES/GIS; specific resource features to be monitored and temporal increments at which they should be monitored; the agency responsible for data collection and analysis of each feature; specific end products to be developed for each feature; software to access, query, display, and analyze the GCES/GIS. Once these objectives have been defined, they will be applied as the standard and template in the development of other GIS sites.

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UNITED STATES DEPARTMENT OF THE INTERIOR ★ **BUREAU OF RECLAMATION**

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CONTENTS

Page

Introduction 1
Background 2
Objectives 2
The Initial GCES/GIS data base development 3
Study area 3
GCES base map production 4
Survey 6
Aerial photography 6
GCES/GIS data base design 7
The consolidation of information into the GCES/GIS 8
Methodology 9
The development of the long-term monitoring pilot 10
Feature selection 10
Applied research 12
Report No. 1: Using a GIS to monitor sediment resources in the Colorado River, Grand Canyon, Arizona, by M.A. Kaplinski 13
Introduction 13
Methods 13
Flow regimes 15
Results 15
Conclusions 22
Report No. 2: Application of GIS to fisheries data bases in Grand Canyon, by R.A. Valdez and T.R. Hougaard 23
Abstract 23
Introduction 23
Integrated tabular data base 24
Application of GIS 24
Discussion 25
Report No. 3: Historical patterns of vegetation change in Grand Canyon based on a GIS analysis, by G.L. Waring 27
Introduction 27
Objectives 27
Discussion 27
Report No. 4: Development of channel-geometry information for flow and sediment-transport models, by Julia B. Graf, Samuel M.D. Jansen, J. Dungan Smith, and Stephen Wiele 29
Introduction 29
Methodology 29
Initial Results 32
Discussion 32
Conclusion 35
Bibliography 37

FIGURES

Figure

1 GCES/GIS post-dam study area profile 4
2 Location map—GIS monitoring sites . . . . . Attached
3 Plot—pilot site No. 5 and resource study sites . . . . . Attached
4 GCES base map development 5

CONTENTS — CONTINUED

FIGURES — CONTINUED

Figure		Page
5	5- by 5-foot control panel	7
6	GIS topography for site No. 5	Attached
7	Tree diagram of data base structure	8
8	Location map of sandbar study sites	14
9	Colorado River hydrograph	16
10	Contour map of the difference between the April 5, 1993, and April 13, 1993, topographic surveys at the RM62.4 sandbar study site	18
11	Hypsometric data from the RM62.4 sandbar survey site	19
12	Pooled hypsometric data and best-fit third order polynomial	20
13	Distribution of SHCR in wide versus narrow reaches	21
14	Location map of bathymetric survey	30
15	Location map of cross-section networks downstream from the Paria and Little Colorado Rivers	33
16	Location map of model reaches, measured cross sections, and streamflow-gaging stations used in the model study	34

APPENDIXES

Appendix		
A	Site segregation	43
B	GCES information and operating protocol	45
C	GCES/GIS classification scheme	63
D	Class definitions	65

INTRODUCTION

Public concerns regarding the impacts associated with the Glen Canyon Dam operations on the Colorado River environment in the Grand Canyon resulted in a U.S. Department of Interior decision to implement the GCES (Glen Canyon Environmental Studies) in 1982. A critical component of the research effort and the base for long-term monitoring is the development and maintenance of a consolidated and integrated long-term data base and GIS (geographic information system). A previous report entitled, "Developing A Geographic Information System For Resource Monitoring On the Colorado River In The Grand Canyon," discussed and outlined the development process for the GIS effort. In this report, the objective is to explain how the GCES/GIS (Glen Canyon Environmental Studies/Geographic Information System) data base is being used for the long-term monitoring of cultural, natural, and recreational resources on the Colorado River in the Grand Canyon.

The overall objective of the GCES/GIS program is to develop and use a geographically referenced data base as the consolidation vehicle for an integrated, ecosystem-based monitoring program.

Prior to full-scale development of the GCES/GIS data base a pilot study was conducted to determine the data sets, methodologies, and computer protocols best suited for the study.

This report documents the pilot study results and establishes a template to be used for the development of the remaining sites. Development of the GCES/GIS long-term monitoring pilot has been a coordinated effort between the Bureau of Reclamation's Remote Sensing and Geographic Information Group and the Glen Canyon Environmental Studies Group. The GCES Office in Flagstaff, Arizona, provides coordination, geographic control, and verification of information and integration of results. The Technical Service Center (the Remote Sensing and Geographic Information Group) is responsible for program and template development.

The participants in the data collection effort include researchers from the NPS (National Park Service), USGS (U.S. Geological Survey), WAPA (Western Area Power Administration), U.S. Fish and Wildlife Service, Arizona Fish and Game, Western Native American groups, Hopi Tribe, Navajo Nation, Hualapai Tribe, contractors, and academic institutions. The GIS data sets developed by these entities are useful in satisfying their specific analysis, and are also being used as tools by other contributors.

This report will describe and discuss the following:

- The strategy for development of the initial GCES/GIS data base.
  - The production of the base maps
  - The design of the GCES data base
  - The consolidation of information into the GCES/GIS

- The strategy and development of the long-term monitoring pilot study.
  - Feature Selection
  - Applied Research
  - Results

Background

Prior to the construction of Glen Canyon Dam, the ecosystem supported by the Colorado River through the Grand Canyon was dramatically different. The pre-dam Colorado River carried a heavy load of sediment, and seasonal water temperatures ranged from 40 to 80 °F. Annual flooding levels of 100,000 or more cubic feet per second (ft^3/s) scoured and redeposited sediment throughout the Canyon.

Post-dam water flows from the depths of Lake Powell were relieved of their sediment load upstream and cooled to a relatively constant 46 °F. The dam-controlled flow rate varies from an average minimum of 5,000 ft^3/s to an average maximum of 30,000 ft^3/s in response to daily hydropower demands.

In 1982, in reaction to public and scientific concerns about the impact of the Glen Canyon Dam operation on the Canyon's resources, the GCES (Glen Canyon Environmental Studies) were initiated. The GCES program is a coordinated group of agencies, designed to be an integrated, ecosystem-based research and monitoring program. This multi-agency approach to resource evaluation is orchestrated by Reclamation (Bureau of Reclamation).

The primary purpose of the GCES is to scientifically quantify the environmental impacts of Glen Canyon Dam operations on the resources of the Colorado River in the Grand Canyon. Among the concerns are beach erosion, invasion of exotic species of plants and animals, decline of native fish species, endangered species, disturbance of archeological and cultural sites, changes in water quality, and economic impacts of redefining operations. These concerns are examined, and modifications in dam management are proposed, in the U.S. Department of the Interior publication, *Operation of Glen Canyon Dam: Final Environmental Impact Statement* (1995).

As part of a long-term monitoring effort, a GIS (geographic information system) data base was proposed as a consolidating tool to allow for integrating data and assessing the impacts of variable flows on Grand Canyon resources. The GIS functions as a visual and analytical tool, as well as an archival device to facilitate data storage, access, and retrieval.

The coordination of the long-term monitoring program and research is under the guidance of the GCES office and Dr. Duncan Patten. Long-term monitoring will be built around specific objectives established by the resource agencies, tribes, and resource managers. Additional applied research will be developed around specific, testable hypotheses necessary to interpret monitoring information. Data management will be designed around the existing GCES scientific data management program and the other Colorado River basin data bases. This system will allow data to be compared, analyzed, and maintained in an ecosystem-based approach for future management.

Objectives

The first and primary objective of this report is to review the development and completion of the GCES/GIS base map products being used in the GCES research and monitoring. By applying the available data in an analysis environment, the pilot study was used to define the specific program objectives:

1. Data that are available and practical for use in the GIS
2. Specific features to be monitored and the temporal increment at which they should be monitored
3. The agency responsible for data collection and analysis of each feature
4. Specific end products to be developed for each feature
5. Development of user-friendly software to access, query, display, and analyze the GCES/GIS

The second objective of this report is to discuss the long-term monitoring pilot application study that has been conducted within 1 of the 17 GCES/GIS monitoring sites, site No. 5, and the protocols established through it.

These program objectives have been established by the long-term monitoring pilot study. The strategy and tools developed in the pilot study is to be used for the remaining 16 monitoring sites.

THE INITIAL GCES/GIS DATA BASE DEVELOPMENT

Study Area

The overall study area is located within Grand Canyon National Park (river mile 0 to 280), Glen Canyon National Recreation Area (Lake Powell and river mile 0 to -16), and Lake Mead National Recreation Area (Lake Mead). Limited funds and time constraints prevented the development of a GCES/GIS data base for the entire Colorado River corridor from Glen Canyon Dam to Lake Mead. A GCES/GIS work group, composed of researchers and resource managers representing Federal agencies, a State agency, Native Americans, and other groups, was formed to identify monitoring sites.

The GCES/GIS work group selected long-term monitoring sites that represented the ecological and geomorphic diversity in the Grand Canyon as well as areas where special studies or critical resources were located. The work group originally selected 13 monitoring sites that comprise a total distance of 63 river miles. The GIS sites represented the specific geomorphic reaches throughout the canyon. The study area in each site extends from the top of the OHWZ (old high water zone) river-right to the top of the old high water zone river-left (see fig. 1).

Since the selection of initial monitoring sites, four special study sites that require monitoring of unique, endangered, cultural, or natural resource components have been added to the data base. These additional areas comprise a total distance of 37 miles. More special study sites may be added if appropriate. A location map of the long-term monitoring and special study sites can be seen on figure 2 as a fold out at the back of this report.

The length of individual monitoring sites ranges from 2 to 13 river miles with an average length of 5 river miles. Monitoring site No. 5 was selected for the pilot study for the following reasons:

1. Data collection by multiple agencies
2. Extensive quantities of current and historical data
3. Cultural significance
4. Ecological diversity
5. Water quality assessment
6. Critical endangered species habitat

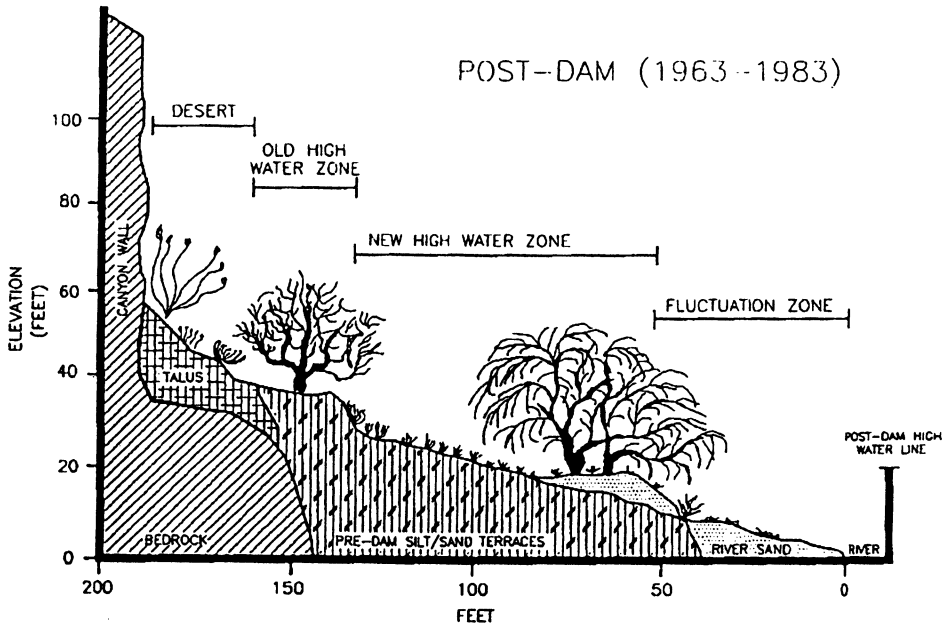

Figure 1. - GCES/GIS post-dam study area profile.

Site No. 5 is located from river mile 60 to 72, and includes 1 mile of the Little Colorado River upstream from the mouth. The confluence of the Colorado and Little Colorado rivers occurs at about river mile 61.5. The Little Colorado flows from the east and merges with the southward flowing Colorado. The pilot site is bounded by the Navajo Indian reservation to the northeast and by Grand Canyon National Park on the west and southeast. A map of site No. 5 representing the 1990 base data and resource study sites can be found on figure 3 at the back of this report.

GCES Base Map Production

A GIS was determined to be necessary in 1989 for archival and analysis of the data being generated through the GCES. A base map product of the scale and accuracy required for detailed GIS analysis of the monitoring sites was not available. The initial effort requires the development of a base map product specifically for the GCES special studies and monitoring sites. A photogrammetric product was established to develop both a hard copy and a digital base map product for each of the monitoring and special study sites.

Specific technologies were used in the development of the large-scale topographic base map products used in the GCES/GIS mapping effort. A horizontal and vertical control network was established within each monitoring site through conventional survey methods. Aerial photography was collected for photogrammetric data. The GCES program established the control network and used the aerial photography to develop the topographic and orthophoto base map products. The various technological components involved in the development of the base map products are shown on figure 4.

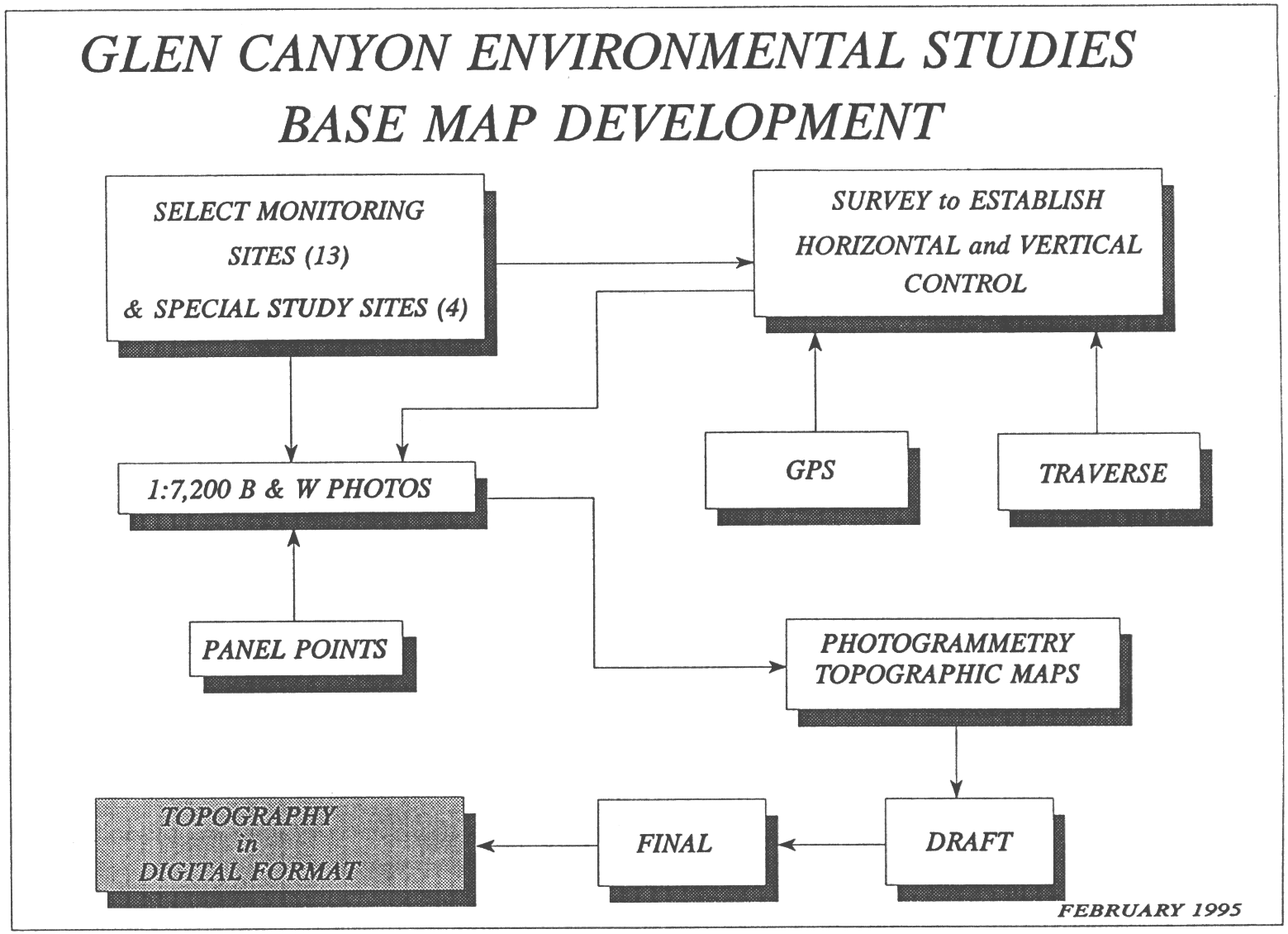

Figure 4. - GCES base map development.

Survey.-Horizontal and vertical control networks were required for the production of accurate base maps. The ground control network was established in the Grand Canyon using a combination of GPS (global positioning system) and conventional surveying. Limited reliable control points existed in the Grand Canyon prior to the GCES effort. Existing geographic control on the rim was transferred down to river level, a distance of over 1 vertical mile, using GPS technology and approved surveying techniques. Limited time, money, and the restrictive nature of the terrain prevented running standard survey level lines down existing trails.

GPS control points were established at the beginning and end of each monitoring site. This study is the first time that GPS technology has been used in extreme environments such as the Grand Canyon. Theodolites and electronic distance measuring instruments were used to traverse along the river between the GPS control points. This process added intermediate control points which were used in producing the base maps and provides consistent ground control to be used by specific research projects.

Aerial Photography.-Aerial photographs of the monitoring sites were collected for developing the orthophoto base maps. Prior to photography, 5- by 5-ft control panels were positioned on both sides of the river within the monitoring sites (fig. 5). The aerial photographs were collected at an elevation of 3,600 ft a.g.l. The monitoring sites were photographed in black and white at scales of 1:7,200 and 1:14,400 during June and July 1990. The Colorado River was at a constant flow release of 5,000 ft^3/s during the time of photo acquisition. Consecutively, the entire river corridor of 291 miles was photographed at a scale of 1:4,800 using CIR (color infrared) photography for mapping natural resources.

Coordinates of the horizontal and vertical control points were used to scale and level stereo models. Contour lines at 0.5-m intervals, with 1.0-m accuracy, and other features up to the old high water line on both sides of the Colorado River, were digitized and plotted as 1:2,400 scale base maps. Figure 6 at the back of this report shows a sample topographic product created for each monitoring site. The four base map products generated in this process are:

1. 1:2,400 hard copy topographic base maps with a contour interval of 0.5 m.
2. A digital topographic data set with a contour interval of 0.5 m in ARC/INFO format[1].
3. 1:2,400 hard copy orthophoto maps with a contour interval of 0.5 m.
4. 1:2,400 hard copy orthophoto grids depicting only the reference tics and without contour lines.

Hard copy map products were plotted on 4-mil mylar. All map products are in the Arizona State Plane Coordinate System (meters) with a Transverse Mercator projection.

Base map products are a valuable tool to georeference data for survey and GIS purposes, including aerial photography and tabular data. The base map products are used by GCES, Remote Sensing and Geographic Information Group, the contributing agencies, and GCES researchers for the development of particular monitoring products.

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[1] ARC/INFO is the geographic information software produced by ESRI, Inc. Mention of this or any other commercial product or vendor is not to be construed as an endorsement by the U.S. Government.

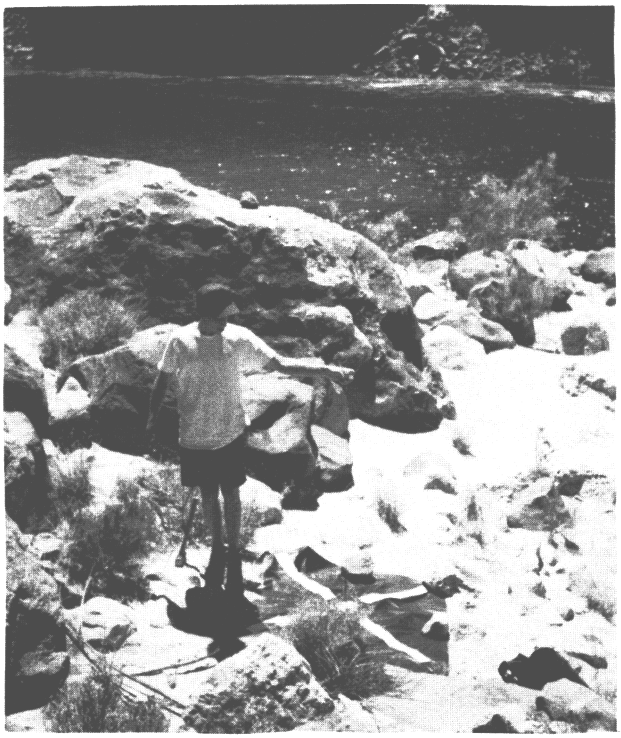

Figure 5. - 5- by 5-ft control panel.

The orthophoto map is a photograph showing images of objects in true orthographic positions. The orthophoto map was rectified and georeferenced for accurate control. The GCES orthophoto products are used to define the coordinates of known point, line, or polygon data to within an initial accuracy of 2.0 meters. The GCES orthophotos are used to establish common control between aerial photography (current or historical) and base maps in the transfer of data to the GCES/GIS data base. By using the historical aerial photography, the Grand Canyon researchers are able to collect and analyze surface data from the past. The topographic product is used in the development of volumetric, slope/aspect data and as an accurate reference tool for surveys and monitoring.

A digital orthophoto was developed for each site to expedite and facilitate the dissemination of these useful data sets to the contributing agencies and researchers.

GCES/GIS data base design.-The design and strategy were developed by representatives of the USGS (U.S. Geological Survey), GCES, NPS, and Reclamation's Remote Sensing and Geographic Information Group in Denver in 1991. The data base design contains two primary components: "structure" and "content." "Structure" includes the layout of computer directories; for example, grouping data by theme (i.e., topography) or by spatial location (i.e., river reach). "Content" includes category and subcategory designations such as "geology and formation" or "hydrology and flow velocity."

All ARC/INFO coverages or data layers are stored in a computer directory tree structure under one master directory called GCES. Two types of sub-directories are found under the home directory GCES. One directory contains basin-wide data such as sampling sites and climatic monitoring stations. The other contains 14 directories dividing the data base by geomorphic

reach (Schmidt and Graf, 1990). The segregation of monitoring and special study sites by geomorphic reach appear in appendix A.

Second-level sub-directories of the 13 long-term monitoring and 4 special study sites reside within each appropriate geomorphic reach. Third-level sub-sub-directories representing data themes are located within each of the monitoring site directories. Within each theme, ARC/INFO coverages represent the data sets developed by the contributors. An example of the data base structure is described on figure 7.

```
                                GCES
                                  |
_____________________________________________________________________
     |          |      |      |      |      |      |      |
BASIN WIDE    REACH2 REACH3 REACH4 REACH5 REACH6 REACH7    ETC.
     |                                       |
_____________________________________        |
 |    |          |  |        |    |         |
 | RIVER MILES   | DATING   |  REFERENCES   _____________
CLIMATE       HYDSITES ELEVATION            |           |
                                           SITE3       SITE4
                                             |
_____________________________________________________________________
 |        |     |   |    |      |   |   |      |      |     |      |
 | TOPOGRAPHY | SOILS | HABITATS | FAUNA | RECREATION | MANMADE    |
LEGEND GEOLOGY HYDROLOGY VEGETATION ARCHEOLOGY REFERENCEPTS TEMP
```

Figure 7. - Tree diagram of data base structure.

The GCES/GIS data base is designed as a multi-level structure which includes data that range from general to specific. Three tiers of accuracy are available within the multi-level structure, and each tier is determined by either the scale of the base map or methodology used in the development of the original data set.

The first tier consists of data referenced to a 1:24,000 quad sheet and, at best, will have the National Map Accuracy Standard of 40 ft in the horizontal and half a contour interval in the vertical. The second tier of data is photo referenced and transferred to the 1:2,400 orthophoto grid base map developed for this project. The methodology used to create the 1:2,400 level can produce a digital product with a horizontal accuracy of 2.0 m and a vertical accuracy of 1.0 m. The second tier of data is being used to develop the digital long-term base products for the monitoring and special study sites. The third tier of data is survey referenced data. This data collection methodology can produce digital data with centimeter-level accuracy. The accuracy of contributed data depends on the methodology used in the collection of the original data set.

THE CONSOLIDATION OF INFORMATION INTO THE GCES/GIS

The Remote Sensing and Geographic Information Group in Denver developed the digital base map products for the long-term monitoring sites, as well as the protocols and methodologies to integrate the research data. Using the 1990 CIR photography, GIS coverages of geological, hydrological, and biological data for all monitoring sites were generated. Only the topographic and orthophoto products were generated for the special study sites.

To establish integration protocols, a pilot study of GIS site No. 4 was completed. This effort defined the parameters involved in generating a 1990 data base of medium resolution hydrological, biological, and geological data (Bureau Of Reclamation, 1993). This effort established the methodology needed to develop the base data described further in this section and prompted the development and implementation of the "Glen Canyon Environmental Studies Geographic Information System Information Guide and Operating Protocol."

The protocol was generated to provide guidance to all GCES researchers and data base developers and as a template for data integration. A short-term objective of the data management program was to ensure that data collected under the GCES program are not lost as the initial research studies are completed. By establishing metadata (data about data), cooperating agencies' roles and responsibilities, GCES research trip checklists, ground control requirements, and data exchange standards were set to ensure that the data developed for GCES will be valid and viable. The "Glen Canyon Environmental Studies Geographic Information System Information Guide and Operating Protocol" is located in appendix B.

Methodology

To standardize the study area being mapped, field work for the monitoring sites was completed during the scientific low flow of 5,000 ft^3/s in 1990.

The 1990 CIR photographs, enlarged from 1:4,800 to 1:2,400 scale (with registered mylar overlays), were used in the field, which defined classes of hydrological, biological, geological, archeological, and cultural features. These features are mapped on the registered mylar overlays using a mylar pencil. The classification scheme and definitions can be found in appendixes C and D. Classes were delineated on each photo within the monitoring site from the top of the old high water zone down to the Colorado River. The interpreted mylars were then quality checked in the field for consistency and accuracy in the mapping. The mylar overlays are used as templates to classify and map information from the 1:2,400 orthophoto base map product. After the template was completed, the data were transferred from the CIR photographs to the georeferenced orthophoto base maps.

A mylar overlay was affixed to the orthophoto grid and registered by drafting the 200-m Arizona State Plane grid tics, represented on the orthophoto, with a 0.012-in-wide drafting pen. The orthophoto grid was placed over the classification template, and all identified classes were drafted to the registered overlay as depicted on the orthophoto, allowing for georeferencing and rectification of the spatial data. Orthophotos are geometrically equivalent to conventional line and symbol planimetric maps and show true orthographic positions of objects. Because they are planimetrically correct, orthophotos can be used as maps for making direct measurements of distances, angles, positions, and areas without making corrections for image displacements (Wolf, 1974). The registered overlay was then scanned and brought into the georeferenced GCES/GIS data base.

Using the defined methodology, the geological, hydrological, and biological base data developed for the long-term monitoring program have a horizontal accuracy of 2.0 m and a vertical accuracy of 1.0 m. Contributing scientists can use this methodology in the generation of their data sets.

THE DEVELOPMENT OF THE LONG-TERM MONITORING PILOT

Long-term monitoring is defined as "measuring the change over time in riparian vegetation, geology, hydrology, population responses, cultural resource areas, and habitat for rare and endangered species. The plan should be integrated with and based upon a sound scientific understanding of the effects of operations on environmental resources. The predictions of effects should be viewed as working hypotheses about river processes; these hypotheses can be tested by use of monitoring data" (National Research Council, 1987).

A GIS is an invaluable tool for integrating data and documenting the effects of dam operations on the environmental resources of the Grand Canyon because it is a georeferenced data base that has the ability to manipulate and analyze spatially referenced data. Because the data within a GIS are georeferenced, the GIS can address questions about:

A. Location - "What is at ...?"

B. Conditions - "Where is it true that ...?"
   1. query by variable or item
   2. query by class or alphanumeric or numeric value
   3. query using logical expression
   4. query can be implemented and displayed graphically or numerically

C. Trends - "What has changed...?" = long-term monitoring
   1. change in area and volume
   2. change in location (x, y, and z)
   3. change in shape
   4. change in class
   5. statistical operations

D. Patterns - "Which data are related ...?"
   1. geographic correlations
   2. statistical correlations

E. Models - "What happens if ...?"
   1. graphic/numeric modeling - grid cell and vector
   2. numeric modeling - AML (ARC macro language) programming - Fortran

The GCES/GIS is being used to address and satisfy many of the objectives for long-term monitoring defined in the draft report "Long-Term Monitoring In The Grand Canyon: Response To Operations Of Glen Canyon Dam" (National Research Council, 1994).

Feature Selection

Over 70 individual research studies have taken place within long-term monitoring site No. 5. Fourteen of these studies were found to be acceptable for inclusion in the GIS pilot study based on:

1) The cooperation of principal investigator—several researchers were either reluctant to release their results, did not have their studies completed on time, or both.

2) The importance of the data set to the integration of other studies or analyses.

3) The compatibility accuracy of the data set with the level of accuracy required within the GCES/GIS.

4) The amount of editing necessary to bring the data set into a useful state.

The remaining studies will be integrated into the data base on an as-needed and availability basis.

Of the 14 data sets used in the site No. 5 pilot, 7 data sets were used to illustrate the analytical capabilities of the GCES/GIS and its applicability for protocol development.

A. Aquatics

1. Bathymetric and thermal mapping at the confluence of the Colorado and Little Colorado Rivers, cross-referenced to indicate relationships and trends.

2. Data collected primarily to address questions regarding the endangered Humpback chub (*Gila cypha*), including:

   a. Net set locations with catch data from individual research trips.
   b. Velocity contour maps at high and low flow, defining habitats in the current.
   c. Shoreline habitat maps.
   d. Radio telemetry information.
   e. Minnow trap locations.
   f. The thermal boundary at the confluence of the Colorado and Little Colorado Rivers measured and delineated under different flow levels to identify optimum thermal habitat for the Humpback Chub. This information will be combined with bathymetry, radio-telemetry, and net set data to better identify habitat availability and use.
   g. River channel boundary at 5000, 15000, and 30000 ft^3/s.

B. Terrestrial

1. Vegetation polygon data analyzed from aerial photography from 1963, 1984, 1990, and 1992 to identify trends in post-dam vegetation growth.

C. Sediment

1. Detailed sandbar surveys correlated with daily photographs of the subject sites to track sediment aggradation and degradation at sites throughout the canyon.

2. A data set which monitors sediment movement throughout the canyon. Collection methods included total station topographic surveys, bathymetric surveys, and rectification of photographs taken daily during the time of lowest flow. These methods were combined for a comprehensive look at sedimentation patterns.

D. Cultural

1. Data of surficial geology and geomorphology compiled for specific sites to study the relationship between erosion patterns and preservation of archeology sites.

2. Historical photographs - locations, dates, and descriptions of features found in the subject photograph assembled into a georelational data base.

3. Campsite delineation - polygons delineated around often-used campsites to serve as baseline data for long-term monitoring.

APPLIED RESEARCH

Four studies were chosen to be highlighted in this paper because they represent established contributions to the long-term monitoring work and research efforts associated with GCES in the Grand Canyon.

The first study was presented by the NAU (Northern Arizona University) Department of Geology. NAU developed an innovative approach to study sandbar aggradation and depletion using the GCES/GIS data base in conjunction with a hypsometric analysis.

REPORT NO. 1
USING A GIS TO MONITOR SEDIMENT RESOURCES IN THE COLORADO RIVER, GRAND CANYON, ARIZONA

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Introduction

A GIS compilation of topographic and photographic data related to sandbars along the Colorado River in Grand Canyon is being developed at the Northern Arizona University Department of Geology. Sandbars are a primary natural and recreational resource of the river corridor because they are the foundation on which the fluvial ecosystem is structured (Bureau of Reclamation, 1994). The sandbar survey studies were designed to monitor the effects of current operating strategies from GCD (Glen Canyon Dam) on Grand Canyon sandbars. This study involved the comparison of topographic and bathymetric surveys at 30 sandbars located in each of the 11 geomorphic reaches of the Colorado River corridor (fig. 8). We have evaluated the applicability of the GCES/GIS (Glen Canyon Environmental Studies/Geographic Information System) as an analytical tool. The first example involves a sandbar located within GCES/GIS site No. 5, at RM (river mile) 62.4, that underwent significant changes during winter 1993 flood events. The second example is a preliminary hypsometric analysis of a subset of the entire sandbar survey data base.

Methods

The sandbar survey data consist of results from two separate studies of repeated topographic and bathymetric surveys at 30 sandbars (Beus et al., 1992; Kaplinski et al., 1994a) and daily photographs collected at 43 camera locations (Dexter et al., 1994). The data base was initially stored in a variety of DOS-based formats. The original data are exported from the DOS systems, typically as ASCII text and AutoCAD DXF files, and imported into ARC/INFO format. The daily photographic data consist of the scanned original oblique images and ERDAS.LAN files of rectified images, arc coverages of polygons outlining the exposed portion of the sandbar, and related tabular information. ARC/INFO macro programs were developed to automate the process of converting from DOS-based to UNIX-based ARC/INFO format transfer.

State Plane coordinates of the individual site control points located within GIS reaches are included in the GCES/GIS and were provided by the GCES Survey Division. These coordinates were used to translate and rotate the survey information from a local coordinate system into the State Plane coordinate system. Once projected in the State Plane system, the surveys were overlaid with coverages of the Bureau Of Reclamation 0.5-m river corridor topography (Werth et al., 1993).

The sandbar survey data consist of up to 17 repeated surveys at each of the 30 sites, which were collected from June 1990 to April 1994. The analysis presented here includes surveys conducted during the interim flow period (July 1991 to April 1994). Study sandbars located within GIS site No. 5 at RM62.4 and RM68.2 were used as pilot studies to develop the methodologies used in the remaining survey sites. Individual sandbar surveys include coverages of topographic and bathymetric survey points with elevation and code attributes, arc coverages of boundary and breakline information used in TIN (triangulated irregular network) model generation, as well

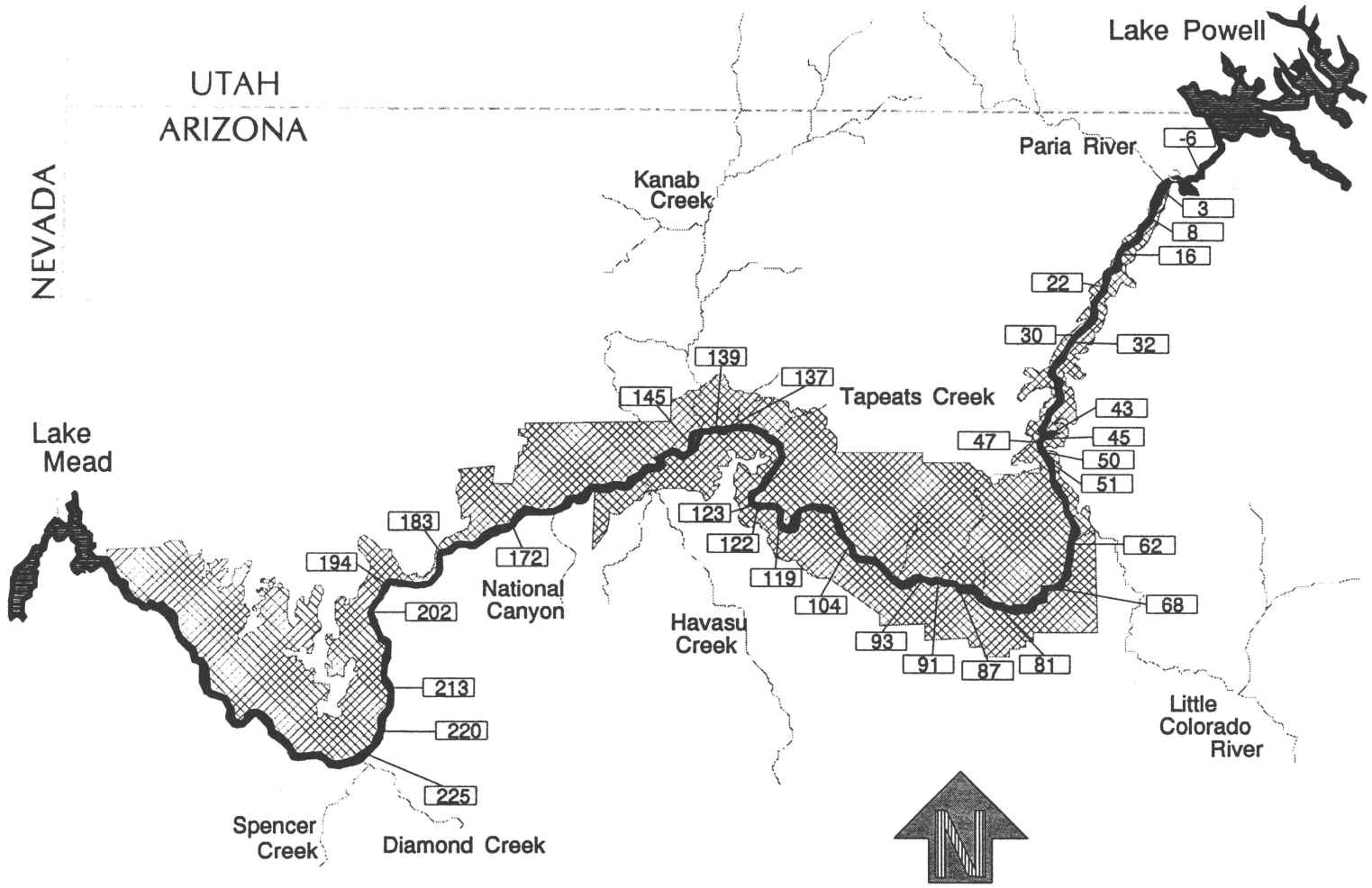

Figure 8. - Location map of sandbar study sites.

as several INFO files of related tabular information. TIN models of the combined point coverages for each survey are formed and used to generate arc coverages of 0.5-m topographic contours and profiles at predetermined locations. Products from this study, in addition to the data base, include a map atlas of site information and reports that reflect detailed descriptions of the methodologies and analyses presented here, listings of the AML's, and FGDC (Federal Geographic Data Committee) compatible metadata developed for this project.

Flow Regimes

Interim flows have been in effect since August 1991 and will continue until a Record of Decision is reached for the GCD Environmental Impact Statement and a new flow regime is indicated. In the past, GCD has been operated to yield maximum hydropower revenues through the production of peaking power. Flows released from GCD have ranged between 85 and 850 m^3/s (3,000 and 32,000 ft^3/s) daily, depending on power demand. Interim flows limit maximum discharge to 566 m^3/s (20,000 ft^3/s) and the minimum to 142 m^3/s (5,000 ft^3/s), with upramp and downramp rates of 57 $m^3/s/hr$ (2,500 $ft^3/s/hr$) and 42.5 $m^3/s/hr$ (1,500 $ft^3/s/hr$), respectively. Daily change cannot exceed 142 m^3/s (5,000 ft^3/s). These interim flows consist of low-, medium-, and high-volume months, with low flows during the late spring and late fall and high flows during mid-summer and mid-winter.

Natural flood events within the lower LCR (Little Colorado River) during January and February 1993 caused a significant deviation from the lower-volume interim flow regimes along the mainstem Colorado River (fig. 9). Three flood events occurred on the LCR on January 12to 16, January 19to 23, and February 23to 26, 1993, that delivered sediment and raised flows in the mainstem Colorado to 955 m^3/s (33,777 ft^3/s), 783 m^3/s (27,980 ft^3/s), and 826 m^3/s (29,450 ft^3/s), respectively. During these floods, sand was deposited in nearly every eddy downstream from the LCR-Colorado confluence for at least 30 mi, to river mile 90.

Results

River Mile 62.4 Sandbar.-A large sandbar located within GCES/GIS site No. 5, at RM62.4, deposited during the first and largest flood event (January 12 to 16, 1993), provides an opportunity to examine sandbar development dynamics (Kaplinski et al. , 1994b). Deposition at this site was consistent with published descriptions of depositional patterns at other Grand Canyon sandbars and in flume experiments (Rubin et al, 1990; Schmidt et al., 1993). Prior to the January LCR flood, no significant deposit existed at this site. The sandbar was deposited entirely during the flood event, whereas most previously described sandbars are a composite of many different depositional packages from different years (Rubin et al., 1990; 1994). Within 6 months of deposition, the entire exposed portion (above about 227 m^3/s [8,000 ft^3/s]) of the deposit had eroded to pre-flood levels. We conducted detailed topographic and bathymetric surveys of the eddy complex in April 1993, October 1993, and April 1994 and will present an analysis of depositional and erosional patterns at the site during and after the flood events.

Comparison of the surveys yields information regarding deposition rates in the eddy during the flood. We used the volumetric difference of 64,644 m^3 between the two surveys to estimate a minimum rate of sediment accumulation in the recirculation zone during the January 1993 flood. Based on photographic and stratigraphic evidence, most of the deposition at this site occurred during the first 12 hours of the flood, perhaps even within the first several hours.

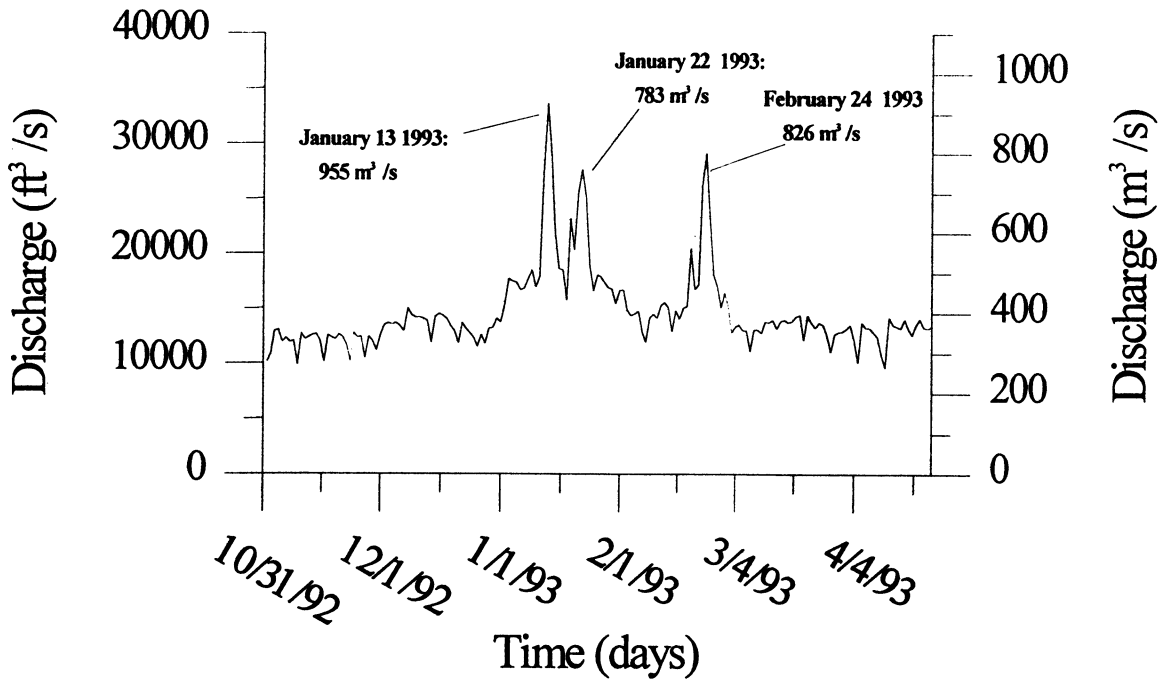

Figure 9. - Colorado River hydrograph.

Assuming a sediment density of 2.65 g/cm^3, we calculated deposition rates of 0.79 to 0.40 kg/s for periods of 6 and 12 hours respectively. These rates are higher than the range of rates (0.22 to 0.05 kg/s) determined from flume experiments of recirculation zone sedimentation (Schmidt et al., 1993). Because of its close proximity to the sediment source (LCR), this site may not be representative of other sandbars along the river corridor during similar flood events. Deposition rates calculated for the RM62.4 site can be considered an upper limit for rates throughout the Grand Canyon.

Comparison of the April 1993 and April 1994 surveys further illustrates the pattern of post-flood erosion at the site (fig. 10). In general, the greatest amounts of erosion within the eddy (-4 to -11.5 m) correspond with areas of maximum current velocity, particularly in the return current channel where currents sweeping across the eddy coalesce and are directed upstream.

Large volumes of sediment were also transported along the main river channel between the surveys. Up to 10 meters of change was recorded along the left bank of the main channel.

We also used the survey comparison, combined with qualitative visual observations of the site between measurements, to estimate approximate erosion rates at the site. About 5 to 10% of the deposit we measured in April had been eroded by June 1993. We estimate that the erosion rates ranged between 50 to 100 m^3/day from April 1993 to June 1993 (Kaplinski et al., 1994a). Dam operations changed from low volume (226 to 368 m^3/s [8,000 to 13,000 ft /s]) to high-volume (340 to 540 m^3/s [12,000 to 19,000 ft^3/s]) interim flows on July 1, 1993. Following this change in dam operations, the portion of the bar above the 227-m^3/s (8,000-ft^3/s) stage elevation had completely eroded within a 2-to 3-week period. We estimated that erosion rates during July 1993 ranged from 2,000 to 2,500 m^3/day. The change from low-volume to high-volume interim flow dam operations may have triggered an order of magnitude increase in erosion rates.

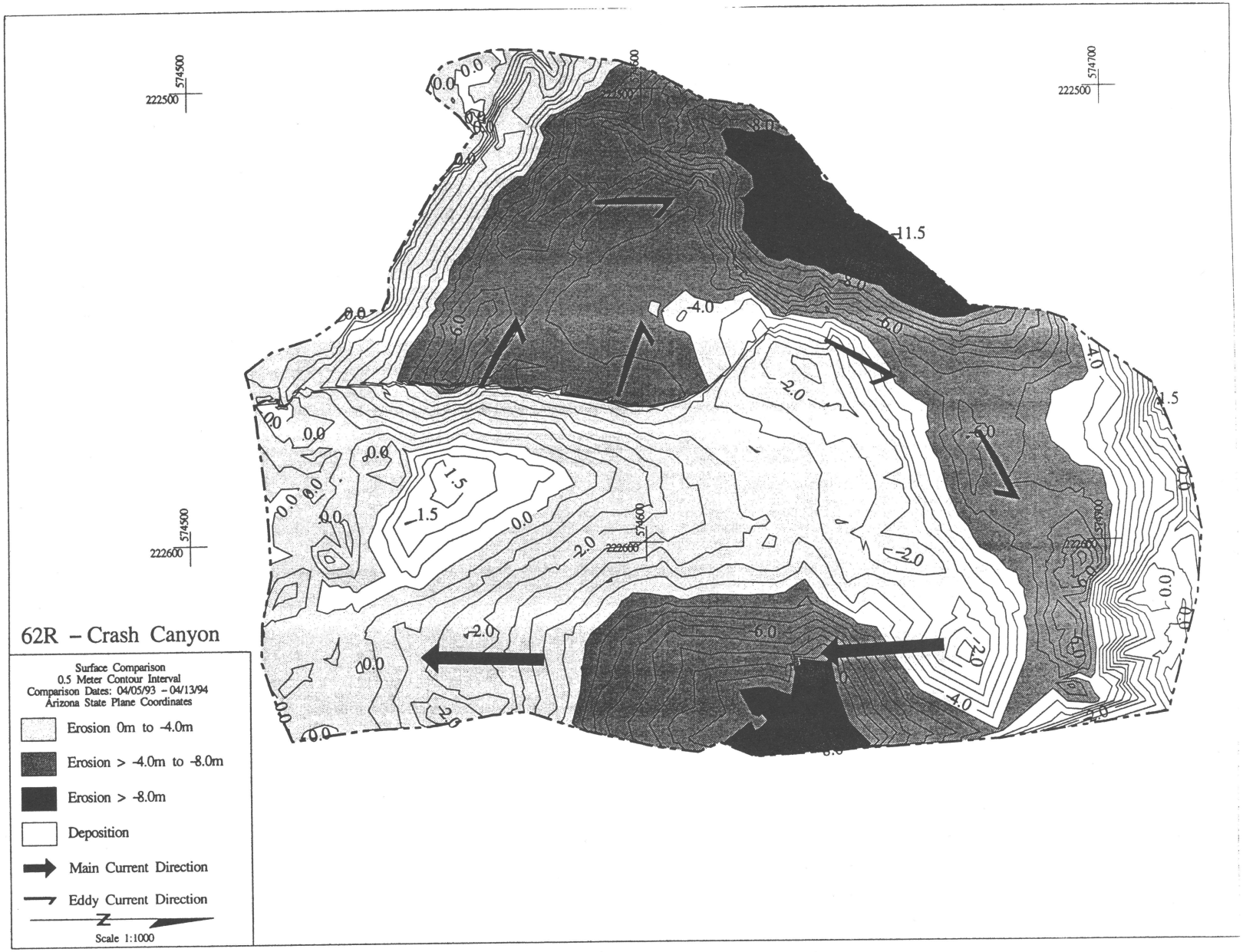

Figure 10.- Contour map of the difference between the April 5, 1993, and April 13, 1993, topographic surveys at the RM62.4 sandbar study site.

Hypsometric Analysis.-A preliminary analysis of recirculation zone hypsometry was conducted to quantify sediment storage changes within the recirculation zones. Hypsometry is the distribution of area with respect to elevation within a defined region. Hypsometric curves have traditionally been applied to drainage basins (Strahler, 1952; Schumm, 1956; Bloom, 1991). In this application, we define the hypsometries of individual recirculation zones along the Colorado River. By using dimensionless parameters, hypsometric curves from individual eddies can be compared irrespective of true scale. We develop a general model of sandbar hypsometry and compare the hypsometries of sandbars throughout this system during the period of interim flow.

TIN (triangulated irregular network) models of the combined topographic and bathymetric data set were constructed within a boundary delineating the recirculation zone. Arc coverages of 0.5-m contour lines are generated from the TIN models and the area enclosed by each contour line is summed to generate the raw hypsometric data (fig. 11a). The raw hypsometric data are then normalized by expressing individual values as a ratio of the total range, and the cumulative relative height versus the relative area is plotted (fig. 11b).

A system-wide hypsometric curve was generated by pooling all terrestrial and bathymetric data from 30 sandbars for six survey runs from July 1991 to April 1994 (fig. 12). This curve was best described using a third order polynomial equation:

$$A_i = 0.991 + (0.146 * E_i) - (2.535 * E_i^2) + (1.401 * E_i^3) \quad (r^2 = 0.895) \tag{1}$$

with A_i as the relative sandbar area in hypsometric interval I, and E_i as the relative elevation of interval I. The elevation intervals used in this analysis were 0.05 m.

An index of the geomorphic condition of individual sandbars was developed by comparing the individual site hypsometry to the system-wide mean. Residuals between the observed hypsometric curve and the system-wide hypsometric curve were calculated at each elevation interval for each survey. These residual values were totaled to generate the SHCR (summed hypsometric curve residual) for each survey. We then analyzed SHCR as a response variable in a three-factor analysis of covariance (ANCOVA, SYSTAT v. 5.1). This analysis included the following predictor variables: sampling run, reach width (wide versus narrow), and depositional environment (separation, reattachment, or eddy bar), with distance from Lees Ferry and the lagged, or antecedent, SHCR value as covariates.

The ANCOVA results show that antecedent bar condition ($p < 0.0001$) and reach width ($p = 0.025$) were the significant variables influencing sandbar morphology through time. The strong correlation between SHCR and antecedent SHCR is best described using a least squares simple linear regression:

$$SHCR_{Ti} = (0.849 * SHCR_{Ti-1}) - 0.209 \quad (\text{adjusted } r^2 = 0.813, F_{1,51} = 201.8, p < 0.0001) \tag{2}$$

The lower values along this line indicate sites near the system-wide mean sandbar morphology, and the length of the line represents the range of bar morphologies in the system during the period of study.

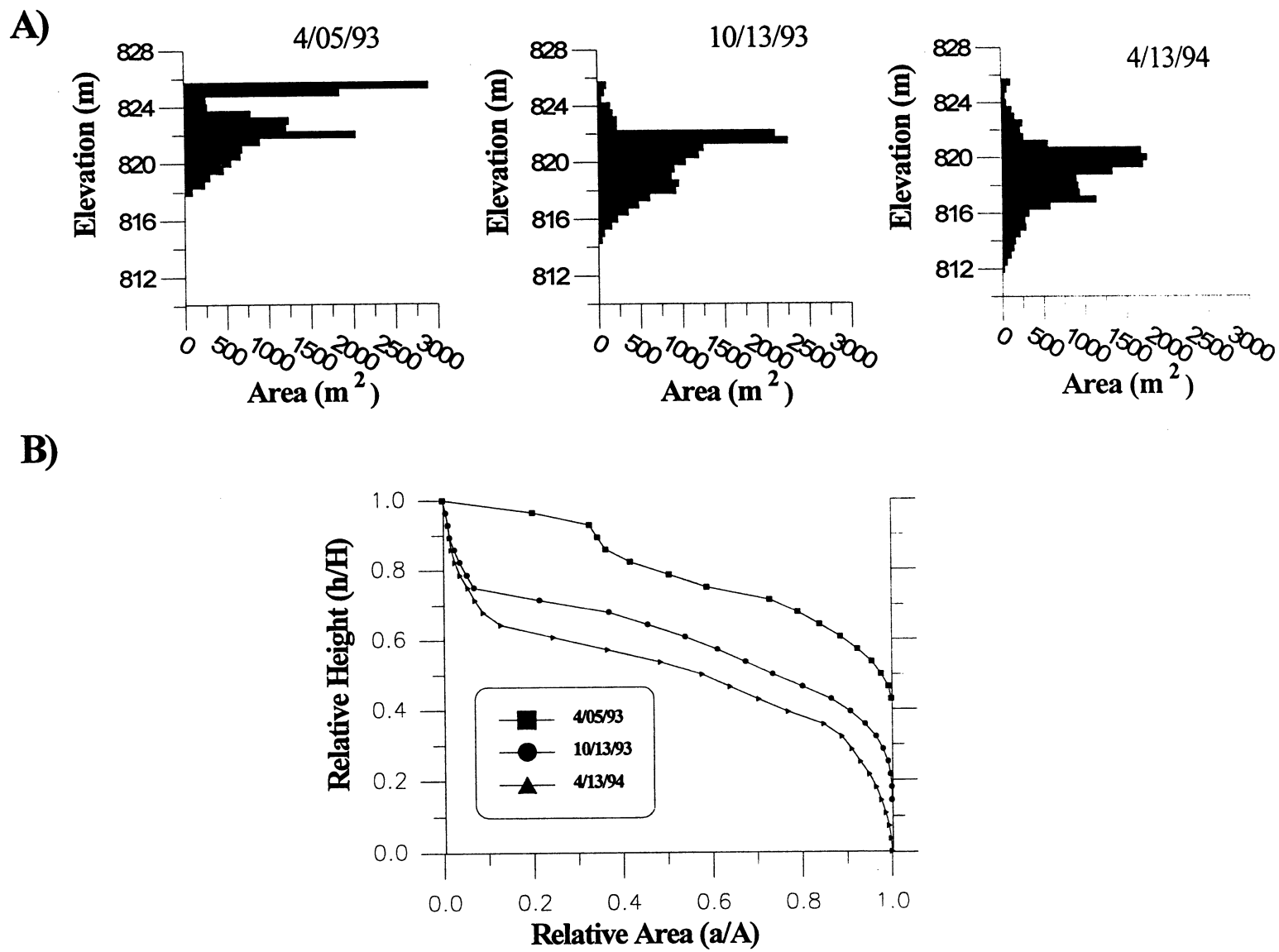

Figure 11.- Hypsometric data from the RM62.4 sandbar survey site: a) area-elevation distribution histograms, b) hypsometric curves.

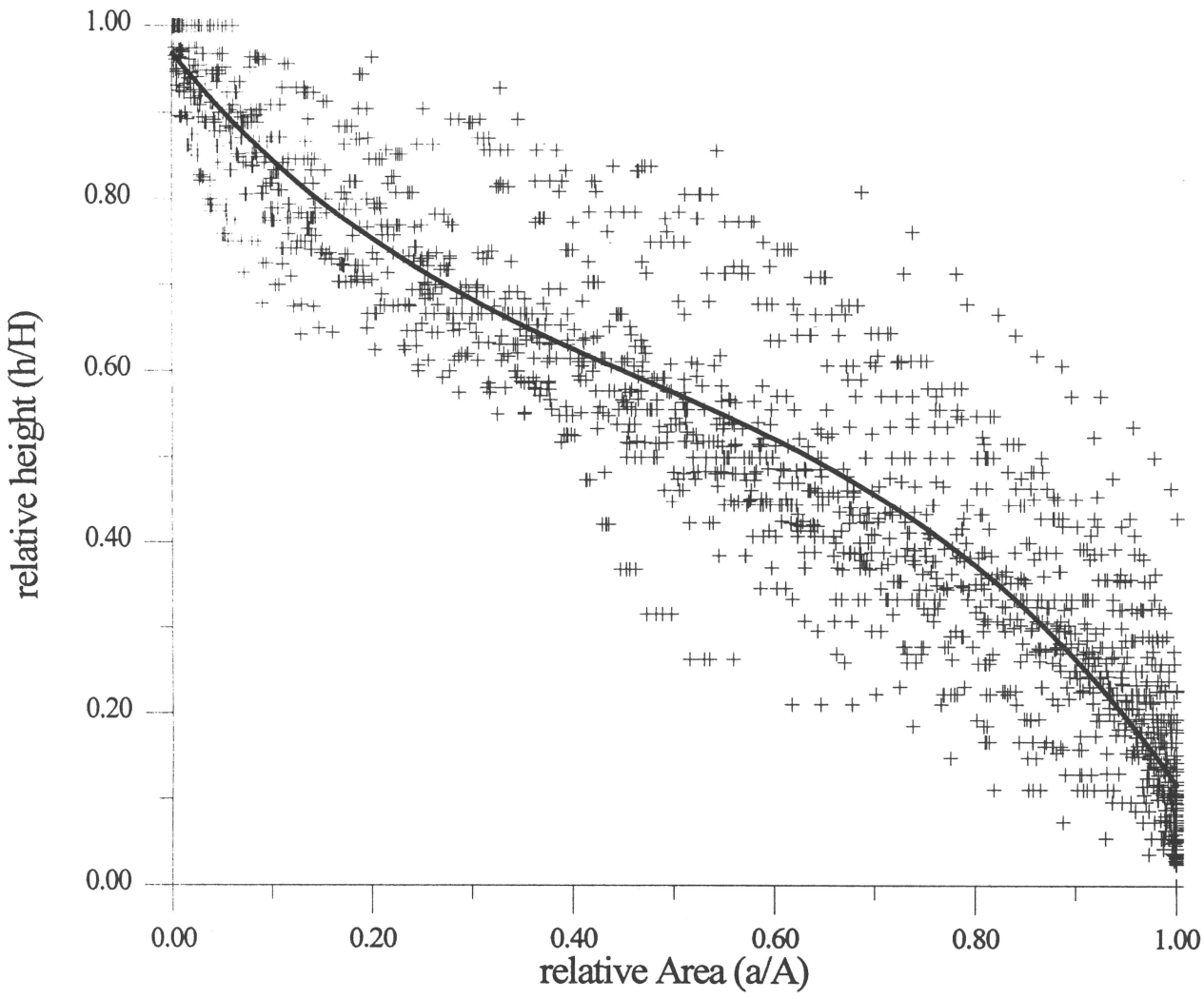

Figure 12.- Pooled hypsometric data and best-fit third order polynomial.

SHCR varied between wide and narrow reaches (fig. 13). The mean SHCR value for narrow reach sites (-0.467) was significantly lower than the mean SHCR of wide reach sites (0.297; p = 0.025). Most study sites in narrow reaches displayed negative values for both SHCR and antecedent SHCR, whereas sites in wide reaches revealed a wide range of values for both SHCR and SHCR. Sites in narrow reaches are characteristically smaller in area and displayed steep faces with relatively little mid-elevation bar platform development. In contrast, sandbars in wide reaches generally contained broad mid-elevation bar platforms.

This preliminary hypsometric analysis demonstrates that the hypsometry can be used to detect changes in sandbar morphology through time and that the antecedent SHCR predicts subsequent bar morphology. Sandbar morphology exists across a rather well-defined range, with sites in narrow reaches typically having near neutral or negative morphologies in relation to the system mean. Sites in wide reaches typically have larger bar platform areas at middle stage elevations. Because of this difference, this analysis should be repeated using a different best-fit hypsometric curve for wide and narrow reaches. In addition, individual sites displayed a cyclic pattern of aggradation and degradation that was highlighted by the SHCR analysis.

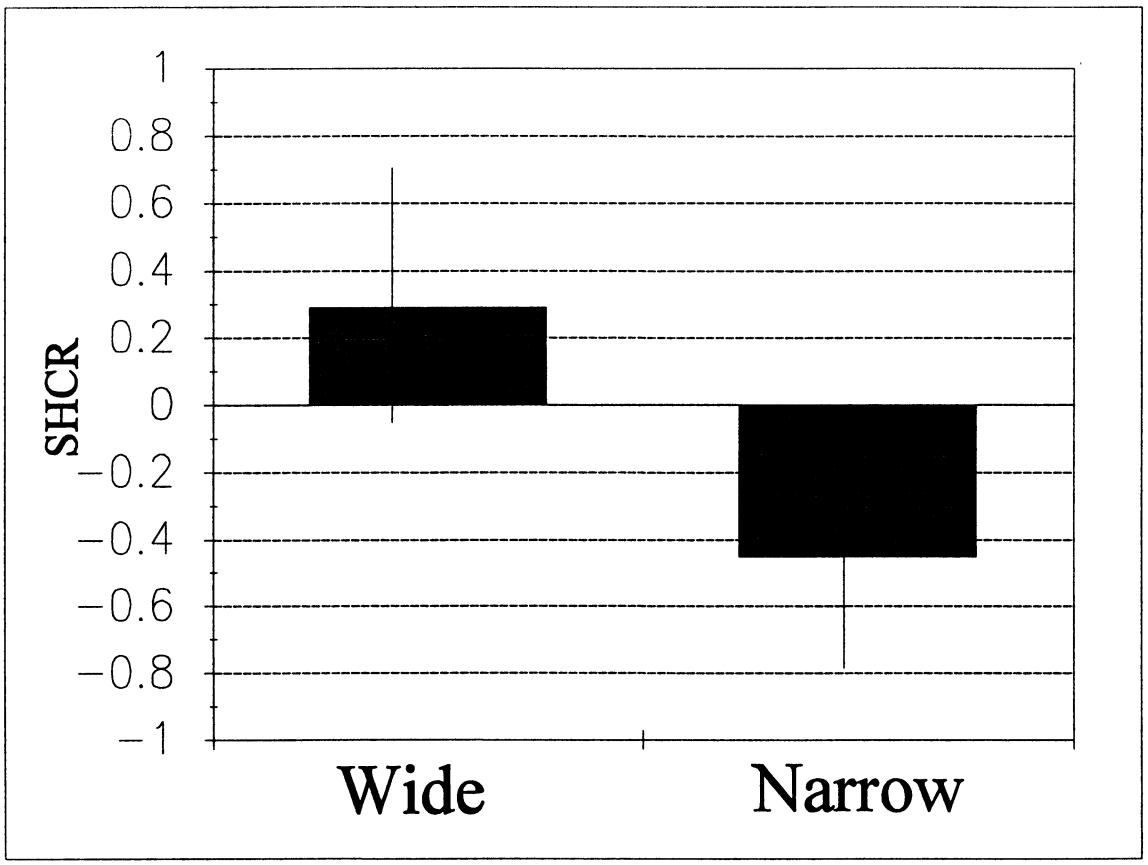

Figure 13. - Distribution of SHCR in wide versus narrow reaches.

Conclusions

In summary, a compilation of topographic and photographic information on Colorado River sandbars is being developed at Northern Arizona University Department of Geology. The preliminary GIS-based analyses of the sandbar study data base demonstrate the value of GIS systems and supporting data bases as an analytical tool for identifying morphological changes in sediment storage. GIS-based analysis should be an integral part of future monitoring plans for Grand Canyon National Park.

The second study was conducted by BIO/WEST INC., a private contractor employed by GCES to generate current and collect historic fisheries data in the Grand Canyon. BIO/WEST addressed the archival needs of GCES by incorporating both current and historical fisheries data through a developed GIS module.

REPORT NO. 2
APPLICATION OF GIS TO FISHERIES DATA BASES IN GRAND CANYON

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Abstract

The GCES (Glen Canyon Environmental Studies) has coordinated fisheries investigations in the Colorado River through Grand Canyon since 1982. Significant data were collected under Phase I (1982-88) and are currently being collected under Phase II (1988-1994); together with historic data, these provide a comprehensive source of information necessary for operating Glen Canyon Dam in a manner that minimizes detrimental effects to the aquatic ecosystem. These data were collected from the Colorado River and its tributaries, and include historic accounts of fish collections, surveys, and intensive cause-effect investigations. Assimilating this large and varied volume of information into a usable form is vital to facilitate access and speed analyses that will provide managers with ongoing, updated, and reliable information that also complements long-term monitoring and applied research.

The framework for a centralized data base was developed for fisheries resources in Grand Canyon to bring together historic, recent, ongoing, and future datasets into a digitized field-specific format with linkages to a GIS (geographic information system). The program is called the GCFIN (Grand Canyon Integrated) Data base and consists of three phases: (1) identify and catalogue datasets, (2) identify integration linkages, and (3) identify GIS application.

Introduction

Fisheries resources have been a focal point of the GCES because of the direct effect of dam operations on aquatic habitats, and because of the presence of sensitive species, including the Federally endangered humpback chub (*Gila cypha*) and razorback sucker (*Xyrauchen texanus*), as well as State-sensitive species such as the flannelmouth sucker (*Catostomus latipinnis*), bluehead sucker (*Catostomus discobolus*), and speckled dace (*Rhinichthys osculus*). The roundtail chub (*Gila robusta*), Colorado squawfish (*Ptychocheilus lucius*), and bonytail chub (*Gila elegans*) have been extirpated from Grand Canyon.

The purpose for developing a centralized tabular data base with linkage to GIS was to provide an integrated and comprehensive set of geographic-based information to aid biologists, resource managers, and administrators in decisions about the operation of Glen Canyon Dam. Development of this data base integration program will lead to the following:

1. Development of a consolidated, centralized fisheries data base template.

2. An archival system for endangered fish information, including individual attributes, meristics, photographs, tag numbers, habitat, etc.

3. Background information for a long-term monitoring program, including past collection sites for historic distribution and abundance, past and recent population demographics, and current research needs and data gaps.

4. Documentation of specific locations of fishery-related data collections to allow repeated site visits, which are essential to long-term monitoring.

5. Visual representation of fishery resources and sample locations in the Colorado River in Grand Canyon to facilitate impact analyses and resource assessments.

6. Facilitation of an exportation of data to other scientists and importation of newly collected information into a common data base.

7. A consolidated fisheries data base for resource managers with the information necessary to assess impacts of Glen Canyon Dam operations on fisheries resources.

Integrated Tabular Data Base

Three principal types of fisheries data were identified, including historic accounts and collections, past surveys, and GCES investigations. Historic accounts include an assimilation of reports, photographs, and diaries of travelers and visitors through Grand Canyon (Kolb and Kolb, 1914), as well as some early fish collections (Miller, 1946; 1955). Past surveys include studies conducted before GCES was implemented in 1983 (McDonald and Dotson, 1960; Stone and Queenan, 1967; Stone and Rathban, 1968; Miller and Smith, 1973; Holden and Stalnaker, 1975; Miller, 1946 and 1955; Minckley and Blinn, 1976; Sutkus, et al. 1976; Minckley, 1978; Carothers and Minckley, 1981; Kaeding and Zimmerman, 1983). Starting in 1983, GCES coordinated several past and ongoing studies (Maddux et al., 1987; Kubly, 1990; Angradi et al., 1992; Arizona Game and Fish Department, 1993 and 1994; Gorman, 1994; Otis, 1994; Allan, 1993; Weiss, 1993; Valdez et al., 1982; Valdez and Hugentobler, 1993; Valdez and Ryel, 1995).

Data from historic accounts and past surveys are assimilated from reports, identified by common format, and digitized in standard fields and codes to enhance archival value. Most data collected under GCES are digitized, and are available with permission and agreements with cooperating agencies and individuals. The data base will provide input to ongoing investigations and modify data collection protocols, if necessary, to facilitate future data integration.

Fisheries investigations in this region of the Colorado River basin have been conducted to evaluate endangered species, native fishes, and a popular trout fishery. Information collected includes data on individual fish (e.g., length, weight, tag number), habitat (e.g., depth, velocity, substrate), and water chemistry. Collection sites have been imprecisely located, using numerous geographic references, e.g., river miles, distance from dam, meters from shore, tributary mouth, etc. To integrate these data bases, accurate physical locations, with respect to geographic position in the landscape, become as important as the specific parameters measured.

Application of GIS

The GCES/GIS data base is being developed as an integrative tool for long-term monitoring, applied research, and assimilation of information across disciplines. This data base is structured with three levels of spatial accuracy. The first consists of data referenced to 1:24,000 quadrangle maps, which will achieve the National Map Accuracy Standard of 40 ft in the horizontal and half a contour interval in the vertical. The second level consists of data photo-referenced and transferred to the 1:2,400 scale orthophoto grid base maps developed for the GCES projects. These map products have 2.0-m accuracy in the horizontal and 1.0 m in the vertical. The third level of accuracy is survey-referenced data with sub-centimeter accuracy.

Previously collected fisheries data identified for entry into GIS were not entirely compatible with the three-level structure developed by the Bureau of Reclamation for the GCES/GIS data base (Werth et al., 1993). To allow for integration of fisheries information, a six-level structure was developed, ranging from level 1 as the most geographically accurate to level 6 as the least geographically accurate. Level 1 was survey information with sub-centimeter accuracy and included bathymetric maps developed from total survey station techniques and superhydro technology. Level 2 was primarily for information referenced to or mapped onto 1:2,400-scale orthophotos developed for the GCES projects, and included radiotelemetry tracking data accurate to the nearest 5 m, and gill and trammel net sample sites located to the nearest 10 m on uncorrected 1:1,200 aerial photographs. Level 3 was 1:1,200-scale maps, and included surficial habitat maps, current pattern maps, and shoreline habitat measurements located within 10 m, to provide an assessment of habitat conditions at different flow stages. Level 4 was 1:24,000-scale maps used for most of the fisheries data collected outside of the orthophoto areas. Level 5 was based on river mile referencing to the nearest 0.20 river mile, and was the least spatially accurate for quantitative fishery data. Level 6 provided a general location, and was used primarily for historic records and accounts with no specific spatial requirements.

Discussion

An integrated, centralized data base and GIS linkage is vital for providing comprehensive information on fisheries resources to managers of Glen Canyon Dam. Using GIS for fisheries information integration is a relatively new application of GIS technology. Traditional fisheries biology has not focused on relating fish locations to mapped information of large river resources. For many fisheries studies, the effort required to map actual river resources is not justified or planned. The increasing importance of the endangered and native fish requires decision makers to make better use of all available information. A GIS offers analytical capabilities in addition to query and viewing of archived fisheries information.

Fisheries information in a GIS data base provides an inventory of endangered and native fish handled by biologists and all associated information, including scanned photographs (to be used for morphometric measurements and archival purposes), tag numbers, meristics, etc. These data can be used as important historic information for developing long-term monitoring to identify past collection sites for historic distribution and abundance, past and recent population demographics, and current research needs and data gaps. Specific locations of fishery-related data collections are documented to allow revisiting previous collection sites.

The greatest long-term benefit of a GIS data base is the capability to share and exchange information between scientists and among managers that is linked both historically and spatially. To more fully understand the relationships between the various resources under study and Glen Canyon Dam operations, individual researchers need to be able to access and use other scientific data bases. An additional benefit of a GIS data base is the visual representation of fishery resources and sample locations. This representation facilitates evaluation of relationships between fisheries and other resources and enhances analysis capabilities for impact analyses and resource assessments.

The GCES/GIS fisheries data base will provide a structure for a consolidated, centralized fisheries data base that will be accessible to managers and decision makers. With a formalized structure, data from current and future research can easily be incorporated into the data base to provide an ongoing information and retrieval system. This data base is unique in that it is geographically referenced, multi-temporal, multi-accuracy, and multi-media. It is currently

being developed for the portion of the Colorado River in Grand Canyon and will serve as a template for the integration of the rest of Colorado River system. A great need exists for a standard fisheries data base structure for the entire Colorado River basin. This data base development can serve as a prototype to be expanded and improved as a valuable information source for many researchers for years to come.

The third study that was contributed to this report was conducted by Northern Arizona University School of Forestry. This work incorporated the use of current and historical aerial photography with existing 1:2400 orthophoto quads to develop a GIS data base to be used for analysis of vegetation change in relation to river regulation.

REPORT NO. 3
HISTORICAL PATTERNS OF VEGETATION CHANGE IN GRAND CANYON BASED ON A GIS ANALYSIS

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Introduction

Several studies have shown the dynamic history of riparian vegetation in Grand Canyon's river corridor (Turner and Karpiscak, 1980; Carothers and Aitchison, 1976; Martin, 1971). The current use of GIS analysis and photogrammetry is in establishing a permanent, quantitative, georeferenced record of vegetation change along the Colorado River. The current effort is unique in its ability to assess the impact of river regulation on riparian vegetation, including the initial damming of the river, post-dam flooding, and a more recent interim flow regime. Our approach considers community-level and species-specific vegetation responses to regulation, which will provide an understanding of large-scale processes and elements that comprise them. The permanent nature of this analysis will permit future riparian vegetation research within GIS reaches in Grand Canyon to consider an historical perspective while studying the present.

Although some data are available on vegetation responses to impoundment (see Waring, 1993), GIS analysis of vegetation change following river regulation is unavailable for most of the world's dammed rivers because of a lack of historical photographic records. The extensive aerial photography record of the Colorado River in Grand Canyon provides the opportunity to identify detailed vegetation responses to initial impoundment and subsequent dam operations.

Objectives

Our objectives are to describe the response of riparian vegetation along the Colorado River in Grand Canyon to river regulation, from the initial damming phase through the present (1965 to 1992). Our efforts will correlate azimuth, different depositional environments (e.g., above and below major tributaries), narrow and wide reaches and distance from the dam with vegetation cover, and will estimate their influence on vegetation responses to river regulation. These data will be archived within the GCES/GIS data base.

Discussion

We primarily consider two broad categories of Colorado River riparian vegetation, OHWZ (old high water zone) vegetation, which includes mesquite and acacia that were established high above the river before the dam, and NHWZ (new high water zone) vegetation, including native coyote willow and exotic tamarisk, that has become established in close proximity to the river following damming. Individual species we are studying include mesquite, which are migrating down into the NHWZ, pre-dam tamarisk in the OHWZ, and Goodding willow, a tree willow which appears to be negatively affected by river regulation.

Minimal vegetation occurred along the river prior to impoundment, mainly Goodding willow and the nonnative tamarisk, which occurred almost exclusively on separation bars. Separation bars may have been relatively stable habitats in the pre-dam environment, and frequent flooding prevented long-term colonization of vegetation in more exposed habitats.

Following impoundment, NHWZ vegetation cover increased by nearly 400% in GIS reach 5, despite a significant, flood-related decrease in vegetation cover in the early 1980s. This result indicates how productive riparian habitats can be in the absence of frequent flooding.

The OHWZ in GIS reach 5 appears to exhibit a trend of increased vegetation cover in 1984, which may relate to the flood conditions that occurred during the early 1980s. High flows may have supplied mesquites with much-needed water for growth. Analysis of OHWZ patterns within the five other GIS reaches will help to determine if this trend is a larger-scale pattern of response throughout Grand Canyon.

One of the environmental variables, depositional environment, may also influence vegetation cover along the Colorado River. Consistently less NHWZ vegetation cover was present in the mile below the Little Colorado River than in the mile above this tributary between 1965 and 1984; however, this pattern is reversed by 1992. Although vegetation cover increases both above and below this tributary from pre-dam times to the present, these data suggest that the rate of increase is greater below the Little Colorado River. A substantial influx of sediments from the Little Colorado River may be providing additional colonizable substrate for vegetation in this otherwise sediment-limited river system. We will measure vegetation patterns upstream and downstream from other tributaries, including the Paria River, Nankoweap Creek, and Tepeats Creek, to determine the extent of this preliminary finding.

This research will also relate to the demography of one riparian species, Goodding willow, which may be negatively affected by river regulation, over the last 30 years. Currently, little evidence of recruitment in this species exists within Grand Canyon; most individuals are mature or decadent. Large populations have become established recently at the end of Grand Canyon on Lake Mead and represent an enormous recruitment event for Goodding willow. We will establish the timing and basis of this event in the course of determining the age distribution of this species' populations through the canyon. Goodding willow's range is restricted to the southwestern United States. The Goodding willow - Fremont cottonwood association in Arizona is listed as threatened by the Nature Conservancy.

A thorough analysis of riparian vegetation responses to river regulation will be provided by this study. As a result of this work, nearly 30 years of data on georeferenced vegetation cover will be available for 50% of all GCES/GIS reaches. This study will provide valuable insights into the impact of river regulation on riparian vegetation, will produce a permanent, quantitative record that can be included in all future research and monitoring efforts involving riparian vegetation along the Colorado River, and will serve as a comparison for other river systems.

The fourth and final study to be included in this report was contributed by the U.S. Geological Survey and discusses how they are using existing GCES/GIS topographic and newly created bathymetric data to generate flow, sediment-transport, and bed-evolution models to predict sand accumulation or losses.

REPORT NO. 4
DEVELOPMENT OF CHANNEL-GEOMETRY INFORMATION FOR FLOW AND SEDIMENT-TRANSPORT MODELS

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Introduction

As a part of the GCES (Glen Canyon Environmental Studies), the USGS (U.S. Geological Survey) began in 1991 to develop a suite of flow, sediment-transport, and bed-evolution models for prediction of sand accumulation or loss in various reaches of the Colorado River and for determination of the response of sand deposits to discharges in the river produced by dam releases. Accurate characterization of channel geometry up to the highest elevation affected by all proposed or possible flows is required for these single and multidimensional models. Topographic information from published USGS topographic maps is not precise enough for use in the flow and sediment transport models under development and does not give channel morphology below the water surface.

The USGS began collecting bathymetric data for the river reaches in Reclamation's (Bureau of Reclamation) GIS data base in 1991 to supplement the topographic information in that archive that was developed photogrammetrically with bathymetry and to define the bed morphology for model development.

Reach 5 of the GCES/GIS set, extending from river mile 60 to river mile 72, was selected as the reach in which to begin model development because the Little Colorado River, which joins the Colorado River at river mile 61, is the largest source of sand for the Colorado River in Grand Canyon National Park, and because the reach downstream from the Little Colorado River mouth is important to native fish. Maps showing the combined Reclamation topographic and USGS bathymetric data are being prepared for the reach from just below the Little Colorado River confluence to just above Tanner Canyon Rapid at river mile 68.5—a 10.3-km segment of the 19-km-long GCES/GIS reach. The maps (fig. 14) will show topography with a contour interval of 1 m, except where near-vertical slopes make contours at that interval unreadable.

Methodology

Bathymetric data were collected with two generations of manual-tracking, range-azimuth positioning systems. Both systems consist of an electronic theodolite to establish the ties to the control network and a modified laser EDM (electronic distance meter)—mounted above the theodolite—to track a boat-mounted target. Depth was measured with a sonic depth sounder, then digital position and depth data were sent directly or via radio modems to a datalogger or laptop computer. Depth also was recorded on paper charts.

Position information is lost or incorrect information is recorded when an instrument operator fails to track the boat within a preset tolerance, when the operator loses sight of the boat as it passes behind a rock outcrop, or when the laser reflects off an object other than the target, such as a tree or a cliff face beyond the boat. Also, interference can occasionally cause the radio

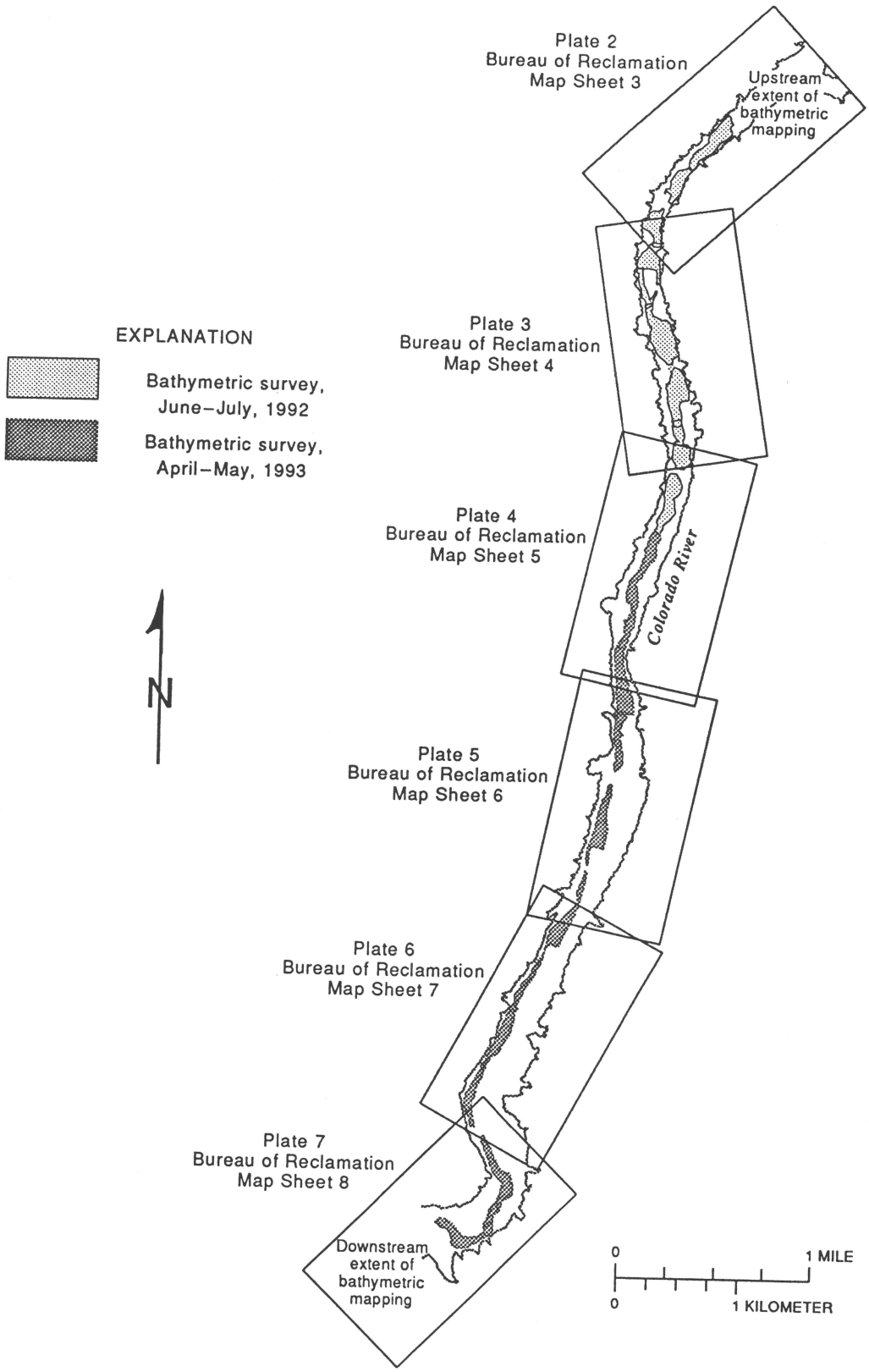

Figure 14. - Location map of bathymetric survey.

modems to send spurious numbers to the recorder. Incorrect points are typically off the line of data defining the path of the boat and are easily identified when plotting a planimetric map of the data. The digital depth sounder can send incorrect digital depth values to the recorder if the water is too shallow, if strong turbulence or air bubbles in the water column reflect the transducer signal, or if the depth changes too quickly for the digital recorder to track.

The digital data collected in the field were edited to identify and remove data with incorrect boat position, incorrect river depths, or both. When small groups of points with incorrect positions but correct depths were found, the depth information was retained and new positions were calculated by linear interpolation between the two positions on either end of the gap along the boat track. Incorrect depths were found by comparison of the digital record with the paper-chart record collected at the same time. Where the channel bottom was recorded on the paper chart but the digital record contained incorrect depths, the paper-chart record was digitized and the incorrect depths were replaced with the newly digitized depths. In some cases, the bottom was not recorded on either the paper chart or the digital recorder, so the navigation data were not used.

After verification of position and depth data from bathymetric surveys, the positions of the data points were converted from the arbitrary x, y coordinate system in which they were collected into the Arizona State Plane coordinate system used in the GCES/GIS data base (Werth et al., 1993). Depth data were converted to elevation using water-surface-elevation information collected at the time of the survey or by adjustment of the bathymetric data to elevation of the topographic data set in areas of overlap.

To generate a surface from which to compute contours, a network of triangles (TIN) was first created from points in the combined topographic and bathymetric data set using the Delaunay method of triangulation (McCullagh and Ross, 1980) as implemented by the ARC/INFO software (Environmental Systems Research Institute, Inc., 1991). An interpolation algorithm using a bivariate fifth-degree polynomial in x and y (Akima, 1978) was used to compute contour-line positions from the network. During development, the interpolation scheme was evaluated for accuracy by comparison of contours computed by interpolation from the TIN to contours developed photogrammetrically for the topographic data set—the contours that are available from the GCES/GIS data base.

The ability of TIN and the interpolation scheme to represent the surface was also evaluated by examining the difference between measured and interpolated elevations of points not used to generate the TIN. No areal pattern was revealed when the deviations of the measured elevation from the computed surface were plotted on a map of the study reach, and no bias or trends were shown by the relation of the deviations to elevation. The difference between measured and interpolated surfaces is a measure of the irregularity of the channel shape resulting from bedrock controls and bedforms. Form drag on these irregularities produces the primary friction on the flow. In the models under development, the roughness parameter used is a measure of the deviation of the bed surface from the local average bed surface and typically is considered to be proportional to the dimensions of obstacles on the bed, such as bedforms, gravel clasts, or boulders. For the flow model, the roughness parameter was determined from the deviation of the measured river depths from the smoothed surface represented by the computational grid.

The combined topographic and bathymetric data presented in the maps were used to develop grids of equally-spaced points representing channel morphology for multidimensional flow, sediment-transport, and bed-evolution models. Grids for model computations were determined

by first computing the x and y coordinates of the grid points in the coordinate system of the data from endpoints of the upstream boundary, the length of the grid, and the grid spacing in the x and y directions. A 5- by 5-m grid spacing was used for initial model computations. Elevation at each grid point was then computed from the TIN developed for the reach using the interpolation scheme described above.

As a part of the interim-flow monitoring program initiated by GCES in 1992, the USGS established networks of monumented cross-sections downstream from the two largest tributaries, the Paria and Little Colorado Rivers, to determine changes in sand storage at these locations resulting from tributary floods and the subsequent remobilization of sand supplied by these major sources (fig. 15). Measurements at the monumented sections, repeated about three times a year since their establishment, demonstrate that inflow of sand from the Little Colorado River and subsequent scour can produce changes ranging from 0 to 12 m in bed elevation at the measured sections. Measurements at the cross-section network downstream from the mouth of the Little Colorado River made before and after a Little Colorado River flood in January 1993 were used to check the accuracy of model results by comparing the bed shape predicted by the model to the measurements at the monumented cross sections.

The volumes of sand deposited by the January 1993 flood in four pools downstream from the mouth of the Little Colorado River (fig. 16) and the processes that determine the distribution of sand among the primary pool-scale depositional sites—eddy-associated, channel margin, and main channel—were evaluated with a combination of modeling and the field measurements described above. The model computes flow fields, sediment-transport fields, and bed evolution, and has been used to interpolate, both in time and space, between the cross-section measurements made before and after the Little Colorado River flood. The difference between the initial bed surface and calculated surfaces for subsequent times was used to determine rates of deposition, both for reaches as a whole and by depositional environments, and to determine total volumes of sand deposited by tributary flood.

Initial Results

Initial model results show that deposition rates and volumes of sand stored are quite variable among pools and depositional environments. The volume stored in pools depends on pool morphology. Of the four pools studied, the pool that is widest and has the largest expansion ratio accumulated about four times as much sand as each of the other three pools. Storage in the other three reaches studied was limited by a relatively short length or long narrow shape. All four reaches accumulated sand rapidly initially and reached their storage capacity within 2 days. Deposition rates along the channel flanks were much lower than in the main channel, but the total volume of sand accumulated in the four study reaches was nearly equally distributed between the main channel deposits and the deposits along the channel flanks.

Discussion

A complete set of topographic data for the full river corridor between Lake Powell and Lake Mead sufficient to use for even crude flow and sediment-transport models does not exist. Cross sections measured by USGS in 1984 (Wilson, 1986) are sufficient to permit determination of reach-averaged topography for a carefully designed one-dimensional flow-routing model for river stages associated with discharges less than 30,000 ft^3/s. For higher stages, no topographic information was available for use in such a reach-averaged model. To overcome this deficiency, we used topographic data from the GIS reaches to obtain the morphologic characteristics of the

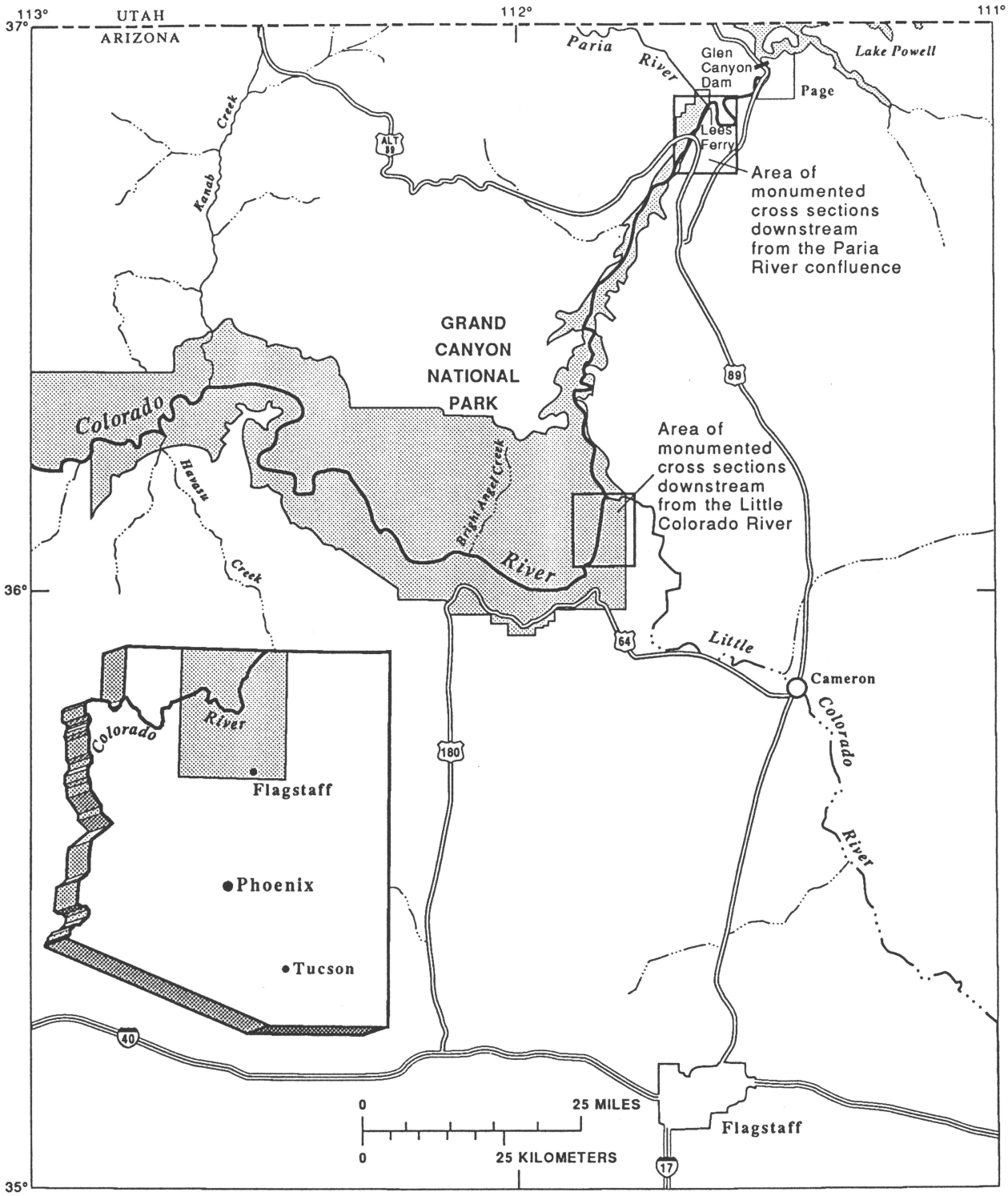

Figure 15. - Location map of cross-section networks downstream from the Paria and Little Colorado Rivers.

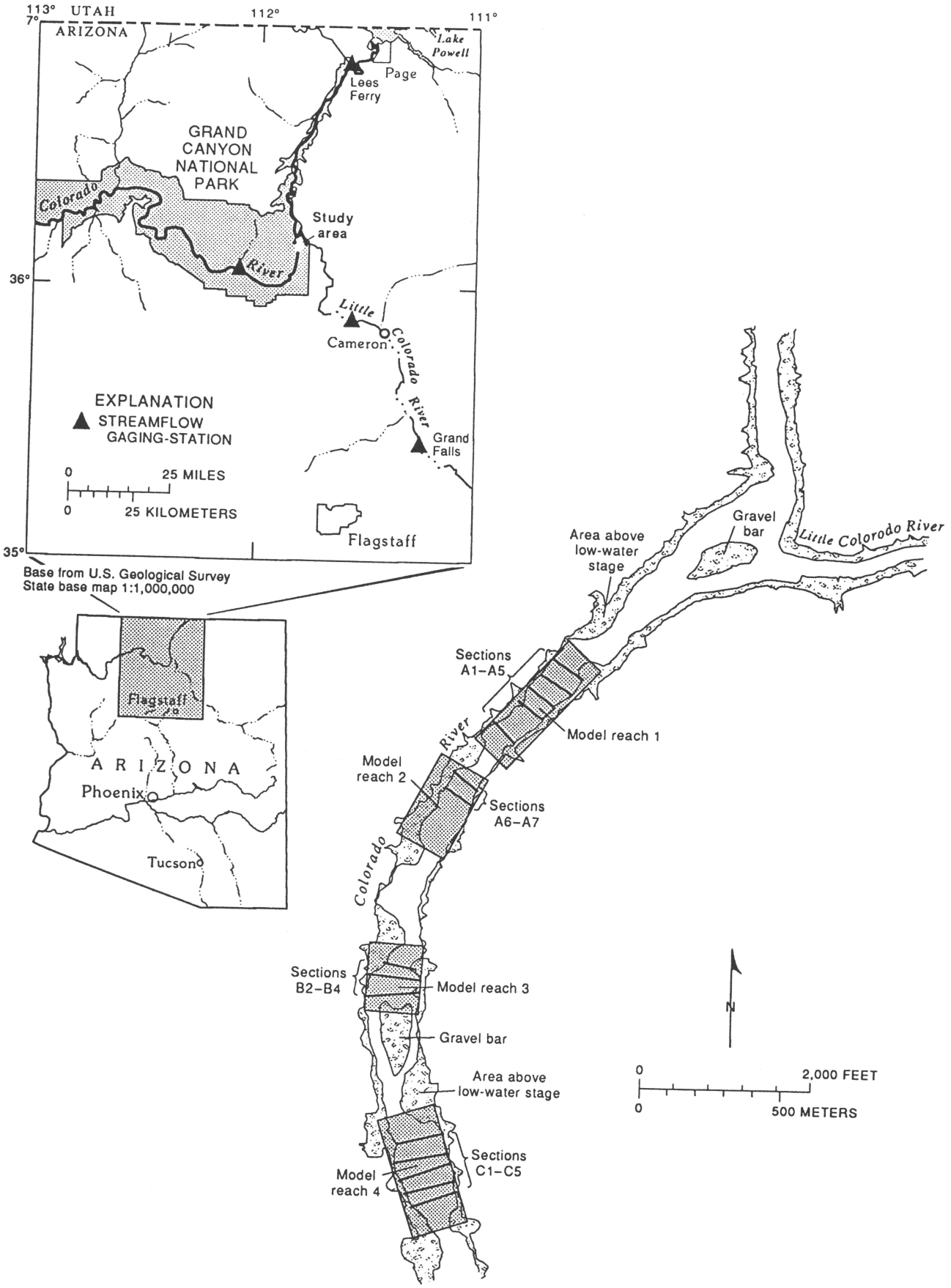

Figure 16. - Location map of model reaches, measured cross sections, and streamflow-gaging stations used in the model study.

river corridor at elevations above a river stage corresponding to 30,000 ft^3/s discharge. Our approach is to determine the river centerline and use it to calculate river width at a discharge of 5,000 ft^3/s as a function of downstream distance in each GIS reach. The river stage corresponding to a discharge of 5,000 ft^3/s that is part of the GIS data base was used for this calculation. From width information, statistical width properties at 5,000 ft^3/s can be obtained. Next, a dense set of cross sections extending to the top of the zone in which topographic data exist was produced for each GIS reach, using the 5,000-ft^3/s centerline. From this information, river width and statistical properties are determined as functions of stage. Cross-sections representing average geometry can then be calculated for each GIS reach, and average cross-sections can be related to discharge using a reach-average roughness that depends on variances of river width, river cross-sectional area, and thalweg depth. The geometric properties of reaches with no GIS sections will be determined by interpolation between upstream and downstream reaches where the properties are known.

CONCLUSION

The GCES/GIS (Glen Canyon Environmental Studies/Geographical Information System) was initiated in 1989 to consolidate and integrate diverse and complex data sets. The objective was to provide a technique to evaluate resource linkages as related to the monitoring and research programs conducted under GCES. Seventeen sites, representing about a quarter of the total area of the Colorado River through the Grand Canyon corridor, were selected as GIS development sites. The 17 sites were selected by researchers and resource managers. The selection was based on representativeness, location of historical or special interest resources, or special study sites relating to Native American or endangered species concerns.

Within each GCES/GIS site, up to 40 resource overlays have been geographically referenced and added to the information data base. These overlays range from velocity profiles to cultural resource site locations. The GCES/GIS will form the consolidation point for future long-term monitoring and research locations related to evaluation of the Adaptive Management Program for Glen Canyon Dam. Future development will include the addition of Lake Powell, Lake Mead, and the Little Colorado River basin into the overall resource base. As these elements are added, a true ecosystem approach to the management of the natural resources can occur.

A pilot study was initiated at the GCES/GIS study site No. 5, the confluence site of the Little Colorado River with the mainstem Colorado River. This site was selected because of its historic importance and the fact that a great deal of scientific information had been collected in the 13-km (8-mi) reach. The objective of the pilot study was to develop the protocols and methodologies necessary to integrate the different resource bases. Use of the GIS protocols would allow for consistent approaches and applications within the other GIS sites. It was also intended that the pilot study would allow for the development of guidance for specific data formats and geographic control for the long-term monitoring and research program.

Development of the pilot study allowed determination of data that are available and practical for use in the GIS. The protocols also allowed determination of specific features that should be monitored and the temporal increment at which they should be evaluated. An administrative benefit derived from the study was identification of the agency that should be responsible for data collection and analysis and specific digital products to be developed. Lastly, the study allowed development of software that would allow user-friendly access, query capability, display, and analysis of GCES/GIS information. In developing consistent protocols, specific application to evaluate trends, patterns, and applications of predictive models could be developed.

Completion of the site No. 5 Pilot Study included development of linkages of specific aquatic, terrestrial, sediment, and cultural resources. These resources were overlain on the already existing base maps. The base maps included the above-ground topography, geology, flow levels, water quality relationships, velocity fields, and bottom topography.

The sandbar study, conducted by the Geology Department at Northern Arizona University, focused on the relationship between sediment deposits of interest along the river corridor in the Grand Canyon. The sediment sites selected represented locations of particular concern for recreation, resource, or cultural concerns expressed by the National Park Service or the Native American tribes. The analysis reported included using the GCES/GIS to develop a comparison of volumetric differences between different flow levels and times. A second analysis integrated into the GIS environment was a hyspometric analysis of the amount of exposed sediment at different flow levels. This information was then integrated with a predictive equation utilizing residual components to evaluate changes in available sediment over time and flow level.

The aquatic fish study, performed by Bio/West (private contractor), focused on the use of the GIS to catalog disparate biological information, integrate numerical data bases with geographic control, and to evaluate fish movement with available habitats. Fish information has historically been very difficult to link to specific ground control and a GIS. Once the linkages were established, it allowed for analysis of movement information, catch data as related to specific population nodes, and habitat analysis. The effectiveness of this approach increased substantially once the ability to link in bottom topography occurred.

The terrestrial/riparian study, performed by the Forestry Department at Northern Arizona University, focused on evaluating the vegetative trends at selected sites along the Colorado River corridor. Specific evaluations included density and species changes over time and flow level, and evaluation of the differences between the Old High Water Line and the New High Water Line (dam controlled). The GIS approach allowed for comparison between years and flow levels and evaluation of demographic information. Results indicate that the GIS can be used to evaluate riparian habitat changes in relation to dam operations.

The final study focused on the linkage of channel geometry and flow information with discharge and sediment levels. This study, initially completed by the U.S. Geological Survey, developed specific methodologies linking flow, sediment transport, and bed-evolution models with the GIS program. The objective is to develop data for predictive models to forecast sand accumulation or loss within the study reach. Initial results show that deposition rates and volumes of stored sand are variable among the geomorphic types and are often positively correlated with pool morphology. Linking the information into the GCES/GIS environment allows for the viewed comparison and evaluation of changes of sediment volumes over time and flow levels.

The GCES/GIS is a valuable tool for the successful implementation of long-term monitoring and research necessary to make the Glen Canyon Dam Adaptive Management Program functional. From this consistent and integrated data base, the resource managers can better set biological and physical goals for the Adaptive Management Program.

The strength of the GIS is in its integrative abilities. Unknown and unstudied relationships allow for more expansive evaluation. The GIS will also help to focus future efforts and will result in more efficient monitoring and research programs. Future work will continue to focus on development of the information linkage to predictive models, equations, and analysis.

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APPENDIX A

Site Segregation

Geomorphic Reach and River Mile	Monitoring Site and River Mile	Responsible Agency
1 = Lake Powell		
2 = Dam to 0	1 = Dam to -10	Reclamation/GCES
	2 = -4 to 2	Reclamation/GCES
	*14 = -10 to -4	Reclamation/GCES
3 = 0 to 11	*17 = 2 to 9	Reclamation/GCES
4 = 11 to 22.5		
5 = 22.6 to 35.9	*16 = 29 to 42	Reclamation/GCES
6 = 40 to 61.5	3 = 42 to 48	Reclamation/GCES
	4 = 51 to 56	Reclamation/GCES
7 = 61.6 to 77.4	5 = 60 to 72 and 1 mi up the LCR	Reclamation/GCES
	*15 = 1 to 11 mi up the LCR	Reclamation/GCES
8 = 77.5 to 117.8	6 = 93 to 99	Reclamation/GCES
9 = 117.9 to 125.5	7 = 120 to 123	Reclamation/GCES
10 = 125.6 to 139.9	8 = 133 to 138	Reclamation/GCES
11 = 140 to 159.9	9 = 143 to 145	Reclamation/GCES
12 = 160 to 213.8	10 = 179 to 181	Reclamation/GCES
	11 = 207 to 210	Reclamation/GCES
13 = 213.9 to 225		
14 = Lake Mead	12 = 225 to 230	HUALAPAI
	13 = 273 to 276	HUALAPAI

* = Special study site

Note: sites that overlapped two geomorphic reaches were assigned to the reach that encompassed the majority of the site.

APPENDIX B

GCES/GIS Information Guide and Operating Protocol
January 14, 1994

CONTENTS

Page

Introduction 49
Purpose of standards 49
Need for metadata 49
Cooperating agencies: roles and responsibilities 50
Historic data 51
Metadata forms 51
Metadata elements and software 51
Future research 54
GCES research study trip checklist 54
Define types of spatial referencing to be used 56
GCES survey department support 57
Data exchange 57
Digital data exchange protocols 57
Non-GIS data 59
Hard copy data 60
Attachments 60
Accuracy levels within the GCES/GIS 60

TABLES

B.1 Suggested mandatory elements for SIM catalog entries 52
B.2 Suggested mandatory elements for data transfer 53

INTRODUCTION

Purpose of Standards

The GCES (Glen Canyon Environmental Studies) **Geographic Information System Information Guide and Operating Protocol** has been developed to provide guidance to the GCES researchers and data base developers and as a template for data integration. The GIS (geographic information system) for the GCES is a cooperative, interagency, and tribal effort to integrate data and information being collected through the GCES research program. The short-term objective of the data management program is to ensure that the data collected under the GCES program, historical or otherwise, are not lost as the initial research studies are completed. However, the most important objective deals with long-term data management, the need to integrate data, and to provide guidance for future data base development.

The GCES/GIS is a component of the larger GCES SIM (Scientific Information Management) system which provides for the coordination of the large amount of varying data types being assembled under the GCES research and monitoring program. A primary objective of the GIS is to provide the analytical ability for integrating and overlaying data. To accomplish this objective, research data sets and study sites must be converted into the GIS in a consistent format, geographically controlled, and maintained.

The **purpose** of the standards presented in this information guide is to provide guidance and protocols to ensure that the data collected under the GCES program, and provided to the GIS and SIM, are capable of being integrated with the other research data.

Need for Metadata

Metadata, or data about data, is important in the expanding role of data base development and management. History is replete with examples where important resource data have been lost, are not compatible with other data, or are questioned because critical interpretation of information is not available. Research and monitoring of the sensitive resources in the Grand Canyon and the Colorado River require that the information collected through the GCES program be usable among a broad range of formats and researchers. Integrated data have an important role in the research and monitoring of resources in the Grand Canyon. In the future, integrated and controlled data will be **mandatory** in the GCES research and monitoring program.

This guide is designed to be dynamic, a document that will change and be modified as new information dictates. The metadata and operating protocol outlined in this document are the first step in setting the data standards for the future. It is our intent that the guidelines established and developed through the GCES will be **mandated** in each new research and monitoring contract to ensure that consistent elements of the data base are maintained.

Your involvement in the development and use of the metadata is very important. Without your input and suggestions, the metadata and use of the information will not be viable.

Cooperating Agencies: Roles and Responsibilities

The GCES/GIS has entered the production phase and will begin the integration of tabular and overlay data and development of a prototype for the long-term monitoring program. To maximize our effort with limited funding we have allocated the work load to several key offices and research groups. Their responsibility is to work under the general guidance of GCES and to develop the templates for the integration of the data.

The primary responsibility for **coordination** of the overall GCES/GIS program is vested in the Flagstaff Office. Sherry Jacobs is the primary contact and directs the overall program requirements. The Technical Service Center, Remote Sensing and Geographic Information Group, under the direction of Michael Pucherelli and Patrick Wright, provide technical guidance and prototype development, and coordinate these aspects with the broader U.S. Department of the Interior requirements. The Technical Service Center is also responsible for assistance in the development of programs to integrate data bases and remote sensing applications. The Hualapai Tribe is providing technical guidance in the lower Grand Canyon.

The technical coordination of the primary resource category templates has been delegated to specific research groups for development. The four areas of fiscal year 1994 effort are listed below:

Aquatic Ecology - The primary responsibility for template development rests with Bio/West, Inc. The focus will be to identify aquatic habitats in the mainstem river and to develop a data base which will integrate ongoing and historic information for scientific studies. Their coordination efforts will include integration of the Navajo Nation's development of the Little Colorado River GIS with USFWS, Bio/West, Inc., AGF and ASU data in a GIS environment.

Sediment Resources - Matt Kaplinski, Dave Best, and Lee Dexter, Northern Arizona University, are leading the coordination and development of the sediment data templates for GCES. Their efforts will include coordinating the studies of Jack Schmidt (geomorphology), Bob Webb (debris flows, and Muni Budhu, Brian Cluer, Julia Graf, Jim Smith, Ned Andrews, and the National Park Services (beach changes). Matt will be focusing his energies on this effort and will coordinate these studies through the Geology Department at NAU.

Cultural Resources - The National Park Service, Glen Canyon National Recreation Area, and Grand Canyon National Park are coordinating cultural resource information with the individual Native American tribes. The intent is to use the GIS as a tool to identify areas of concern. This identification will assist future researchers and long-term monitoring personnel in evaluating how changes in dam operations or management of the river system may affect specific locations of interest. Included will be identification of areas of significance from a cultural perspective: archeological, botanical, or religious.

Riparian Resources - The GCES, the NPS, and the NBS (National Biological Survey) will coordinate the development of the riparian GIS templates. The NPS will take the lead on the vegetation and marsh studies, the NBS will focus on the avifauna and eagle studies, and the GCES will focus on the physical relationships. The Hualapai are providing primary direction in the lower Grand Canyon.

The overall intent is to make the GIS a consistent, integrative tool for long-term monitoring. The main strength of the GIS rests with its overlay and integrative ability and in its function as a visual tool showing where data are geographically located and what research is being conducted in those areas.

HISTORIC DATA

Metadata Forms

Metadata (data about data) are an integral part of a functional GIS (geographic information system), for contemporary as well as historic spatial data. Metadata allow users of the GIS to identify, understand, and use contributed datasets.

The specific goals of the metadata effort are as follows:

1. **Catalog existing data.** This process allows scientists to easily identify data produced in the past and begin the retrieval process.

2. **Understand data contents.** Identification of the type of data collected during a study allows scientists to distinguish between data bases that may be useful to their research and those that may not.

3. **Facilitate use of data.** Knowledge of data format, projection, classification, and use of other systems for identifying spatial elements in the data base allows scientists to apply them to current studies.

4. **Catalog data in production.** Awareness of projects in process avoids reproduction of data, and also alerts interested parties to data bases that will be available for future use.

Metadata Elements and Software

To accomplish the goals listed above, GCES and Reclamation's Remote Sensing and Geographic Information Group have compiled a list of essential metadata required from all contributing scientists. The elements listed here are established on FGDC (Federal Geographic Data Committee) standards for metadata. Table B.1 lists the suggested metadata elements to be included in the SIM (Scientific Information Management) catalog work. Table B.2 lists the metadata elements required with the submittal of any contributed data for the GCES/GIS.

Table B.1. - Suggested mandatory elements for SIM catalog entries.

Identification Section	Source Information
Data Set Identity	Source Name
Theme Keywords	Bibliographic Reference
Representation Model	Source Scale
Data Set Description	Creator of Source
Data Set Extent	Date(s) of Source Materials
Resolution of Data	
Projection Information	**Metadata Reference Section**
Projection Name	Metadata Revision Date
Horizontal Datum or Ellipsoid	
Vertical Datum or Ellipsoid	
	Data Custodian Information
	Contact Organization
	Contact Person or Title
	Contact Mailing Address
	Contact Telephone

Table B.2. - Suggested mandatory elements for data transfer.

Identification Section	Source Information
Data Set Identity	Source Name
Theme Keywords	Bibliographic Reference
Representation Model	Source Scale
Data Set Description	Creator of Source
Resolution of Data	Date(s) of Source Materials
Transfer Format	
Transfer Size	
Projection Information	**Data Quality**
Projection Name	Positional Accuracy
Horizontal Datum or Ellipsoid	Positional Accuracy Method
Vertical Datum	Attribute Accuracy
Projection Units	Attribute Accuracy Method
Standard Parallel	Data Model Integrity
Longitude of Central Meridian	Completeness
Latitude of Projection Origin	
Zone Number	
False Easting	
False Northing	
Table Definitions	**Data Custodian Information**
Table Identity	Contact Organization
Table Definition	Contact Person or Title
Table Definition Source	Contact Mailing Address
	Contact Telephone

The purpose of the **Identification Section** is to describe the general data content, spatial extent, and use of data. The **Projection Information** defines the horizontal and vertical coordinate systems used for the spatial data. **Data Custodian Information** provides "points of contact" for the data. The **Data Quality** section describes the quality of the data in terms of accuracy. The **Metadata Reference Section** reports the date that metadata was submitted, and persons to contact regarding the metadata. **Source Information** provides a description of documents used to compile the data.

For past and present research to be valuable to the GIS, the defined metadata must be completed and received for documentation. To simplify this process, the Technical Service Center has assembled a program that automates the retrieval of metadata. It is presented to each scientist in the form of a WordPerfect file on a disk with explanatory text. The file to be filled out is simply a series of cells, preceded by examples, into which the requested data can be submitted. The WordPerfect file is then saved and returned to the responsible agency. It will then be converted into a DBase file that can be entered into the SIM program and queried.

FUTURE RESEARCH

GCES Research Trip Checklist

This checklist must be used for all river trips associated with GCES-funded research. Use of this checklist minimizes the potential for errors or omissions in the data collection and reduction process, and minimizes the potential for duplicating data collection efforts.

1. _____ Trip Request Approval

Submit a completed Trip Request Form (attached) and this checklist to _____ for review. A preliminary discussion with the GCES surveyors may be necessary to determine the spatial referencing method that is best suited to your accuracy needs, so that you can clearly state your logistics and support requirements. GCES will not proceed with logistics and support coordination until this item has been signed off by the GCES Program Manager.

The attached Trip Request has been approved. Please proceed with the necessary planning/coordination.

_____ _____

Dave Wegner **Date**
GCES Program Manager

2. _____ Survey Coordination

Have the GCES surveyors verify that the proposed spatial-referencing method will meet your accuracy requirements. At this time, you should also acquire all necessary spatial referencing materials from the surveyors, (i.e., maps, photos, control point coordinates and documentation, etc.). The surveyors must sign off on this item before logistics reservations can be made.

The GCES Survey Department is available (as scheduling permits) to assist with field data collection and reduction. The following field surveying services are available:

GPS Surveys - This technology is useful for referencing study sites to within ±1 m (assuming selective availability is off). GPS is also used in a differential mode to establish network control points to accuracies of a few centimeters. GPS technology is constantly evolving. Call the GCES surveyors to find out if this technology can be used to meet your referencing needs.

Total Station (Conventional) Surveys - This is the most common survey method used for GCES studies. A total station is set up on a known point, and another known point is backsighted for position reference. This method is useful for acquiring very accurate topography (up to 0.25 m, or better, if you have the time); delineating boundaries of vegetation plots, habitat zones, and cultural sites; locating individual plants, nesting sites, etc. An electronic field book simplifies the storage and retrieval of this information, allowing for easy compilation of maps and digital output products.

Bathymetric Surveys - These are a take-off on total station surveys that are used for mapping underwater topography. The GCES super-hydro unit has an accuracy of ±0.5 m vertical and ±1 m horizontal. Data can be output in an ASCII format. This type of survey is useful to define underwater habitats or sand movement over time.

Automatic Level - This instrument is available for determining precise elevations of study sites, and is accurate to ±0.005 m.

Hand Level - A nice tool to have on a trip when relative elevations are needed. Hand level accuracies vary significantly from one operator to the next. Consistent field procedures should yield vertical accuracies of ±0.1m.

Spatial-referencing methodology has been reviewed with this trip's Principal Investigator. On this trip, we have elected to:

_____ Accompany the trip to provide surveying services.

_____ Train trip members to perform the necessary surveying or referencing.

_____ Verify the proposed methods, procedures, and experience of the field survey crew for the trip.

In addition, we have provided the following reference materials:

_____ Maps (describe)

_____

_____

_____

_____ Photos (describe)

_____

_____

_____

_____ Survey Control or Point Descriptions (describe)

_____

_____

_____

_____ If GCES survey methods and protocol are followed, expected accuracy for data collected on this trip should be no greater than

_____

_____ Other (describe)

_____

_____

_____

OK to proceed with logistics coordination.

_____ _____

GCES Surveyor Date

3. _____ Data Exchange

Data exchange format and delivery schedule has been reviewed for compliance with GCES protocol. Metadata form has been reviewed with this trip's Principal Investigator.

Proposed data type and exchange format:

_____
_____
_____
_____

Proposed delivery date(s):

_____
_____
_____

OK to proceed with trip logistics scheduling.

_____ _____

Sherry Jacobs **Date**
GIS Coordinator

Define Type of Spatial Referencing to be Used

Data collection methodologies all have advantages and disadvantages, including time requirements, accuracy level, and cost. Three basic classes of data collection methodologies were available: photo, survey, and map-referenced data. The following text summarizes the fundamental data collection methodologies and their corresponding time and accuracy constraints.

1. Photo-referenced data are point, line, or polygon data drafted onto a mylar overlay that is registered to an aerial photo. The data then must be corrected for photo distortion and transformed into the proper map projection, generally Arizona State Plane coordinates. Three basic methods of rectification and transformation can be used:

a) Data can be transferred to an orthophoto base map, which can be supplied by GCES.
b) A stereo or mono transferscope can be used to correct for photo distortion.
c) An analytical stereoscope can be used to achieve the same results.

The resulting data must be converted to digital format by either scanning or digitizing, and then must be attributed. Time demands, accuracy level of the final data, and cost of these methodologies vary. The accuracy of the data also depend on the scale of photography used and the specific methodology.

2. Survey Referenced Data are point, line, or polygon data that are referenced by a survey crew on site. Using the ARC/INFO command "Generate," the data can be transferred from coordinate data to digital GIS relatively quickly. Depending on the amount of control used to define the spatial data, survey referencing can be very accurate. However, it is also very time and cost intensive.

3. Map Referenced Data consist of point, line, or polygon data that are referenced to a mapsheet, generally topographic. The resulting line data must be converted into digital format by digitizing or scan-digitizing and then must be attributed. Accuracy in this methodology depends on the scale and accuracy of the topographic map used, as well as the ability of the interpreter to correctly assess lines of elevation between the map and the real-world.

GCES Survey Department Support

1. Training - The GCES surveyors will train individuals in the use of surveying equipment and methods if it is determined to be the most efficient approach to the task at hand. A GCES surveyor often must accompany a data collection trip to provide training in the specific procedures that will be used to collect a given type of data. Training is a time-consuming process. We welcome the opportunity to train others in field survey techniques, but ask that a commitment be made by the trainee's agency to use the trained personnel on future data collection trips.

2. GCES surveyors can provide the following data reduction services:

a) Edit super-hydro data and deliver in ASCII file format.

b) Edit total station data and deliver in ASCII file format.

c) Produce digital and hard copy maps from total station and bathymetric surveys.

d) Reduce GPS surveys and deliver real-world coordinates for surveyed points.

e) Provide problem solving assistance for collected survey data.

f) Accompany data collection trips when necessary.

For items b) and c) above, we prefer to train individuals to do the work themselves because our workload precludes us from completing items in a timely fashion.

DATA EXCHANGE

Digital Data Exchange Protocols

Glen Canyon Environmental Studies data development is intended for scientific monitoring, evaluation, analysis, and planning. The GCES Geographic Information System is being used for GCES data base development and analysis. Completed data sets will be available for distribution. The following protocols are to be followed when requesting data from GCES.

1. OFFICIAL REQUEST

To maintain an accurate record of data distribution, GCES will require that each request for specific data base records be initiated with a `Letter of Request' to our Research Librarian, Richard Quartaroli. The request should identify who and what organization is requesting the data, and other pertinent information. The request should be sent to:

Richard Quartaroli, Research Librarian
C/O GCES
P.O. Box 22459
Flagstaff, AZ 86002-2459

2. MEDIA FORMATS

Once the `Letter of Request' is received and recorded, the data transfer process will begin. The GCES requires that each data base request include the desired media for the specific data base transfer (please supply disks or tapes to be used). The following media formats are supported at GCES:

- 1/4-in. cartridge tape in Qic 150 Mb (SUN default) format

- 8-mm (Exabyte) tape in 2.5-GB and 5.0-GB formats

- GCES can also support 3.5-in., 720-kb and 1.44-Mb DOS formats, although the recommended media is either the 1/4-in. or 8-mm tapes because the data size will usually cover numerous diskettes.
- The Technical Service Center can use 4-mm media formats, but the turn-around rate cannot be guaranteed.

If you do not have these options available, you may be able to use the resources of local governmental agencies or institutions of higher learning. If an agency or person requesting information from GCES is unable to use the aforementioned data transfer formats, other options may be worked out on a case by case basis.

On the `Letter of Request,' identify the contact person(s) at your particular organization. This person should be someone who is usually in your office and who can be contacted for information regarding the data transfer if any problems should occur.

3. ARC/INFO FILE TRANSFERS

GCES will require all data being transferred to be in EXPORTed format. All GIS data that comes from GCES will be in ARC/INFO EXPORT format. Data bases that are not spatially referenced in the GIS will be transferred as specified between the requester and GCES. Contact Richard Quartaroli for information on non-GIS data transfers.

4. METADATA

Data base files transferred from GCES will always contain metadata or information on the specific data bases included. Metadata standards are currently being developed by numerous organizations. An example is included from the Bureau of Reclamation metadata format currently being used by GCES, but this format is in development and subject to change in the near future. Once a final metadata standard is agreed upon, all data received by GCES will be required to contain the specific information requested. Until the final metadata standards are in place, the information shown in the metadata example will be required for all data transfers with GCES.

5. UNIX PROTOCOLS

In almost all transfers, the data should be written in uncompressed "tar" format. Because tar does not support multiple volumes (tapes), "cpio" will be supported in cases where data will span multiple tapes. When a 1.44-Mb DOS floppy will be used to transfer data, "tar" will be used to create a single file (all data and metadata files), which will then be copied to the floppy. This file can also be "compress"ed (UNIX) to fit on a single floppy if necessary (or possible). A "readme" file should then be copied to the floppy to describe how to read the floppy once it gets to its destination. Non-spatially referenced data will usually not require large storage space, and the procedure stated above will not be necessary.

VERY IMPORTANT - When the directory or files are written to the media for transfer, "relative" pathnames should be used, not "complete" pathnames. For example, if the directory "roads" were going to be transferred to another system, the "tar" command might look like this:

```
GCES% tar cvf /dev/rst1 roads
```

The "tar" command should **NOT** look like this:

```
GCES% tar cvf /dev/rst1 /home/earth/workspace/roads
```

When a "complete" pathname that begins with "/" is used to write the media, the "complete" pathname gets created when the media is read back. That "complete" pathname makes it VERY difficult for the person receiving the data to restore it where room is available on the system or network!

6. HELP

Any questions or comments concerning these procedures can be directed to **Richard Quartaroli, Sherry Jacobs, Glenn Bennett, or Jeff Wilkerson at GCES, (602) 556-7455.**

Non-GIS Data

The GCES (Glen Canyon Environmental Studies) Research Library holds non-GIS data in various formats. Final reports from Phase I, numbering 39, and Phase II, now numbering 16 of about 106, are foremost among the printed documents. Many other technical reports are housed in GCES's SIM (Scientific Information System) library, including the multi-volume, 770-page, GCD (Glen Canyon Dam) DEIS (Draft Environmental Impact Statement).

The most heavily used and valuable of the library holdings are aerial photographs of the Colorado River corridor through the Grand Canyon from Glen Canyon Dam (river mile -16) to Lake Mead (river mile 283). Dating from 1965, the images lend themselves to comparisons of pre- and post-Glen Canyon Dam (1963) riparian environments. Especially important are the pre-dam images, because they show vegetation, sedimentation, and geomorphic examples of the river corridor during a time when the Colorado River flowed unregulated.

Aerial video images only date from 1984, the middle of a period of unusually high post-dam flows. Usually used on the MIPS (Map and Image Processing System), the 3/4-in.-format videos are useful for providing a comprehensive view of the river corridor and in identifying areas of research interest.

Unfortunately, no aerial visual images of the high volume flood flows of 1983 are extant in this office, and, in fact, none are believed to exist. However, images from pre- and post- high water years do, providing another valuable tool for evaluating varying flow regimes.

All GCES Research Library holdings are available for in-house use by interested researchers, scientists, the PI (principal investigator), and the public. Phase I final reports may be purchased through NTIS (National Technical Information Service). Eventually, all Phase II final reports will also be archived and disseminated through NTIS. Loan of these and other printed documents will be evaluated on a case by case basis.

Aerial visual images may be temporarily loaned to an authorized PI for research purposes. If long-term use of aerial photographs is required, copies may be purchased through the originating contractor.

All requests for information concerning holdings, use, or loan should be directed to the GCES Research Librarian, Richard Quartaroli.

Hard Copy Data

Several topographic and photographic products are available for use by contributing scientists. Purchase of these products is negotiable with the GCES office. All map products are plotted on 4-mil mylar in Arizona State Plane Coordinate System (meters), with a Transverse Mercator projection. Only products within delimited monitoring sites can be obtained. Contact the GCES office for information on river mileages available. The base maps are as follows:

1. 1:2400 topographic mylar base maps with a contour interval of 0.5 m. These contours have 1-m accuracy.

2. 1:2400 orthophotomaps with topography, contour interval of 0.5 meters. Contours have 1-m accuracy. Orthophoto products conform to map accuracy standards at 1:2400 scale, 6.6-ft accuracy.

3. 1:2400 orthophoto grids, photo product only, with reference tics but not contour lines. Orthophoto products also have 6.6-ft accuracy.

To inquire about using any of these products, please send an official "letter of request" to the GCES office. Product usage and time limitations are at the discretion of GCES. Products can be purchased through GCES. This procedure also requires a letter of request and approval. The approximate cost of the mylar base map products is $200 for each mapsheet. This estimate is subject to change.

ATTACHMENTS

Accuracy Levels Within the GCES/GIS

The GCES/GIS data base is a multi-level structure which includes data that range from general to specific. Three tiers of accuracy are available within the multi-level structure. Each tier of accuracy is determined by either the scale of the base map or methodology used in the development of the original data set.

The first tier consists of data referenced to a 1:24,000 quad sheet. At best, it will have the National Map Accuracy Standard of 40 ft in the horizontal and half a contour interval in the vertical.

The second tier of data is photo referenced and transferred to the 1:2,400 orthophoto grid base map developed for this project. The methodology used to create the 1:2,400 level can produce a digital product with a horizontal accuracy of 2.0 m and vertical accuracy of 1.0 m. This second tier of data is being used in the development of the digital products for the 13 long-term monitoring and special study sites.

The third tier of data is survey referenced data. This data collection methodology can produce digital data with sub-centimeter accuracy. The GCES office has surveyors on staff to assist contributing scientists in developing new data sets or georeferencing historic data with local control. It is important to note that the accuracies mentioned here are the best case scenarios and that the accuracy of contributed data depends on the methodology used in the collection of the original data set.

APPENDIX C

GCES/GIS Classification Scheme

Theme	Type	Class	Contributor
Sediment	Travertine ledge	6	
	Rock ledge	7	*
	Alluvial fan	8	*
	Rock face	9	*
	Talus slope	10	*
	*Camping beaches	11C	
	Cobble bars	14	*
	Gravel bars		
	Sandbars	17	*
	Boulders	15	*
	*Contours	18	BOR-RS
	*River miles	19	*
Terrestrial Veg	Other	20	
	Native (OHWZ)	21	BOR-RS
	Exotic (NHWZ)	22	BOR-RS
	Bare soil	23	*
	Marsh	24	*
	*Endangered species	25	
	Seep vegetation	26	*
	Sparsely vegetated slope	27	*
Aquatic Biology	Cladophora	39	*
	Riffles	32	*
	Runs	33	*
	Rapids	44	*
	Isolated pools	38	*
	Backwaters	35	*
	Eddies	36	*
Recreation	Mooring sites	41	NPS
	Lunch spots	42	NPS
	Trails	43	NPS
	Attraction sites	45	NPS
	Indian ruins	47	NPS

APPENDIX D

Class Definitions

Sediment

1. Travertine ledge: calcium carbonate ledge formed from seepage through limestone.

2. Rock ledge: a bed of several beds projecting in a steep-like manner.

3. Alluvial fan: a cone shaped deposit of alluvium created by the path of a stream when it meets a level plane or another stream.

4. Rock face: a vertical or almost vertical wall of rock.

5. Talus slope: a collection of fallen disintegrated material which has formed a slope at the base of a steeper declivity.

6. Cobble bar: a bar or ridge of rounded rock fragments between 76 and 256 mm in diameter, built up to or near the surface of the water by river currents in a river.

7. Gravel bar: a bar or ridge of rounded rock fragments between 4.6 to 76 mm in diameter, built up to or near the surface of the water by river currents.

8. Sandbar: a bar or ridge of rock fragments between 0 and 4.6 mm in diameter, built up to or near the surface of the water by river currents.

9. Boulder: a large rounded block of stone 1 m^2 or larger, lying on the surface of the ground, or sometimes embedded in loose soil, that has been transported from its place of origin.

Vegetation

1. Native vegetation (old high water zone): apache plume (Fallugia paradoxa), redbud (Cercis occidentalis), hackberry (Celtis retculata), honey mesquite (Prosopis glandulosa var. torreyanna, acacia (Acacia greggii), and in the lower reaches of the canyon Creosote bush (Larrea divaricata).

2. Exotic vegetation: (new high water zone): desert broom (Baccharis sp.), willows (Salix sp.), saltcedar (Tamarix chinensis), and arrowweed (Pluchea sericca).

3. Bare soil: soil that is not currently supporting plant life.

4. Seep vegetation: vegetation associated with a spring.

5. Sparsely vegetated slope: a slope area of soil and rock supporting less than 5% vegetation cover.

6. Marsh: a shallow lake, the waters of which are stagnant or actuated by very feeble current. In the temperate zone, they are filled with rushes, reeds, and sedge.

Hydrology

1. Riffle: a turbulent area in the river, not violent enough to be classified as a rapid, often caused by cobble bars.

2. Run: any area of uniform smooth water.

3. Rapid: a very turbulent area in the river, formed by boulders from side canyons or when blocks tumble from cliffs, obstructing the river and making it narrower and faster.

4. Isolated pool: a pool of water separated from the main river channel with no apparent surficial inflow or outflow.

5. Backwater: a body of water with no current, attached to the main channel.

6. Eddy: current of water moving against the main current and with circular motion.

7. Side channel: a secondary river channel that deviates from the main channel only to converge with the main channel later.

Figure 2

LOCATION MAP—GIS MONITORING SITES

Figure 3

PLOT—PILOT SITE NO. 5 AND RESOURCE STUDY SITES

Figure 6
GIS TOPOGRAPHY FOR SITE NO. 5