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Sandbars in the Colorado River: An Environmental Consulting Project

Jennifer A. Hoeting

Abstract. The National Park Service funded a study to determine the impact of water released from the Glen Canyon Dam on sandbars downriver through Grand Canyon National Park. The project involved considerable amounts of messy and missing data. Some of the challenges faced and lessons learned during this project are described.

Key words and phrases: Sampling interval, environmental monitoring.

1. WHY SANDBARS?

In 1990 the National Park Service (NPS) funded a project to measure sandbars in the Colorado River. The goal was to investigate the impact of water released from the Glen Canyon Dam on sandbars downriver from the dam (Figure 1).

When Glen Canyon Dam began operation in 1966, the annual flood cycle was eliminated as the dam controlled all water flow. Floods scour the river bottom, bringing up sediment deposited there. When flood waters recede, the sediment is left on the shore of the river in the form of sandbars. Surveys of the river show that sandbars have decreased in size and number since the dam opened in 1966 (Kearsley, Schmidt and Warren, 1994).

Measuring sandbar sizes may sound like another government boondoggle, but sandbars play a key role in the ecosystem of the Colorado River. For birds and insects, the sandbars offer a small strip of riparian habitat in a harsh desert environment. The sandbars also create eddies where endangered fish and other fauna feed. Finally, rafters camp on the sandbars during their trips down the Colorado River. Not only do fewer sandbars mean reduced habitat for fish and other wildlife, but reduced numbers of sandbars force all campers to use the same sandbars, thereby increasing the user impact on a fragile environment. For these reasons, the NPS wanted to investigate how patterns of water released from Glen Canyon Dam influence sandbar size.

In this paper we provide some insights on the scientific and statistical issues related to this project.

2. THE DATA

From September 1990 to July 1991, 17 helicopter flights were made above 230 miles of the Colorado River below the Glen Canyon Dam. On each flight the same 58 out of the total population of about 600 sandbars along the river were photographed. Each photograph was digitized to determine the size of the sandbar (Cluer, 1995b). The helicopter flights occurred during periods when the water was released at a constant level from the dam. Between flights, water was released from the dam in different patterns of discharge, called test flows.

The original study design called for flights every 15 days, which would result in a series of equally spaced observations over time. However, weather conditions and other difficulties resulted in a variable number of days between flights. On average, there were 20 days between flights, but flight intervals ranged from 12 to 70 days.

The original study design also specified that each of the 58 sandbars was to be photographed on every flight. Out of this sample of 58 sandbars, an average of 18 and a maximum of 40 sandbars were missed per flight. The data were missing for various reasons, primarily due to blurry photographs.

From the sandbar photographs, four numbers were recorded for each sandbar: gross area; area of erosion since the previous flight; area of deposition since the previous flight; and net change in size, where net change is the difference between sandbar size for the current flight and sandbar size for the previous flight.

In addition to sandbar size measurements, sandbar characteristics and hydrological data were recorded. The individual sandbar characteristics that were recorded included location in terms of miles from the dam, left or right river bank and type of sandbar. Nine hydrological measurements were used to characterize the test flows, including

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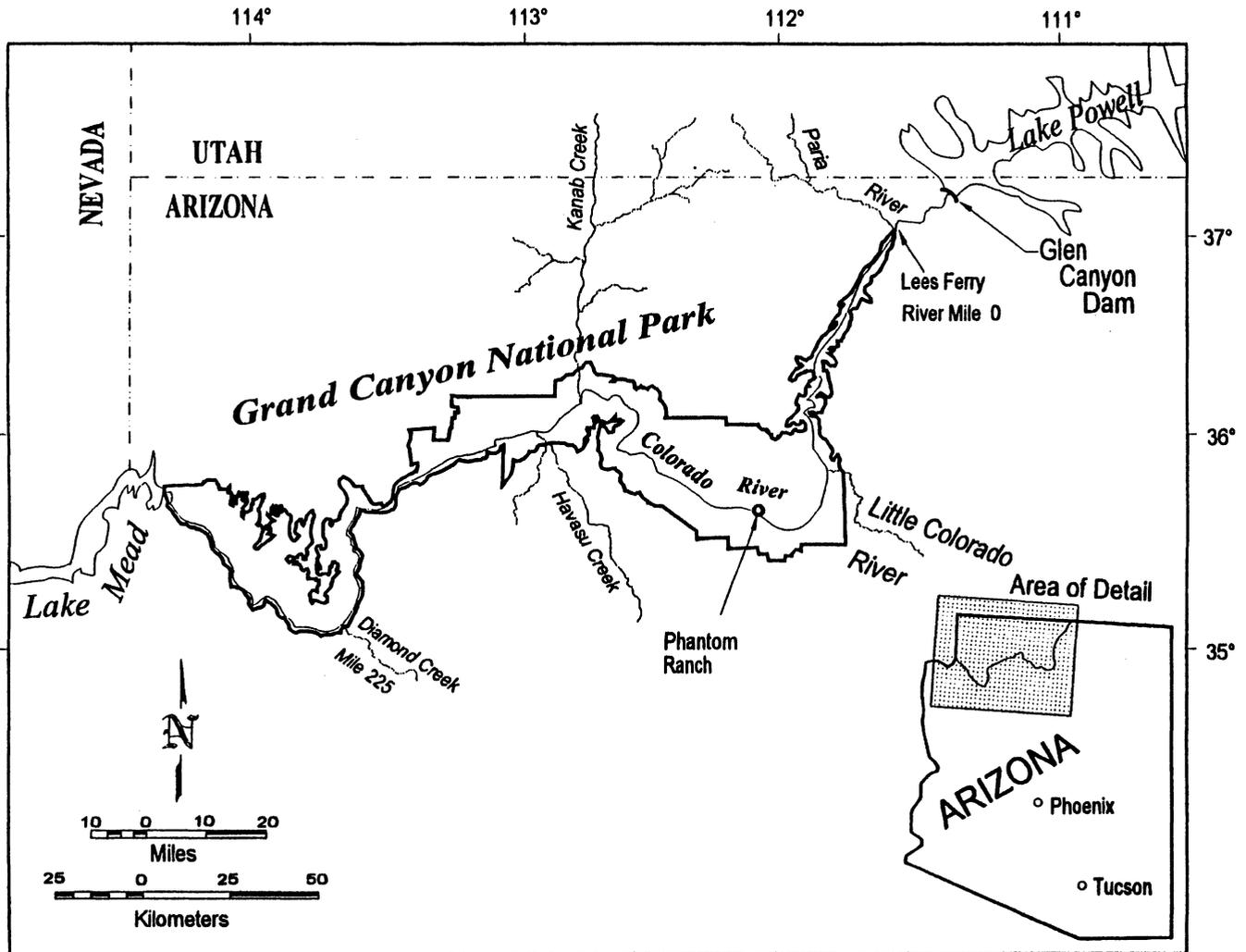


FIG. 1. Geography of the Colorado River in the Grand Canyon. Map created by Brian Cluer, National Park Service.

means and standard deviations of daily discharge over the flight period. "Upramp" (the increase in the level of the river at a specified point along the river) was available as mean daily maximum up-ramp, the average of the maximum rise in river level per day at five different gauging stations along the river. The average amount of sediment per day entering from the Little Colorado River during each inter-flight period (sediment supply) was also measured, as sediment from this tributary of the Colorado River could impact sandbar size (Figure 1).

3. PREDICTING SANDBAR SIZES: CHALLENGES IN CONSULTING

Although these data had been previously analyzed by the NPS, the NPS was interested in whether we could extend their findings using statistical models. Thus, we became involved in the project only after all the data had been collected.

We addressed several important questions in this project.

3.1 Does Sediment Supply from Tributaries Influence the Sandbars?

To address this question we presented an autoregressive model to predict net change per flight averaged over all sandbars below the Little Colorado River. The auto-regressive model is of the form

$$Y = X\beta + u$$

where $u = \rho Wu + \varepsilon$ and $\varepsilon \sim N(0, \sigma^2)$ (Upton and Fingleton, 1985). In this model, Y is the net change per flight averaged over all sandbars below the Little Colorado River and X is the matrix of predictors with the elements in the first column equal to 1. The parameter ρ can be interpreted as a measure of dependence between observations of the response. The weights matrix W is described below.

The auto-regressive model is sometimes called a spatial error model. The auto-regressive model takes into account previous observations of the response as well as previous observations of the predictors to improve predictions about the response for the current flight. One way to interpret this model is that it takes time for the predictors to impact the size of the sandbars. For example, results might indicate that the mean daily discharge from the previous flight is related to the response from today's flight.

In general, $W = [\omega_{i,j}]$ where $\omega_{i,j}$ is a nonnegative weight, which is representative of the "degree of possible interaction" between observation i and j and $\omega_{ii} = 0$. In this application, W was used to account for the variable number of days between flights. For example, for a lag 3 model

$$\omega_{i,j} = \begin{cases} 1/(\# \text{ of days between flight } i \text{ and } j), & \text{if } 0 < i - j \leq 3, \\ 0, & \text{otherwise.} \end{cases}$$

We considered several different lags (the number of previous flights in the weights matrix) and typically observed significant lag coefficients, but with so few observations we were reluctant to make definitive conclusions with respect to the lag component.

The results from the auto-regressive model indicated that mean daily water discharge from the dam and presence or absence of sand added to the river from the Little Colorado River were the most important predictors of net change. The estimated coefficients in these models were highly variable because the lag component was estimated using only 15 observations (2 of the 17 flights had too few observations to be included in these analyses).

Exploratory plots as well as results from the auto-regressive model indicated that there is a relationship between sand supply and changes in sandbar size in the Colorado River. One important finding was that increased sediment supply from the Little Colorado River appears to take longer than one flight period to impact sandbars. Future studies of sandbar dynamics should collect data on sediment supply from important tributaries and investigate a possible lag between sediment input and changes in sandbar size.

3.2 Can Dam Release Characteristics Predict Changes in Sandbar Size?

To answer this question we considered a standard regression model to predict net change per flight averaged over all sandbars included in the study. The regression results indicated that, as mean daily discharge increased and upramp re-

mained fixed, the sandbars tended to increase in size on average. As mean daily maximum upramp increased and mean daily discharge remained fixed, the sandbars tended to decrease in size on average. The other dam release characteristics were not significant predictors of change in sandbar size.

The results from both the auto-regressive model and regression model are somewhat suspect due to the small number of observations used to model a complex system. We described several limitations of these results in our final report to the NPS (Hoeting, Varga and Cluer, 1997). One concern is that both the response and predictors were averages, which makes interpretation of the models difficult. For example, the *mean* daily discharge may not be a good measure of the water release pattern, because two very different water release patterns could have the same mean daily discharge.

3.2 How Do Dam Release Patterns Impact Individual Sandbars?

Another goal of the project was to produce a space/time model to predict sandbar size for each sandbar based on sandbar characteristics and dam release measurements. The model was intended to provide scientists with some guidelines on how different patterns of water released from the dam impact different types of sandbars. Our analyses indicated that the large amount of missing data and, more importantly, the long time intervals between observations made this goal unattainable.

Recent data show that large time intervals between sandbar measurements can lead to erroneous conclusions. For example, it is common for large-scale rapid erosion events to occur in a matter of days or even over several hours. Figure 2 compares daily observations taken via automatic camera to results from 10 samples collected via a more traditional terrestrial survey for one sandbar in the Colorado River in 1991. (Note: a different representation of these data appears in Cluer, 1995a.)

Three substantial errors would be made if inferences were based on the 10 terrestrial survey data points. In case A daily observations show a gradual increase in area from February 2 until April 16 when the sandbar decreased from 130% to 70% of its original area over a 24-hour period. The two observations collected via terrestrial survey on February 2 and April 21 would, on the other hand, simply show a negative trend in sandbar area over the 70-day period. In case B the observations collected at 30-day intervals would completely miss a substantial erosion event and severely underestimate the variation in sandbar size. In case C the intermittent observations would both overestimate

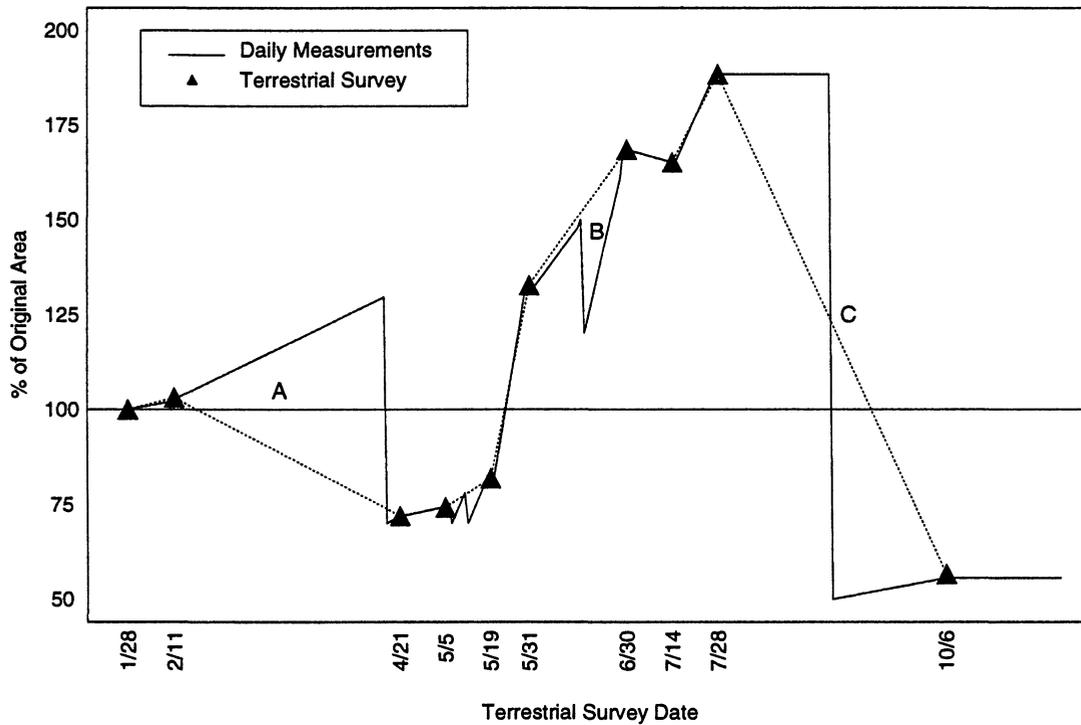


FIG. 2. 1991 Colorado River sandbar survey, sandbar 172. Comparison of 288 daily measurements collected via automatic camera (solid line) to 10 intermittent measurements collected via land surveys (triangle symbols and dotted line).

the time over which the erosion occurred and miss out on a portion of the erosion. These data show the danger inherent in basing inferences on sandbar data collected at sparse intervals over time. Since data analyzed in this paper were collected at intervals from 12 to 70 days, we have a very incomplete picture of what actually happened to the sandbars.

Another challenge is the large amount of missing data. With up to 40 sandbars out of the original 58 sandbars to be photographed missing for each flight, the missing data were an important concern. While we considered using data interpolation methods or likelihood-based approaches for the analysis of missing data, the high degree of uncertainty about sandbar behavior in the intervals between observations made it inappropriate to use these methods.

3.4 Suggestions for Future Studies

This is the best data set ever obtained for a sample of Grand Canyon sandbars; indeed, a large sample of sandbars was monitored over a long period of time as compared to previous studies of sandbar size. Since the data were collected via aerial photography from an airplane, it was cheaper to collect more sandbars per flight but to have fewer flights. In designing these types of studies, one must consider this tradeoff between the number of sandbars included in the study and the num-

ber of observations obtained for each sandbar. In this study there were 58 sandbars, but, with as few as 9 observations per sandbar collected over a long period of time, it was difficult to produce a credible model for individual sandbars. Our results indicate that future studies should focus on obtaining more observations of fewer sandbars which will allow scientists to understand the relationship between hydrological characteristics and changes in sandbar size more fully.

Related to this is the issue of sampling interval. In our final report to the NPS, we argued that not only will more frequent sampling result in better understanding of the underlying natural processes, but more frequent sampling of fewer sandbars can save money. Traditional sampling techniques use either aerial photography or land-based surveying. Flying at low altitude deep in the Grand Canyon is expensive, dangerous and may be ecologically unsound. Land surveying is similarly expensive and time-consuming, so it is best to budget for few flights or few surveys where many sandbars are measured. A better design would be to set up automatic cameras at a few sandbars to take photographs at specified intervals. Our analyses showed that, despite the reduction in the number of observed sandbars, more information about the questions of interest would be gained through our sug-

gested design. A formal cost model would be a good way to present these tradeoffs.

4. SOME LESSONS LEARNED

This project reinforces several basic rules for statistical consultants.

First, always check the data for errors at the start of the project. These data had been analyzed previously and thus we assumed that the database was error free. In fact, there were some serious problems still remaining. One of the most important was errors in the computation of net change, the response of main interest to our clients. We also discovered other errors, for example, in computation of the number of days between flights. Our experience on this project emphasizes the need for simple checks of data accuracy before beginning any analyses.

This project also demonstrates why statistical consultants should make every effort to obtain the raw data, if available. The original goal of the study was to relate the change in sandbar size to characteristics of the test flows for each flight, but only the summary statistics of the test flows were made available to us. While statistics such as mean and standard deviation of daily discharge over the flight period numerically characterize the test flows, the raw measurements would have provided us with further insight into the nature of each test flow.

We were also unable to obtain the raw values for daily maximum upramp from each of the five gauging stations along the river. Since we received only summary statistics averaged over the five stations and averaged over the flight period, it was impossible to relate upramp to the distance of each station from the dam, which is important because upramp increases with distance from the dam. Without doubt, increased access to raw data would have improved our ability to draw useful scientific inferences.

Finally, as consultants we must guard ourselves against standing on the "statistician's pedestal" from which we lecture scientists on the limitations of their studies. It is easy for a statistician to criticize a study after the data have been collected. We should recognize that, just as statisticians make compromises while doing analyses, investigators are under considerable constraints when designing their studies, including financial, time management and political constraints. Even with the best intentions in study design, we recognize that collecting high quality, complete data outside of a

controlled laboratory environment can be an extremely difficult endeavor.

5. CONCLUSIONS

The NPS gained a considerable amount of useful information from our efforts. We provided insight into the relationship between net change in sandbar size and mean daily discharge, upramp, presence or absence of sand added to the river from the Little Colorado River and improved methods for collecting and evaluating data on sandbar sizes. Previous statistical analyses of sandbar size data have been limited, being based on simple models that ignore spatial and time correlations (Beus and Avery, 1992; Cluer, 1995b). Thus our study was a step in the right direction toward the collection of additional data and the development of useful models to predict sandbar sizes. Despite data limitations that prevented the use of highly sophisticated space-time models, we were able to identify the need for such models and the type of data and analyses that would be most useful for future studies.

The U.S. Bureau of Reclamation (USBOR), which operates the dam, faces the continual challenge of balancing the needs of the ecosystem with the needs of the power companies. In the past, discharge of water through Glen Canyon Dam has been controlled to optimize peak load hydropower production. In the spring of 1996, USBOR released a large controlled flood intended to reinvigorate the sandbars on the Colorado River. Preliminary observations show that this goal was at least partially achieved (Wegner, 1996).

Our analyses, along with analyses of data from the controlled flood, will help scientists further understand the relationship between sandbar size and dam water releases. The need to understand the impact of dams on ecosystems is continually increasing: it is predicted that by the year 2000 over 60% of the world's rivers will be regulated (Gore and Petts, 1989). Statisticians can play a key role in this research by helping scientists design good studies and by continuing to develop methodology to assist in the analyses of these and similar data.

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