A Methodology and ArcView Tools for Predicting Channel Migration

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Abstract

At present, no practical methodology exists for routine prediction of stream meander migration and uncertainty concerning the level of risk to infrastructure remains unacceptably high. This paper describes a Handbook that includes ArcView 3.2-based Bend Measurement and Channel Migration Predictor extensions, which provides a practical methodology to transportation engineers, floodplain managers, planners, developers, geographers, etc. to predict the rate and extent of meander migration through the use of sequential historic aerial photographs and maps. Results of a recent Beta test by highway hydraulic engineers and watershed planners indicates that the methodology will provide valuable analytical and planning tools to practitioners.

Introduction

Rivers prone to channel migration may be in close proximity to urban infrastructure, spanned by structures, and paralleled by fixed highway alignments and other appurtenances. Channel migration (alluvial river meander planform deformation) is a major consideration in designing bridge crossings, transportation facilities, and other static features in affected areas. Channel migration near a bridge reach can result in the following: (a) excess bridge pier and abutment scour, (b) threats to bridge approaches and other highway infrastructure, (c) increased debris problems, and (d) obstructed conveyance through bridge openings. In an urban setting, active channel migration and attendant bank erosion can threaten infrastructure and disrupt municipal services.

Channel migration includes lateral channel shift (expressed in terms of distance moved perpendicular to the channel center line, per year) and downvalley migration (expressed in distance moved along the valley, per year). Engineers are concerned with predicting channel migration as the channel moves within close proximity to structural features.

Geomorphologists may view channel stability from the perspective of hundreds or thousands of years. For engineering purposes, however, a stream channel can be considered unstable if the rate or magnitude of change is such that the planning, location, design, or maintenance considerations for infrastructure are significantly affected during the life of the facility. The kinds of changes that are of concern are: (1) lateral bank erosion; (2) aggradation or degradation of the streambed; (3) short-term fluctuations in streambed elevation (scour and fill); and (4) avulsion. This research is concerned specifically with only lateral channel instability (including down valley migration) resulting from meander migration.

Project Objective

The objective of National Cooperative Highway Research Program (NCHRP) Project 24-16 was to develop a practical methodology to predict the rate and extent of lateral and down valley channel migration in proximity to transportation facilities. The methodology will enable practicing engineers to locate and design new bridges, highway facilities, or other structures, accommodate for anticipated channel migration, evaluate the risk to existing facilities, and if necessary, determine the need for and design countermeasures against the effects of channel migration. A prediction of channel migration could also be used to alert bridge inspection personnel to the potential for channel change that could affect the safety of a bridge.

The research products include not only a final report (Lagasse et al. 2003a) describing the predictive methodology, but also an extensive archived data base, published on CD-ROM, that contains detailed morphological data, aerial photos, historical banklines, and maps for more than 1,500 bends on 89 rivers and streams across the United States. In addition, a stand-alone aerial photo/map comparison Handbook that provides a complete applications supplement for Project 24-16 has been prepared (Lagasse et al. 2003b). The comparison techniques in the Handbook include the ArcView 3.2-based Data Logger (for measurement and data storage) and Meander Migration Predictor extensions. While the archived data base and Handbook were developed for use primarily by Federal Highway Administration (FHWA) and State Departments of Transportation (DOTs), they should also be of interest to researchers and practitioners responsible for river channel maintenance, river restoration/rehabilitation projects, and floodplain planning and management.

Research Approach

The fluvial processes involved in predicting meander migration are very complicated and the variables of importance are difficult to isolate. The major factors affecting alluvial stream channel forms are:

- Stream discharge (magnitude and duration), temperature, and viscosity
- Sediment load (including types and caliber of sediments)
- Longitudinal valley slope
- Bank and bed resistance to erosion
- Vegetation
- Geology (including bedrock outcrops, clay plugs, and changes of valley slope)

- Human activity

In an analysis of flow in alluvial rivers, the flow field is further complicated by constantly changing discharge. Significant variables are, therefore, quite difficult to relate mathematically. It is often necessary to list measurable or computable variables, which effectively describe the processes occurring, and then to reduce the list by making simplifying assumptions and examining relative magnitudes of variables. This means that it is necessary to strive toward an acceptable balance between accuracy and limitations posed by data needs and analytical complexity.

Many laboratory and field studies have been carried out in an attempt to determine the variables controlling river response. To the present time, the problem has been more amenable to an empirical solution than an analytical one. Computer solutions to complex hydraulic problems have extended the range of fluvial process problems that can be solved analytically, but simplifying assumptions are still required. While the mathematical complexity of the analytical solution may be justified for research purposes, empirical approaches may produce results of greater utility to practicing engineers. After careful review of empirical and deterministic (physical process mathematical modeling) approaches to predicting meander migration, it was concluded that empirical approaches are more likely than deterministic approaches to yield a practical methodology that will be useful to practicing engineers.

The approach consisted of the following tasks:

- Conduct a complete and thorough literature review on meander migration
- Access and evaluate a number of relatively complete existing data sets
- Enhance existing data sets by acquiring recent aerial photography at selected study sites and obtain data on hydrologic, hydraulic and sediment characteristics
- Analyze the enhanced data sets with photogrammetric comparisons
- Develop a screening procedure to identify *stable* meandering reaches
- Develop a classification system for river/meander types for stratification of the data base
- Develop a stand-alone Handbook for map/aerial photograph comparison techniques for measuring and predicting meander migration
- Compile and archive a data base on CD-ROM that contains all acquired meander site data
- Evaluate statistical relationships and regression equations for potential use in predicting meander migration
- Conduct necessary internal and external testing and evaluation and revise as necessary
- Develop a detailed plan and recommendations for incorporating the results of this research into ongoing FHWA/National Highway Institute technology transfer programs

Procedure for Developing the Methodology to Predict Meander Migration

The following six steps were necessary to achieve the goals of NCHRP Project 24-16:

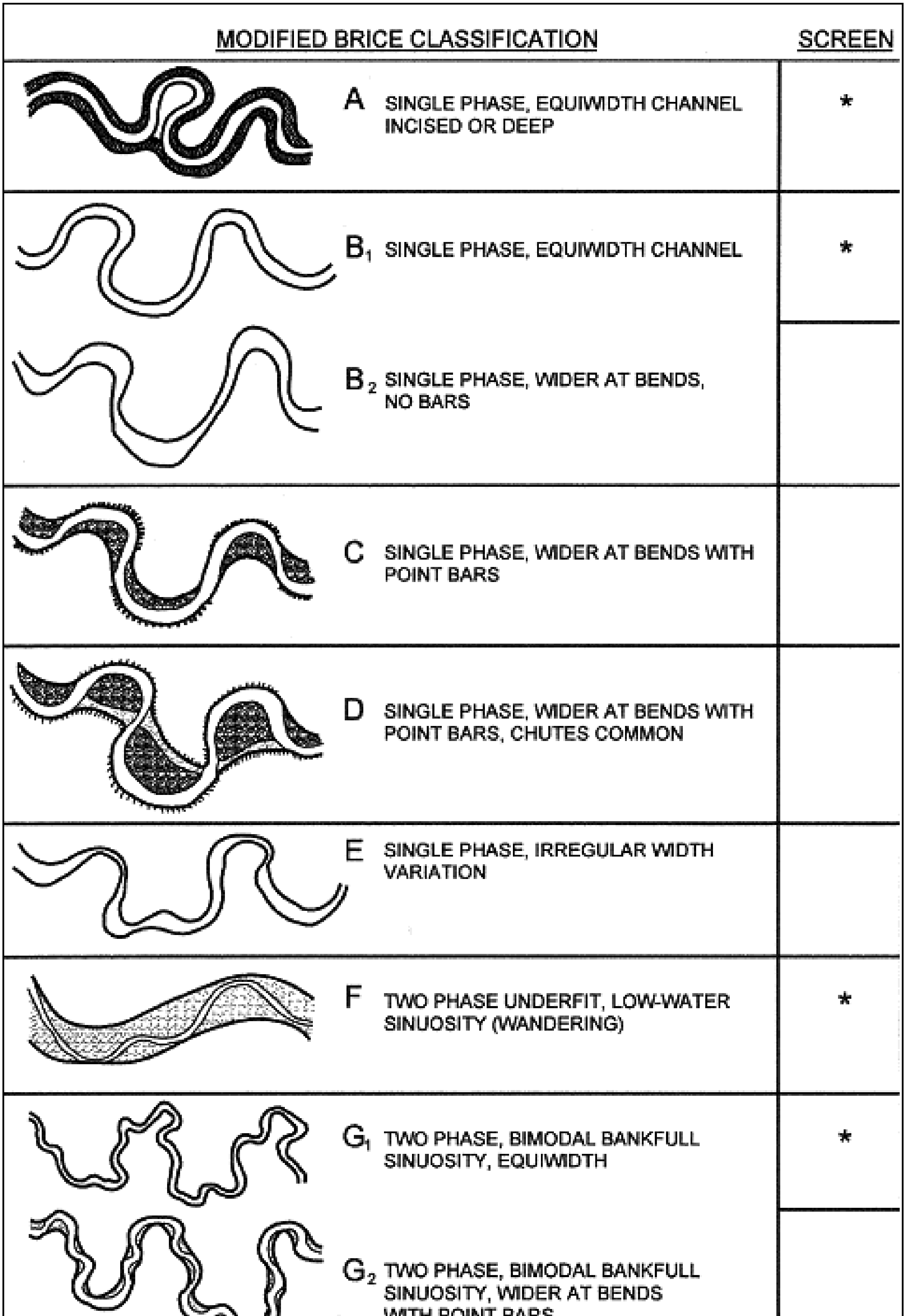
(1) Assemble Final Data Set. In order to develop a methodology for predicting meander migration that can be used by transportation engineers, floodplain managers, planners, developers, geographers, and other practitioners, it was necessary to obtain data on numerous meandering rivers having a wide range of morphologies throughout the United States. The necessary data typically includes channel cross sections, channel planform, bed and bank material characteristics, vegetation, discharge data, sediment loads, floodplain characteristics, geology, and watershed characteristics. The data for each site was assembled and compiled into Microsoft Excel workbooks containing spreadsheets designated for each bend.

Existing data was collected from a variety of sources and researchers. The primary data set upon which much of this project is based comes from work conducted by Dr. James Brice of the U.S. Geological Survey. The Brice data set consists of morphometric data (Brice 1982) as well as aerial photos, maps, and historic bankline tracings for 805 bends at 82 sites on 59 rivers. Under a research project at Johns Hopkins University, the data set was inventoried and additional data was derived for 133 of the Brice sites by Cherry et al. (1996). Additional survey and sediment data was collected for the Brice sites by field personnel from the U.S. Army Corps of Engineers Waterways Experiment Station (WES), the U.S. Geological Survey (USGS), and the University of Nottingham, UK in 1999. Eight additional data sets, some with historic banklines or channel position atlases, covering 646 bends at 57 sites on 28 rivers were acquired from other sources.

Attempts were made to acquire appropriate historic aerial photography from various agencies for the data sets that had no historic bankline comparisons. Aerial photography from the 1990s and topographic maps were acquired for all the data sets. Updated discharge data was also obtained for each of the sites used in this project.

(2) Screen and Classify River and Meander Types. According to Brice (1982), it should be possible to identify stable meanders by their width characteristics. A simple stratification of meanders would be of value to the bridge engineer as a screening procedure, allowing identification of meanders that are very stable. Rather than developing regional relationships, a geomorphic classification was developed during this step to lead the user of the methodology to a suitable procedure for a particular river or meander type. A classification scheme modified from the channel pattern classification originally developed by Brice (1975) is presented in **Figure 1** as an approach for both screening and classification. The most common river types (or meander modes) encountered in the field can be addressed by this classification.

(3) Measure Meander Morphology. In order to relate a meander to rate and type of change and to correlate its behavior with other variables, it is necessary to describe the meander quantitatively. Numerous investigators have done this by measuring amplitude, wavelength, radius of curvature, sinuosity, width and depth of the channel, width-depth ratio, and ratio of centerline radius of curvature to width. Following selection of meanders or sets of meanders for study, the maps and aerial photographs were compared in order to determine the rate of migration or change for each meander or segments of meanders.



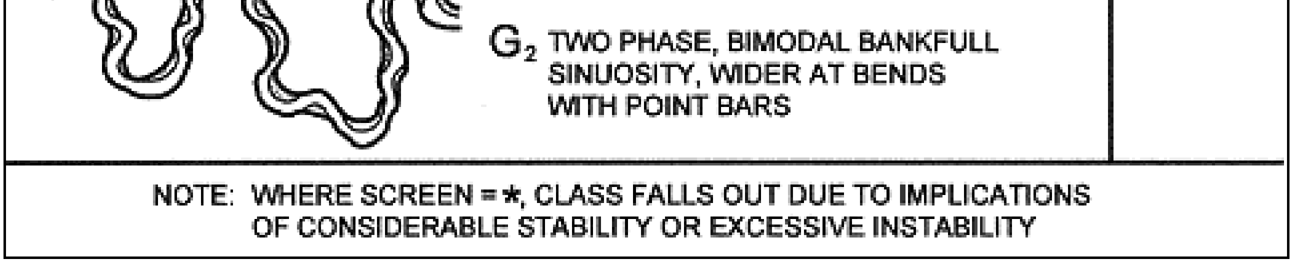


Figure 1. Modified Brice Classification of meandering rivers.

(4) Collect Data on Controlling Variables. Each meander will be affected by its location and by the controlling variables that act upon it. This study assembled data on the character of the valley (slope, alluvial variability, bedrock controls), hydrology, and sediment type. Sediment type in the bed and banks of an alluvial river reflects the type of sediment load moved through the channel. Hydrologic data was obtained from nearby gaging stations. Channel dimensions and valley slope were obtained from topographic maps and aerial photographs. These data plus data on bed and bank sediments were obtained from various sources. Schumm (1960) concluded from his studies of Great Plains and Australian streams that width-depth ratio and sinuosity are determined by the type of sediment load moved through a channel. Although sediment loads will not be measured, width-depth ratio can be used as a surrogate for sediment load data.

(5) Develop Methodology. Based upon these steps, a predictive methodology has been developed. Meander change or lack of change can be determined by comparing maps and aerial photographs of different dates. Because comparative aerial photography or maps are generally available, this may represent the most reliable predictor of meander migration for a specific site. A methodology and guidelines are provided for comparison techniques ranging from the use of simple overlays to GIS techniques that can be implemented with the hardware and software normally available to most agencies and companies. The predicted meander change is then compared with a frequency distribution of measured rates from the data set to assess the reasonableness of the prediction.

Measuring Meander Migration

Before predictive tools for channel migration can be developed, one must be able to measure and describe channel migration. A standard approach for use in analyzing data sets must be developed and this approach should be adhered to for all subsequent measurements.

Bend migration can be reasonably described by four modes of movement (**Figure 2**). Extension is across-valley migration and is easily measured at the center of the bend radius (R_c). Similarly, translation is down-valley migration and is also measured at the center of the bend radius. Expansion (or contraction) increases (or decreases) bendway radius. Rotation is a change in the orientation of the bendway with respect to the valley alignment.

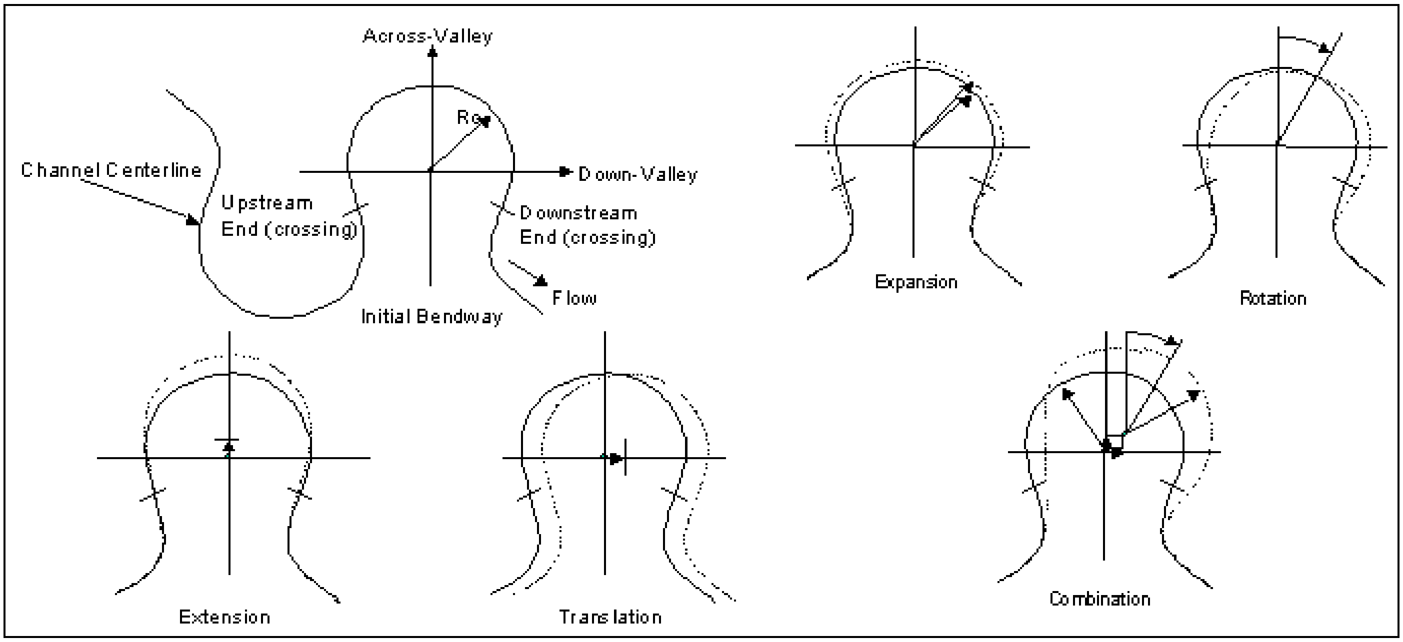


Figure 2. Measuring meander migration.

A change in any of these four modes of movement results in a change in the location of the outer bankline. Combinations of these modes of movement would result in a wide variety of bendway shapes through time. To apply this approach one must identify a valley orientation, locate the radial center of the bend, and measure the bendway radius and the orientation of the bendway with respect to the valley. If this is performed for consecutive aerial photos, rates of change in each of the modes of movement can be computed. This type of geometric information is needed to graphically depict channel migration of individual bends.

Predicting four modes of movement is a significant task for every bend of interest (Figure 2). However, actual bend migration is even more complex. For example, one part of the bend may be expanding faster or translating down-valley faster than another. This would result in changes in bend symmetry. As a concession to practicality one must limit the number of modes of movement to the fewest possible. The channel migration prediction methodology includes extension and translation directly (as a vector sum). Expansion (a change in R_c) is included, as it can have a major impact on the location of the outer bank and because rates of migration appear to be correlated to R_c/W (bend radius of curvature/width). If movement in these three modes can be predicted, the primary threats to a bridge, highway, or other facility will be established. Rotation is considered only indirectly as a component of the combined movement in the other three modes relative to adjacent bends.

An ArcView 3.2-based Data Logger tool was developed for this project to obtain the necessary data for both photogrammetric and statistical analyses. The Data Logger tool stores the data necessary for use with an ArcView 3.2-based Meander Migration Predictor tool, which was developed to assist in predicting (extrapolating) meander migration at a given bend where the necessary sequential aerial photography or mapping is available.

Aerial Photo and Map Comparison Handbook

The principal product of this research was an Aerial Photo and Map Comparison Handbook. The Handbook covers the following topics:

- Screening and classification of meander sites
- Sources of mapping and aerial photographic data
- Basic principles and theory of aerial photograph comparison
- Simple overlay techniques
- GIS or computer supported techniques
- ArcView-based measurement and extrapolation techniques
- Sources of error and limitations
- Illustrated examples and applications

The Final Report for NCHRP Project 24-16 provides a complete summary of the findings, recommendations, and implementation plan resulting from the project. The Handbook provides the specific techniques and guidance to apply those results. The Handbook also covers the screening and classification techniques (as a first step in any meander migration analysis) and includes the software and a detailed description of the ArcView 3.2-based Data Logger and Meander Migration Predictor tools.

The key to application of the methodologies presented in the Handbook is obtaining time sequential aerial photography (or maps) of the meander site to be analyzed. Historical and contemporary aerial photos and maps can be obtained inexpensively from a number of Federal, State, and local agencies. The Internet provides numerous sites with links to data resources and sites having searchable data bases pertaining to maps and aerial photography (e.g., Terraserver – usa.com). It is this ready availability of aerial photography resources that makes the methodologies presented in the Handbook powerful and practical tools for predicting meander migration.

Research Results

As an example of the basic methodology, aerial photograph comparison techniques were used to predict meander migration on the White River in Indiana. Aerial photographs from 1937 and 1966 were acquired for a reach of the river, the banklines were delineated on each set of photographs, and the banklines were registered for comparison. Planform variables were measured for each bend for each year by inscribing best fit circles on the outer banklines for each year (1937 and 1966). While this was done manually for the White River prediction, it can also be accomplished using the Data Logger tool (**Figure 3**) which also stores the data for use by the Meander Migration Predictor tool.

The rate of movement of the bend centroid (extension and translation) and the rate of expansion (or contraction) of the radius of curvature are determined for each bend of interest for the 29 year period. The rate of change of bend centroid position and length of the radius of curvature are then extrapolated to construct a circle that would describe the location of the outer bankline of each bend at some selected date in the future. For the White River, the selected date was 1995 and the prediction was accomplished using manual overlay techniques. The Meander Migration Predictor tool (**Figure 4**), could also be used to automate the prediction of bankline positions based on data stored in the Data Logger.

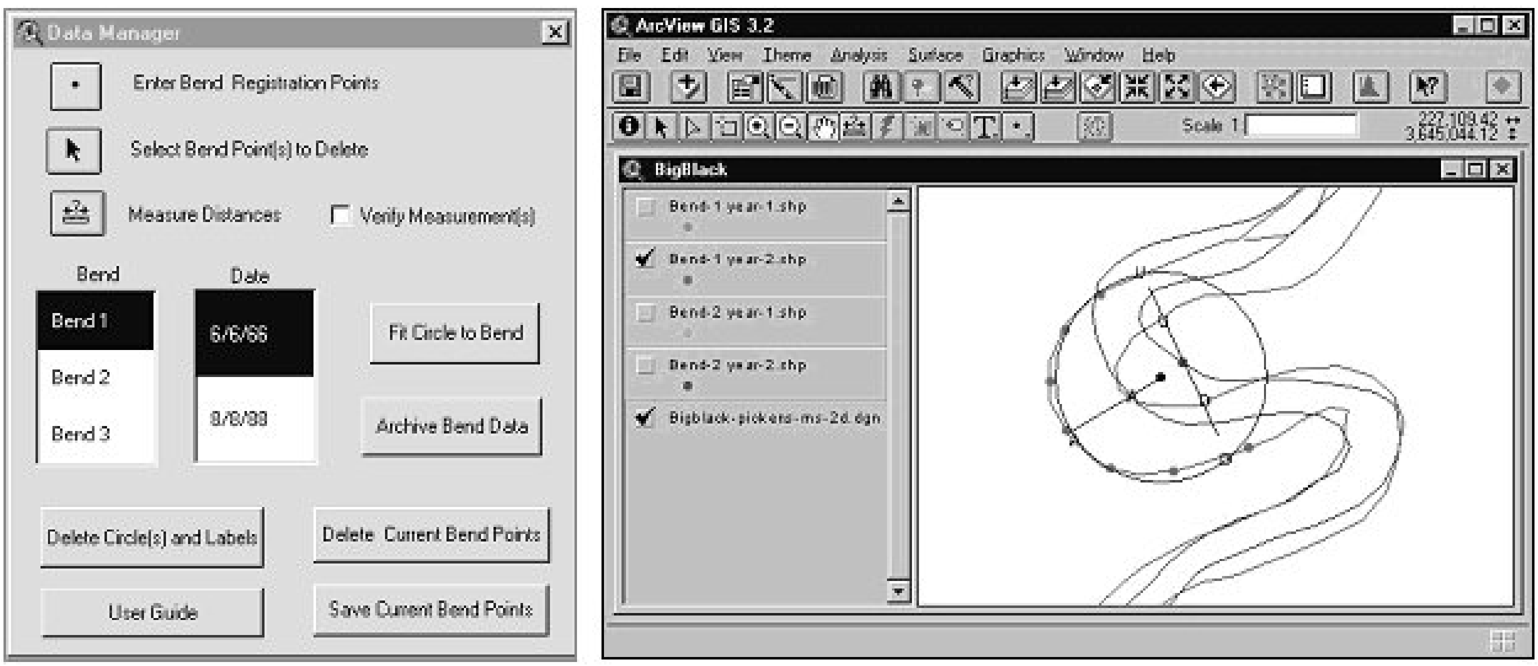


Figure 3. ArcView 3.2-based Data Logger windows used to measure and store meander planform variables.

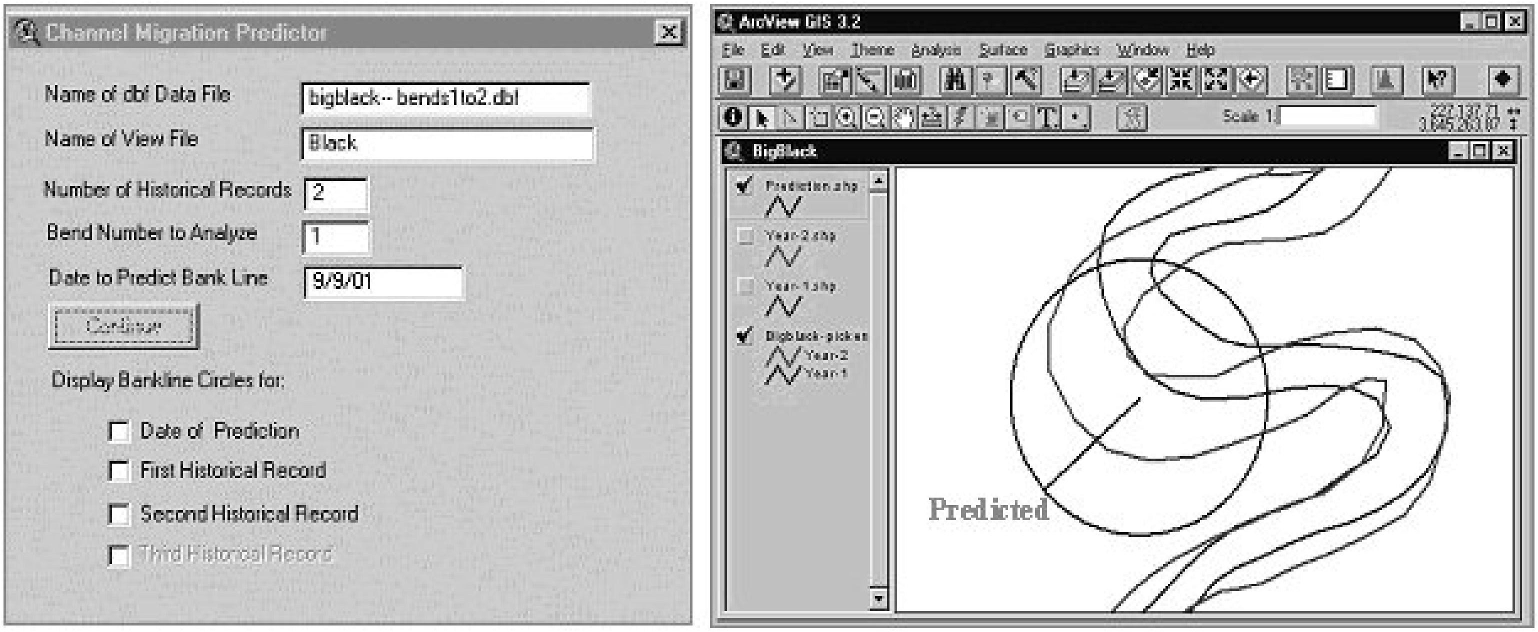


Figure 4. ArcView 3.2-based Meander Migration Predictor windows used to predict meander migration for a future date.

Figure 5 shows the actual 1937 bankline position of seven meander bends and the predicted 1995 bankline positions of the bends superposed on the 1966 aerial photograph. The predicted 1995 bankline positions of the bends were then overlain on the 1995 photograph obtained for this reach to evaluate the quality of the "prediction." **Figure 6** shows the predicted 1995 bankline position superposed on the 1995 aerial photograph of the river.

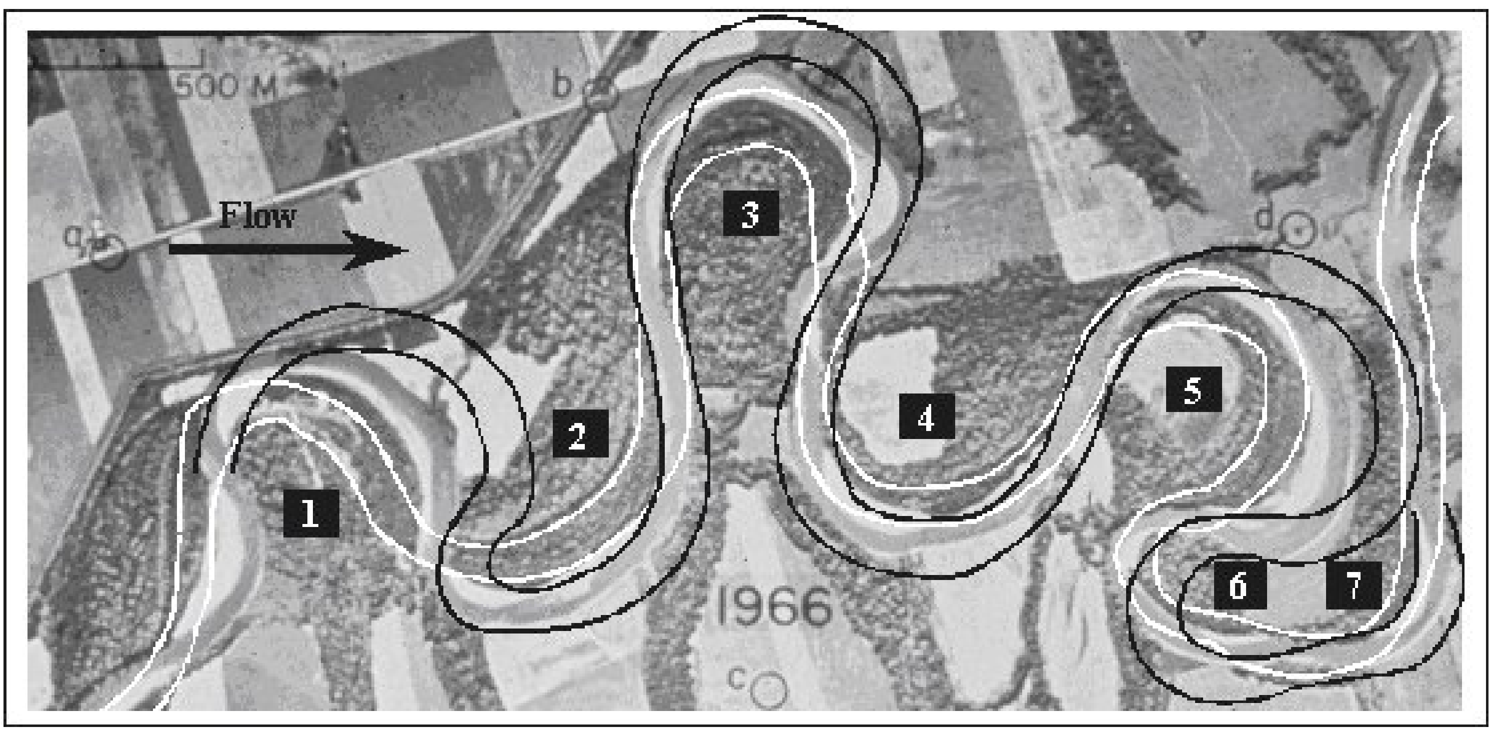


Figure 5. Aerial photo of the White River in 1966 showing the actual 1937 banklines (white) and the predicted 1995 bankline positions (black).

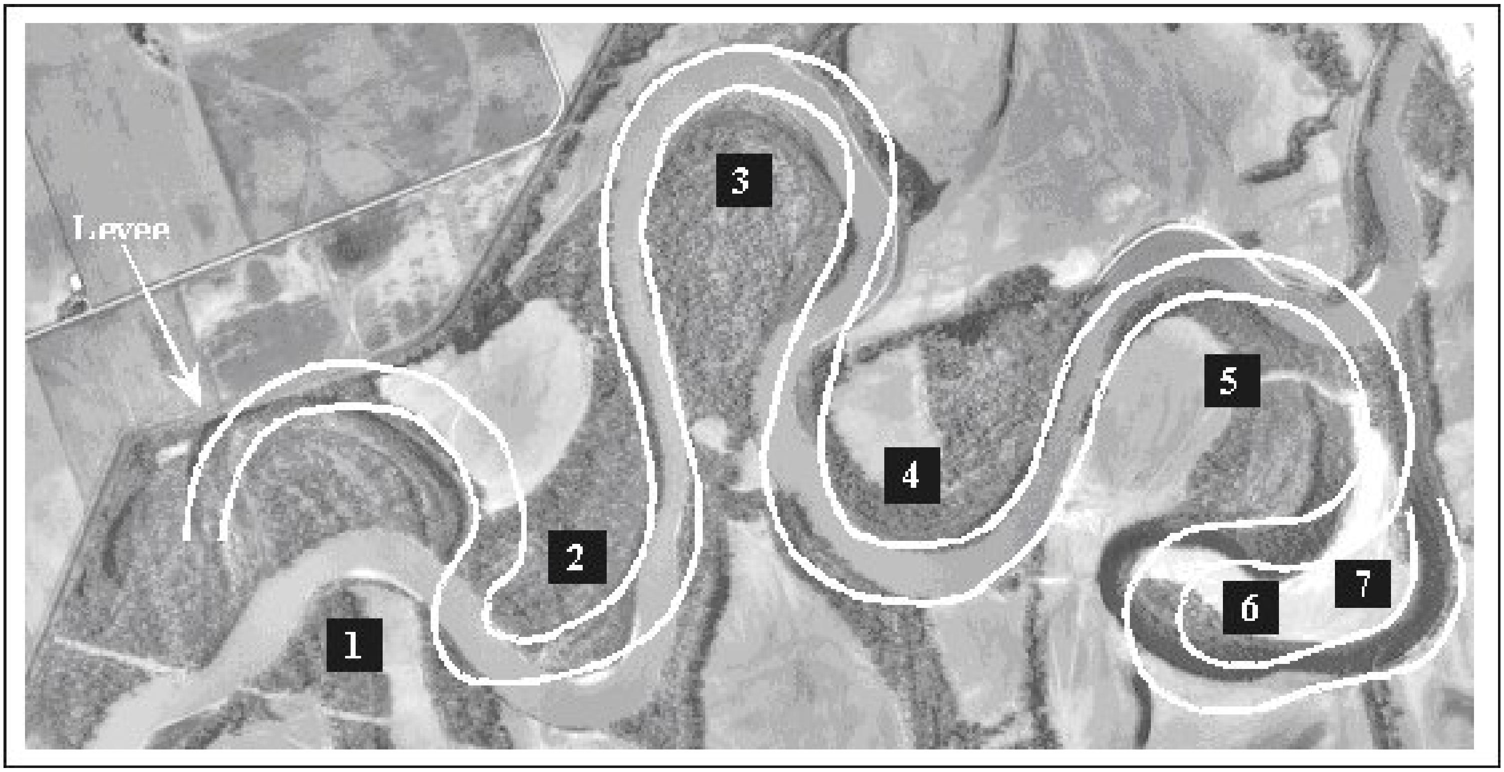


Figure 6. Aerial photograph of the White River in 1995 showing the predicted bankline positions.

A comparison of the actual bankline locations with the predicted bankline positions reveals that aerial photograph comparison techniques can predict meander migration with relatively good accuracy. As seen in Figure 6, the 1995 bankline positions of Bends 3 and 4 and the cutoff at Bend 5 were accurately predicted. The unexpected and anomalous bankline positions can be accounted for by a man-made cutoff (Bends 1 and 2), a natural cutoff (Bends 5, 6, and 7), and, possibly, bank protection (Bends 3 and 5) prior to 1995. The man-made cutoff of Bend 1 may have been in response to the major threat posed by meander migration to a levee nearby. The cutoff has also caused Bend 2 to become distorted compared to the predicted shape. The cutoff of Bend 5 has resulted in the distortion of Bend 5 and abandonment of Bends 6 and 7. The migration of the outer bank along the downstream limb of Bend 3 and at the apex of Bend 5 has been partially halted by apparent bank protection. It is quite likely that the bankline positions of Bends 1 and 2 as well as the revetted portions of Bends 3 and 4 would have closely matched the predicted positions if not for man's influence.

The GIS-based predictor was applied to 43 bends in the archive data base where three time periods of photography were available. As in the White River example, the bankline positions for the first two periods were used to "predict" the known position for the third time period. The direction of migration was predicted within a 30 degree arc for 80 percent of the bends, and the maximum amount of bank migration was predicted within 1 percent of the channel width per year over the time period covered by the prediction. A qualitative assessment of the procedure indicated that the majority of the predictions were reasonable and compared well with the actual channel migration.

Summary

The analytical products of this research, map/aerial photograph comparison techniques, and guidelines to predict channel migration in proximity to transportation and other facilities, provide a practical quantitative methodology that enables informed decision making at all levels. The methodology will be useful in reconnaissance, design, rehabilitation, maintenance and inspection of highway facilities. The end result will be a more efficient use of highway resources and a reduction in costs associated with the impacts of channel migration on highway facilities. The prediction techniques can also be used by other practioners responsible for river channel maintenance, river restoration/rehabilitation, and floodplain planning and management.

An archived data base includes all meander site data acquired for this study. With the archived data set, future researchers will have a readily accessible data base in a very useable format for a variety of studies. These studies could include additional empirical analyses and more complex regressions based on the archived data. Additional data could be added to supplement or complement the data base. As deterministic modeling code improves, this archived data may facilitate calibration and verification of physical-process models of river meandering, providing additional tools beyond the empirical techniques of this research.

Acknowledgement

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