

TECHNICAL REPORT

Geographic Visualization of the 1993 Midwest Flood Water Balance

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1. Introduction

This report documents the construction of three visualization projects based on hydrologic modeling of the 1993 Midwest flood. The modeling procedures and results have been described in “Water Balance of the 1993 Midwest Flood,” by Mizgalewicz and Maidment (1998). In their report, a water balance was calculated for the Upper Mississippi River basin for all of 1993 using streamflow, precipitation, and evapotranspiration data sets. In both this study, and Mizgalewicz’ and Maidment’s study, the Upper Mississippi River basin (UMRB) includes the Mississippi River basin from the river’s headwaters in Minnesota to Cairo, Illinois, and the Lower Missouri River basin below Gavins Point dam, South Dakota, to St. Louis, Missouri (Figure 1.1). Using a digital elevation model of the study area, the daily flow into and out of the basin was calculated, and a series of 365 maps of basin water storage were created. The basin was subdivided into watershed boundaries as delineated in ArcInfo using a digital elevation model and a coverage of U.S. Geological Survey (USGS) stream gaging stations. The water storage values within these watershed boundaries were then spatially averaged into the standard USGS 8-digit hydrologic unit code (HUC) boundaries, and these maps and data sets were used in the construction of several hydrologic visualization projects.

As a follow-up to Mizgalewicz’ and Maidment’s study, the water balance data sets and maps were used to create several map-based, computer-generated scenes that depict the catastrophic flooding that occurred in 1983 in the Upper Mississippi/Lower Missouri River basins. Three primary geographic visualization products have been generated during the course of this research: (1) an area-based map animation of the 1993 basin water storage, (2) a point-based map animation of the 1993 water storage, and (3) a line-based map animation of 1993 basin streamflow.

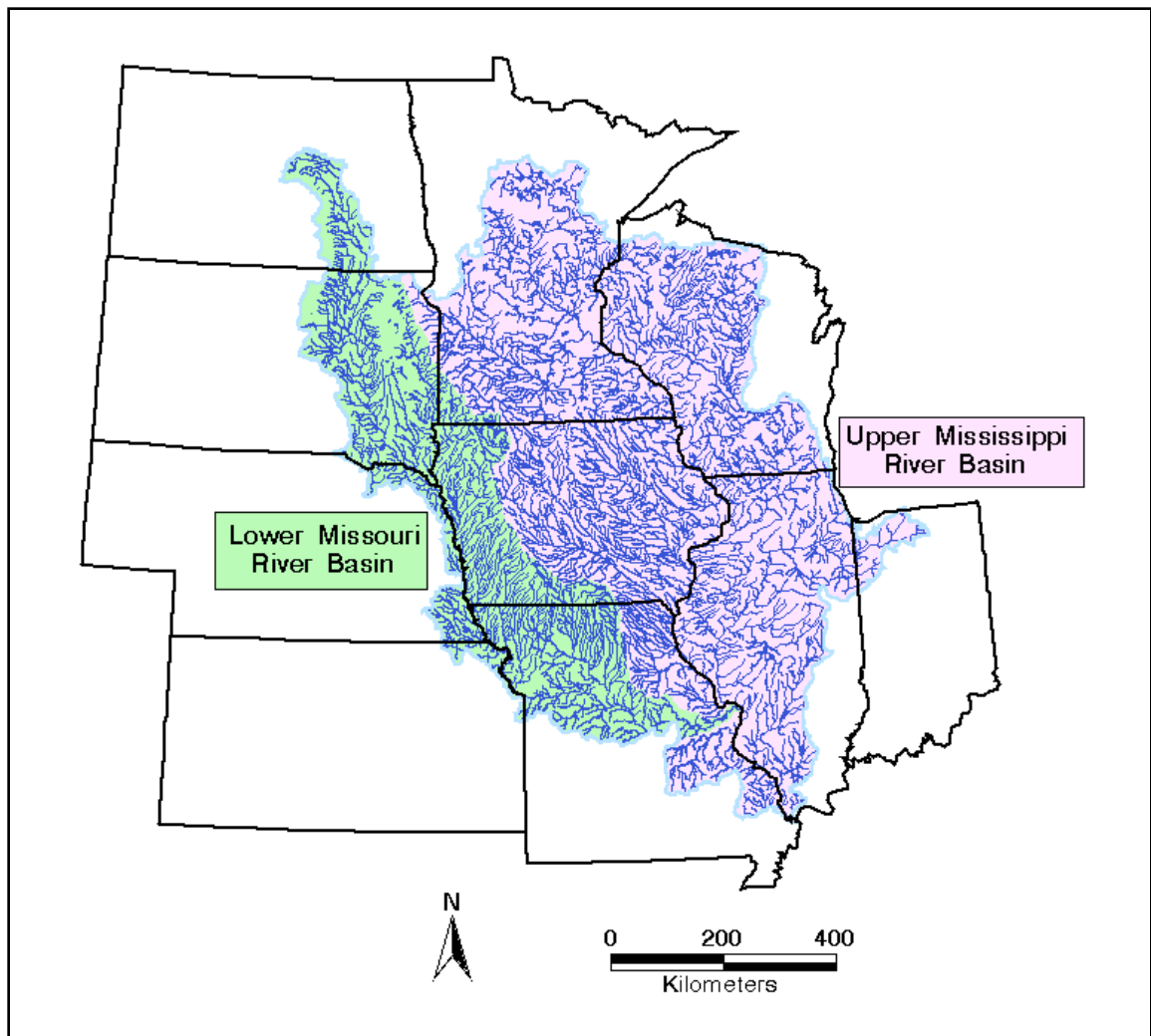


Figure 1.1. The Upper Mississippi River Basin (UMRB) study area (includes the Lower Missouri and Upper Mississippi River Basins proper).

2. Geographic Visualization

Until very recently, the output from a GIS-based analysis was often a series of static map products. Even time-dependent data sets investigated using GIS technology were prone to a reduction in utility and understanding when final products were presented because of the limitations of the GIS software in handling such data. These statements are still somewhat true today, and there has been much discussion amongst the geoscientific community as to how the results of a GIS analysis can be made more understandable to a wider range of users. To this end, geoscientists have been investigating for the last ten years or so, the field of visualization in scientific computing (or scientific visualization) as a means of creating more meaningful and useful GIS products. The following paragraphs briefly summarize the field of scientific visualization as it relates to cartography and GIS, and provide some background on the various uses of visualization tools and methodologies in the geosciences.

2.1 Visualization and Map Representation

Visualization in scientific computing (ViSC) was first formalized in a National Science Foundation report by McCormick and others (1987; known informally as the "McCormick Report") as both a computing method that transforms symbolic representation into geometric representation, and as a tool for interpreting image data and creating new images from multidimensional data sets. Their definition also discusses ViSC in terms of human perception, use, and communication of the visual information.

Visualization has been a part of cartography since the inception of mapmaking. By definition, maps represent a way of visualizing or constructing a mental image of some area. The purpose is to provide humans with spatial information that not only can be useful and instructional, but also can promote interactivity with the human user. Cartographic communication models stress the construction of a mental map in the mind of the map user through the visual language of the cartographer (Robinson and Petchenik, 1976). With the release of the McCormick Report in 1987, geographers and cartographers started to realize the scientific visualization methodologies and software used in computer science and other related fields could be applied to the construction of maps that facilitated human visual thinking and cognition.

The word "visualization" was used in a cartographic context by DiBiase (1990), who described the development of a graphic model of map-based scientific visualization. His model of geographic visualization portrays a sequence of map uses from private

visual thinking (data exploration and confirmation) to public visual communication (data synthesis and map presentation). A similar model was proposed by MacEachren and Ganter (1990) who used the term "cartographic visualization" to describe a mental process facilitated by public-private map use distinctions. MacEachren has expanded upon his original descriptions of visualization in cartography to a definition of geographic visualization, a term now favored by many cartographers over cartographic visualization. His emphasis on the use of maps as visual displays is depicted as the (CARTOGRAPHY)³ or "cartography cubed" diagram. MacEachren's diagram (Figure 2.1) shows the cube as representative of map use space, with visualization and communication occupying opposite poles within the cube. The space is further defined by continua along the three axes that describe the type of map use (public or private, revealing unknown or presenting known information, and high to low user interaction). Both DiBiase and MacEachren stress the role of maps in research – the private, revealing unknowns, high user interaction portion of the map use cube. This is the portion occupied by geographic visualization. Communication lies at the opposite end, emphasizing the presentation of cartographic information to the general public. MacEachren and Kraak (1997) further refined the map use cube to show the sequencing of four map use goals (Figure 2.2). Each of these goals (exploration, analysis, synthesis, and presentation) is based not on map type, but on the map audience, data relations, and map interaction level associated with the goals of a particular map product.

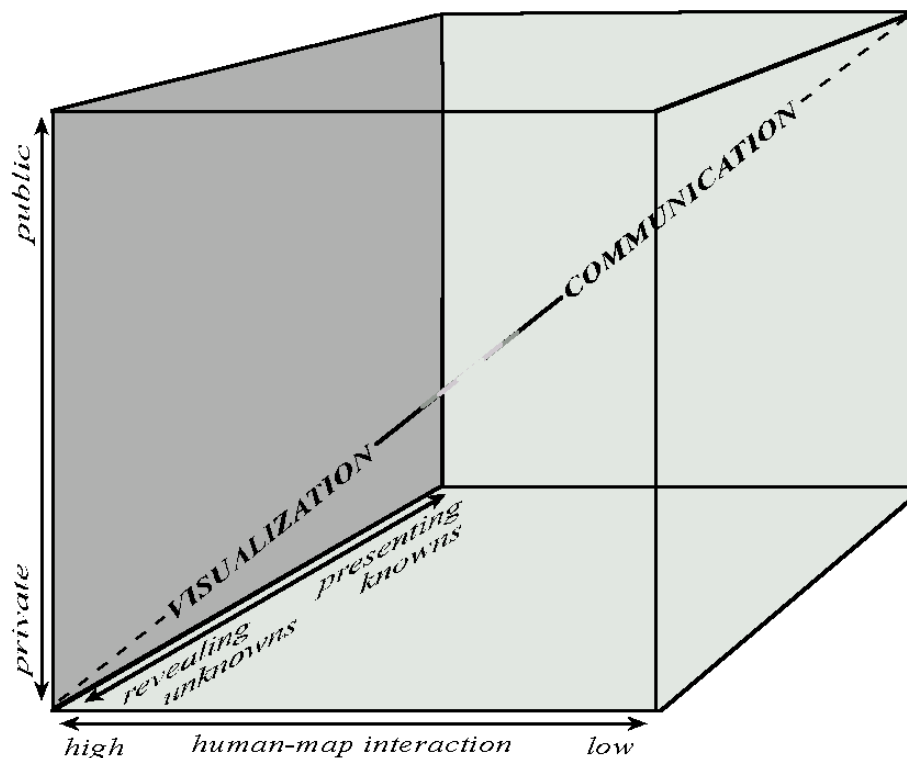


Figure 2.1 (CARTOGRAPHY)³ – A representation of 3-D map use space

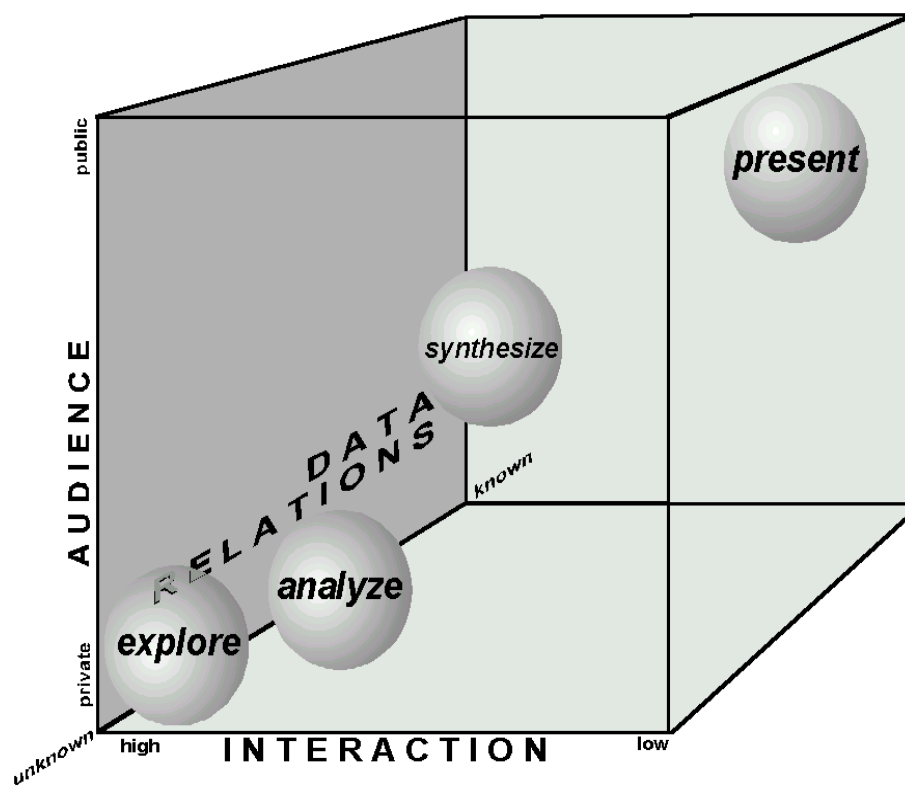


Figure 2.2. The four goals of map use as positioned within the map use cube (modified from MacEachren and Kraak, 1997).

2.2 Visualization Tools and Techniques

The tools of visualization are directly related to the four primary goals of map use as described by MacEachren and Kraak (1997). Whether the results of a geographic visualization procedure are designed for private, exploratory, high user-interaction map use, or whether they are presented to the public with low user interaction, visualization software tools are important to the process. MacEachren (1995: p. 359) defines three tasks that visualization tools may be used to address (listed in order of increasing complexity):

- (1) Feature Identification: recognition of known features or discovery of unknown features
- (2) Feature Comparison: identification of features and the relationships between them
- (3) Space-Time Feature Analysis: feature identification and feature comparison within a spatiotemporal domain

Kraak (1998) and Blok and Kobben (1998) list several tools needed for exploratory visualization. Among these tools are computer display, navigation/orientation, database querying, generalization, data transformation ("re-expression"), hyperlinked views, animation, and World Wide Web/Internet search and retrieval engines. Many of these tools exist today, either as commercial software packages (public availability), or as shareware or freeware computer programs (public or private availability). Indeed, several popular GIS programs, such as ArcInfo and ArcView, incorporate most of these tools in various degrees of sophistication and usability.

Animation, a relatively recent addition to commercial GIS software, has been used by cartographers since the late 1950s (Peterson, 1994). Thrower (1961) described the potential of cartographic animation through motion pictures. Cornwell and Robinson (1966) advocated using computers to create individual frames in a cartographic motion picture. However, due to the time-intensive nature of working with computers in the 1960s and 1970s, few examples were described in the literature. Peterson lists Tobler's city growth animated maps (1970), and Moellering's animated maps of traffic accidents (1972, 1973a, 1973b) as notable exceptions. Today, animation is a common geographic visualization tool, primarily because of the widespread availability of powerful computer workstations and PCs. Peterson (1994: p. 623) defines cartographic animation as "the

depiction of change through the presentation of maps in quick succession." He subdivides cartographic animation into temporal animations (depicting change through time) and nontemporal animations (depicting change caused by factors other than time). In non-temporal animation, the viewer's perspective may change with time, but the actions of the main subject matter remain stationary over time. Tasks performed through non-temporal animation include generalization, classification, identification of spatial trends, and 3-D movements through space. These latter animations include "fly-bys" or "fly-throughs," and commonly depict movement over a 3-D representation of terrain as if the viewer was flying over a fixed land surface in some form of aircraft.

2.3 Visualization of Surficial Hydrologic Processes

The U.S. Geological Survey, U.S. Army Corps of Engineers, and U.S. Army (military branch) have led the way in the United States with several publications and computer programs related to surficial hydrologic visualization. Traub (1994) used a scientific visualization program (AVS – Advanced Visual Systems, Inc., Application Visualization System) to study how a highway bridge at Chester, Illinois, affected velocity vectors and channel scour at the highway crossing during the 1993 floods. Other USGS efforts towards hydrologic modeling and visualization include Hay and Knapp's (1993) paper on early efforts by the USGS to model the sensitivity of the Gunnison River basin in Colorado to climate change. This study utilized a three-component system consisting of an orographic precipitation model (RHEA-CSU), a GIS (ArcInfo), and a scientific visualization system (IBM Visualization Data Explorer). The GIS stored the basin database and provided input to the RHEA-CSU model. Output from the model was analyzed by the GIS, and subsequently fed into the visualization program to animate sequences of images over space and time. Hay and Knapp note that, despite the limited analytic capabilities of the visualization system, the use of Data Explorer filled a gap in GIS visualization capabilities, and they stressed the need for a more integrated GIS visualization system.

The U.S. Army Corps of Engineers (USACE) has developed several hydrologic visualization tools over the last several years. The GRASS GIS program has several vector and raster visualization capabilities including 3-D image generation and time series animation. Brigham Young University, in conjunction with the USACE Waterways Experiment Station, has developed the Watershed Modeling System (WMS), which provides tools for the delineation of watersheds and flood plains, using GIS, DEMs, and TINs as input data. WMS also interfaces with industry standard hydrologic models such as HEC-1 and TR-20. The Surface Water Modeling System (SMS) was also developed by BYU and the USACE as a comprehensive graphical user environment for 2-D numerical modeling. SMS includes tools for mesh and grid generation, interfacing with five popular hydrologic models, and visualization using 2-D contour plots of meshes and vectors and animations of water flow and sediment transport over time.

The Mississippi Basin Modeling System (MBMS), developed by the USACE Hydrologic Engineering Center, is a real-time unsteady flow forecasting system that was designed as a response to the Midwest flood of 1993. MBMS' primary objective is to forecast flood events, but it is also capable of analyzing low-volume flows so that routine daily forecasting needs of the USACE and other users can be met (U.S. Army Corps of Engineers, 1998).

The U.S. Army Construction Engineering Research Laboratories (USACERL) Environmental Modeling & Visualization Group and researchers at the University of Illinois Geographic Modeling Systems Laboratory have utilized the GRASS GIS program to construct several different landscape process simulations including surface, rainfall runoff, and soil geomorphology models, along with multidimensional interpolation and visualization for the Chesapeake Bay environmental monitoring program. They have also experimented with conversion of the GRASS results to the VRML format for interactive use on the Web (Mitas and others, 1997).

3. Animation Methodology and Descriptions of Visualization Projects

The primary goal of this research was to develop methods of visualizing the storage and movement of floodwaters through a large drainage basin over a specific period of time. The large basin in this study is the Upper Mississippi River Basin (UMRB), and the flooding events occurred during the spring and summer months of 1993. Preliminary steps have occurred, as outlined below, in order to reach the point where the visualization project could begin:

- 1) Collection of flood data (precipitation, potential evapotranspiration, and streamflow measurements)
- 2) Acquisition of geospatial data (DEMs and GIS coverages)
- 3) Evaluation of hardware and software needs; acquisition of computer equipment
- 4) Construction of GIS-based flood database
- 5) GIS-based modeling of the water balance during the 1993 floods

These steps are described in detail in Mizgalewicz and Maidment (1998). The resulting water balance maps were used in the construction of the visualization projects described in the following paragraphs.

3.1 Approach to Geographic Visualization

Geographic visualization techniques have been used in this study to develop a set of animation projects depicting the spatiotemporal dynamics of a catastrophic flood. Prior to the construction of these projects, data derived from the 1993 Midwest floods (streamflow, precipitation, and evapotranspiration) were used to define a water balance

for the year 1993. This data and the resulting series of maps have been used in the construction of several visualization scenes that show the dynamics of the flood water balance and the streamflow during the flood months.

The techniques developed in this research represent the first known use of geographic/scientific visualization theory in the development of models of the spatiotemporal change that occurs during a major flooding event. Geographic visualization (GVis) is a term describing an approach to cartographic communication, which seeks to incorporate new computer technologies and display techniques to further the cartographer's goal of creating maps that are highly readable and understandable to a wide audience. This type of map analysis often results in new map forms that deviate from the traditional, often static product of cartography – the paper map. By incorporating computer technologies, GVis provides cartographers with the ability to analyze spatial processes that occur over a specified time interval. Surficial hydrologic processes are ideally suited to representation in a GVis environment. This is particularly true of GIS-based studies of such phenomena, which are already in a database format that can easily integrate with GVis techniques.

3.2 Visualization 1: Area-based Animation of the 1993 UMRB Water Storage

The objective of the initial visualization project was to create a HUC-based animation of the daily water storage amounts that were derived from Mizgalewicz' and Maidment's hydrologic modeling. Output from the modeling included a series of 365 maps representing basin water storage values for the year 1993 (January 1 through December 31), including the primary flooding months of April through September. The intended purpose of this particular visualization experiment was to model the changes in water storage as the flooding progressed through the summer months of 1993.

As shown in Figure 3.1, the spatial configuration of the HUCs exhibits a fair degree of similarity, in terms of shape and area. The six largest rivers in the study area are displayed in this figure to aid in geographic reference. The UMRB watershed map was examined in ArcView, along with the daily values of water storage for each of the HUCs. Individual cumulative water storage values, spatially averaged across each HUC, ranged from -138.864517 to 253.566864 mm. Negative water storage values indicated a water deficit in a given watershed (more outflow and evapotranspiration from the watershed than inflow and precipitation), while positive values indicated a water surplus. It should be noted that these values have been spatially averaged across the watersheds and were derived from the water balance equation. Deficits and surpluses of precipitation and evapotranspiration were variable across any given watershed, and across the UMRB as a whole. These values were used to construct a series of water storage maps, which when sequenced together, provide a chronological picture of water storage during 1993 in the UMRB.

3.2.1 Cartographic Design

A typical map layout, depicting the UMRB water storage for August 1, 1993, is shown in Figure 3.2. A cartographic template was constructed in ArcView, consisting of the main map of the UMRB watersheds, a UMRB location map, a legend for the water storage values, a temporal legend showing the date of the map, a scale bar (in kilometers), title, and north arrow. Wasted space between the main map and the outer map border was minimized, however a cluttered appearance to the map was purposely avoided. The two most salient features of the map, the UMRB watersheds and the temporal legend, were drawn as fairly large objects to emphasize their importance over the other map elements. The ArcView map template was saved and reused each time a new day's set of water storage values were placed in their corresponding HUCs. The only changes in the maps from day to day were the UMRB watershed colors (representing different levels of water storage) and the temporal legend.

Five shades of blue were used to represent the positive water storage values ranging from a very light blue for the lowest range of positive values, to a dark blue for the highest range of positive values. Intermediate ranges were assigned a shade of blue based on a color ramp between the light and dark blue end ranges. White was used to represent all water storage values at or below zero.

The classification scheme used for the water storage values was the equal interval method, also known as the equal steps based on the range of data method. This method

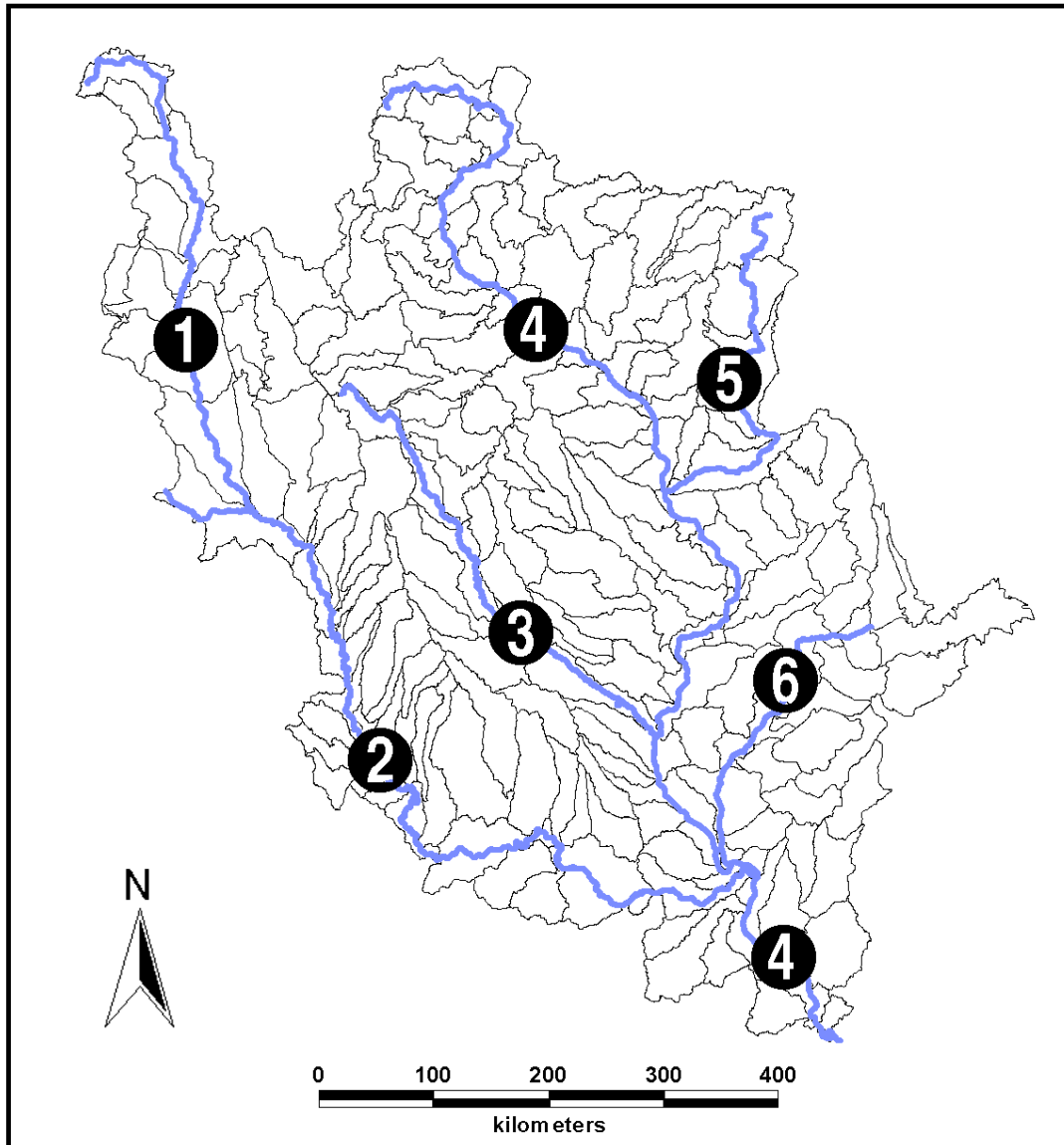


Figure 3.1. HUCs in the Upper Mississippi River Basin study area. Important rivers (depicted by the heavy lines) in the study area are the (1) James, (2) Missouri, (3) Des Moines, (4) Mississippi, (5) Wisconsin, and (6) Illinois rivers.

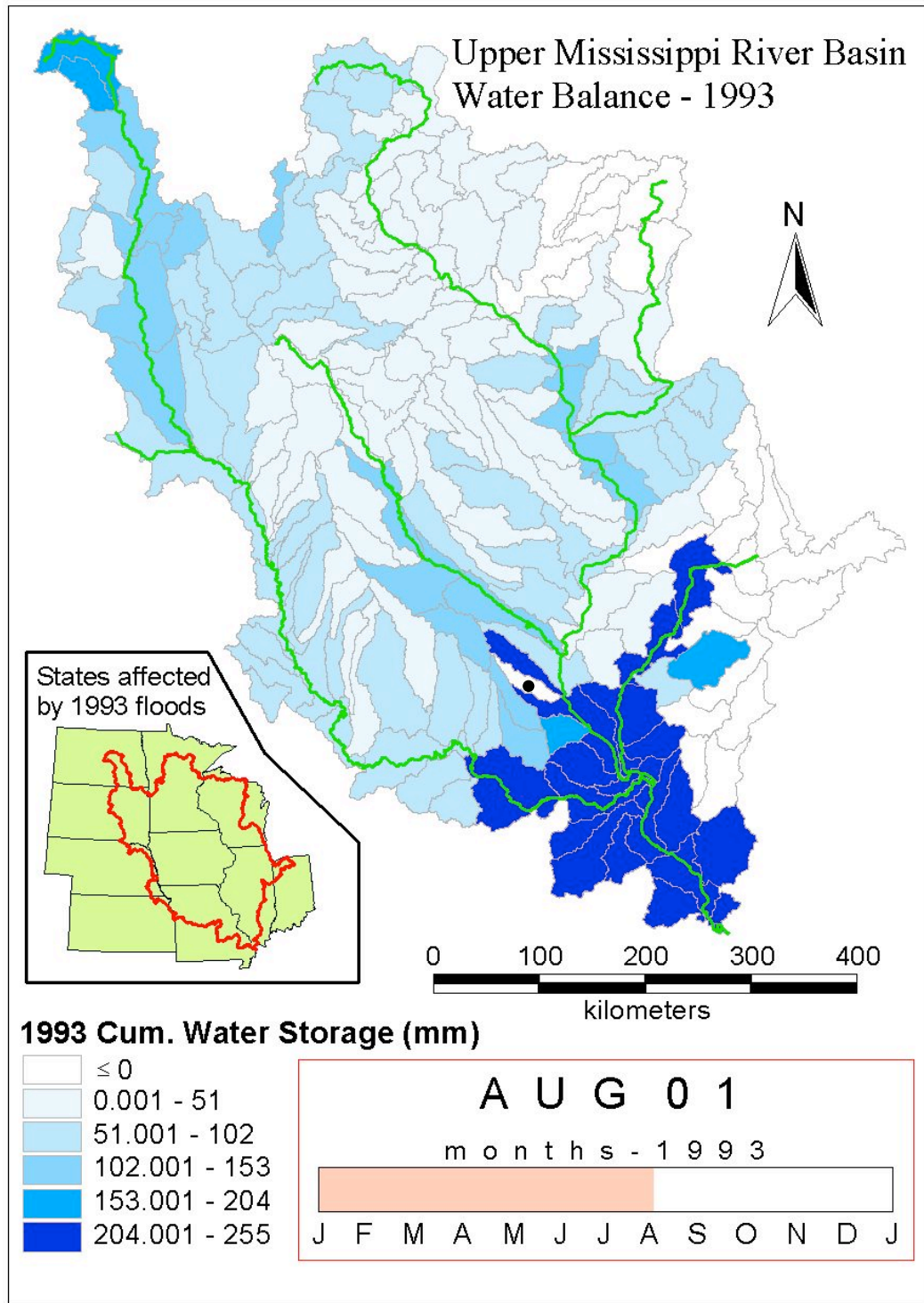


Figure 3.2. Map layout used in the construction of the individual water storage maps for visualization project 1. This particular map shows water storage in the study area watersheds on August 1, 1993. Black dot in south central portion of the map marks the South Fabius watershed (HUC 07110003) mentioned in the text.

divides the range between the high and low values by the desired number of classes (in this case, five classes were desired for the positive water storage values) to obtain the common difference. The difference value is then successively added to the data values beginning with the lowest value, to obtain the next higher class limit. This classification scheme provided a simple method of categorizing the water storage values. As raw data were used in the mapping, this visualization method provided a way of simply observing the amount of water stored on an entire watershed during a given day of 1993.

The other important map element shown in Figure 3.2, and used in all of the map layouts, is the temporal scale. This simple scale bar consists of two time identifiers – an abbreviation of the month and day ("AUG 01," in Figure 3.2, for August 1st), and the first letters of the months arranged below a colored bar. The bar was enlarged through each map layout using ArcView's "graphics size and position" feature, in which a selected graphic can be enlarged, decreased, or repositioned in the layout window. Through the 365 days, the bar increases toward the right of the map layout as the days progress from January 1 (no bar) to December 31 (full bar).

One final point about the map in Figure 3.2 should be made with regards to a particular HUC. The South Fabius watershed (HUC 07110003), marked by a black dot in Figure 3.2, lies just south of the confluence of the Des Moines and Mississippi Rivers. This watershed exhibited extremely low water storage values throughout all of 1993 with most values less than zero. Upstream and downstream watersheds contained no such abnormally low values, thus posing a problem with the South Fabius' water balance data. Both daily streamflow and precipitation values were not found to be significantly different from daily values in upstream and downstream watersheds. Monthly potential evapotranspiration values covered an area considerably larger than HUC 07110003 and did not appear to be the cause of the problem. Further research is warranted to explain the anomalous water balance values in HUC 07110003.

Each map was exported to a JPEG (Joint Photographic Experts Group) image at a screen resolution of 72 dots per inch (dpi). The JPEG format was chosen primarily due to file size limitations of the hardware and software. At 72 dpi, the resolution of the JPEG images was sufficient for their use in animation software. Another consideration is that JPEG images are viewable using Internet browser applications such as Microsoft Corp. Internet Explorer[®] and Netscape Communications Corp. Communicator[®] software.

3.2.2 Animation of the Maps

The exported map images were imported, sequenced, and animated using Adobe Systems Inc. Premiere[®] software (v. 4.2). Premiere is a (Microsoft) Windows[®]-based digital moviemaking program that allows the user to record, create, and play movies. The software has the ability to work with video files, as well as sound files, pre-existing animation files, images, text, and other materials (Adobe, 1994).

Based on the layout page settings of the maps created in ArcView (9 inches x 6.5 inches), each exported JPEG was 622 pixels long by 442 pixels wide (8.639 inches x

6.139 inches or 21.94 cm x 15.59 cm, where 72 pixels = 1 inch). A new Adobe Premier presentation file was created, and the directory containing all 365 maps (as JPEG images) was imported into the presentation. Once the directory containing the images had been imported into the presentation, the directory icon was placed in the Premiere construction window. This window displays all of the images sequentially according to their file names. Each image's file name corresponded to a date of water storage, thus the sequence of images was displayed in chronological order from January 1 to December 31, 1993. From a pull-down menu in Premiere, the "Make Movie" command was used to create the animation. After experimenting with various frame rates, the rate of 1 frame per second (fps) was used as it was found to be a good compromise between speed of the map frame movement with individual map frame dwell time. Hydrologic patterns and trends emerged when viewing the animation at 1 fps, without sacrificing continuity between individual map frames. The animation was subsequently saved in the Windows AVI (Audio Visual Interleaved) format. AVI files, along with pertinent GIS files and the JPEG images are stored in the CD-ROM appendix to this report.

3.2.3 Description of Visualization 1

When viewed at a frame rate of 1 fps, the sequence of 365 images show the changes in water storage amounts in the UMRB study area during the spring and summer flood months of 1993. The animation corresponds well with documented meteorological events that happened in the basin. The descriptions below refer directly to the animation files located in the CD-ROM appendix to this report. Files "vis1_halfsec.avi" and "vis1_onesec.avi" contain the animations constructed at $\frac{1}{2}$ fps and 1 fps, respectively, in this first visualization project. Selected still frames of the animation are shown in Figure 3.3.

According to Rodenhuis' (1996) description of the weather events that led to the flood, the period from April to May, 1993, was the "build-up phase," as precipitation intensified over the central United States. In his flood chronology, Changnon (1996) describes several minor to moderate floods along the Upper Mississippi River from March through May. Many agricultural fields throughout the basin contained standing water during the early spring months of 1993. The animated sequence of flood water storage maps (file "vis1_onesec.avi") from January 1 through April 30, 1993, show initially very low water storage values in all of the UMRB watersheds, a result of both the time of the year and the zeroed water balance values at the start of 1993. This continues through most of March, with positive water storage values primarily concentrated in the upper half of the basin in central Iowa and southern Wisconsin (Figure 3.3a).

As the winter gave way to spring, the rains started and several notable floods occurred in the Kansas City area (May 6-8), southwestern Minnesota (May 9-10), eastern Kansas (May 11), and southern Minnesota and South Dakota (May 15-16) (Changnon, 1996). The Minnesota flooding is apparent in the water storage map

animation during much of May, 1993, although the eastern Kansas flooding does not appear to have as much of a signature on the animated maps (Figure 3.3b). This could be due to decreased soil moisture in eastern Kansas watersheds during May as compared to soil moisture values in southern Minnesota watersheds.

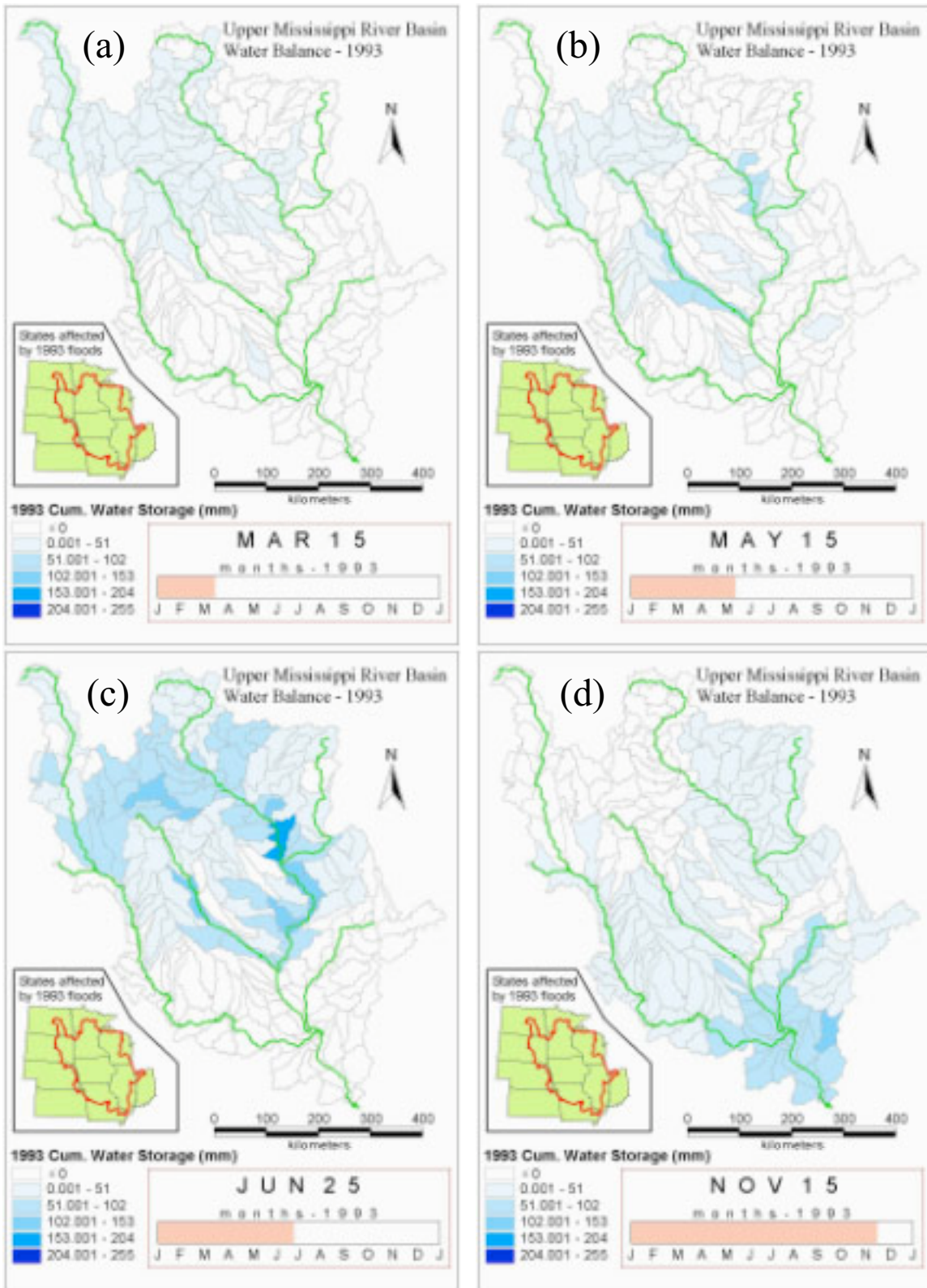


Figure 3.3. Still frames from water balance animation. 1993 UMRB water storage for March 15 (Figure 3.3a), May 15 (Figure 3.3b), June 25 (Figure 3.3c), and November 15 (Figure 3.3d) is shown.

June, 1993, has been described by Rodenhuis (1996) as a period of transition in which a series of rapidly moving spring storms traveled across North America, resulting in even higher precipitation amounts throughout the central United States. Some important weather events that occurred during June included moderate to heavy rainfall events in early to mid-June in South Dakota, Iowa, Minnesota, and Wisconsin. Also, flooding developed along the major tributaries of the Mississippi River in Iowa, Minnesota, and Wisconsin during mid-June, and along the Minnesota River near Mankato (south-central Minnesota) in mid- to late June. The June series of water storage maps show increasing amounts of water storage in the watersheds along the Des Moines River (Iowa) and the upper Mississippi (Minnesota and Wisconsin). Water storage in the central and northern parts of the UMRB dramatically increased during June, with notable precipitation events and flooding occurring southwest of Minneapolis-St. Paul and just north of the confluence of the Mississippi and Wisconsin Rivers. The flooding in south-central Minnesota during mid- to late June can also be seen in the animation during the last two weeks of the month (Figure 3.3c).

The sustained phase of precipitation started in late June, and continued in the central United States through July and extended into August. Flooding was widespread during this time resulting in peak flood crests in many locations along the Mississippi and Missouri Rivers and their tributaries. In the animation, the areas of greatest water storage were along the Des Moines River in Iowa and the Mississippi River in southwestern Wisconsin/northwestern Illinois during the first of July. As the month progressed, so did the precipitation, flooding, and water storage. By the middle of July, large amounts of water were being stored in the southern part of the UMRB, particularly around the St. Louis area where the Mississippi and Missouri Rivers meet. Water was also being stored in larger than normal amounts along the Missouri River west of St. Louis. By the end of the month, the peak flooding was occurring along the lower reaches of the Missouri River and along the Mississippi River, particularly along the boundary formed by the river between Illinois, Iowa, and Missouri. These high water storage amounts were sustained through the end of July and into August in the southern part of the UMRB (Figure 3.2).

By August, the character of the precipitation and flooding changed. During this month, occasionally intense rainfall events occurred, rather than the more widespread and intense events that had occurred in July. These events are marked on the animation by the decreasing values of water storage in the upper two-thirds of the basin. By the end of August, water storage values were moderate in the middle and southern parts of the basin, and low nearly everywhere else.

Intermittent flooding continued into the fall months of 1993, but the precipitation events were generally weaker than those that had occurred during the summer months. Changnon (1996) notes that there were several isolated flood events during September and November. Water storage values tend to decrease during September throughout most of the basin, but increase rapidly in the southern part of the basin on September 23 and remain high until October 3. During that time, heavy rains fell on saturated soils in Kansas, Missouri, and Illinois, creating new flooding on the Missouri, Mississippi, and Illinois Rivers. Heavy rains and flooding also occurred during mid-November in Missouri

and Illinois, and this is shown by the rapid increase in water storage amounts in the southern part of the basin from mid- through late November (Figure 3.3d).

The animated series of water storage maps can also be favorably compared to Figure 3.4, which shows the reaches of rivers in the UMRB that experienced severe flooding during 1993. Record flood reaches in this diagram correspond well with those watersheds showing high water storage amounts in the animation. The correlation between the animation of water storage and the reported precipitation amounts is not surprising as the same precipitation values that were recorded by meteorological stations were used in the water storage calculations. Rapid increases after a major precipitation event are visible, in most cases, on the animated series of maps. Gradual decreases in water storage are not as striking on the animated series of maps, but are apparent as the animation shows a gradual basinwide decrease after August, 1993.

3.3 Visualization 2: Point-based Animation of the 1993 UMRB Water Storage

In the second visualization project, basin water storage depths were again used, but the symbology was considerably different than in the first visualization project. Whereas area-based symbols were used to indicate water storage depths in the first project, point-based symbols were used in the second project to indicate water storage values. As with the first project, the primary objective of the second visualization project was to model changes in basin water storage during the 1993 flood months. This particular visualization project was undertaken to attempt to design a model of downstream flow that followed the UMRB river network. Each selected river segment would consist of a certain number of dots per segment, based on the daily water storage value for the HUC that the reach flowed through. Animation of the resulting maps would then show a type of movement downstream as the flooding occurred.

3.3.1 Cartographic Design

The same output maps that were used in the first visualization project were used in the second project, with some major changes. The primary change was in the depiction of a series of dots along a selected set of river reaches. River reaches were selected based on their mean annual streamflow values and their location between HUC boundaries. The construction of a series of dots along the stream network presented some challenges due to the limitations of the ArcView GIS software. Since ArcView does not contain any built-in functionality that can convert a line feature to a series of points, the ESRI ArcScripts web site (<http://www.esri.com/arcscripsts>) was accessed and a search for an Avenue script designed to convert line features to points was initiated. Avenue is the object-oriented scripting language that is used to customize ArcView. Users of ESRI software, as well as ESRI software developers, regularly submit new scripts to the

ArcScripts web site that can be downloaded at no cost. A script (filename "divide1b.avx," written by Steven Lead of ESRI Australia, June 16, 2000), contained in an ArcView extension, was downloaded from this web site, and activated in ArcView. The script was designed to add a user-specified number of points spaced evenly along a line, and add points separated by a user-specified distance. Lines were converted to linear dot networks without any problem; however, there appeared to be no way to control the number of dots per stream reach based on the HUC water storage values. Although the resulting dotted lines contained uniform dot patterns and spacing, this method was ultimately abandoned.



Figure 3.4 The reaches of rivers in the UMRB study area that experienced new record floods and those that experienced nonrecord but still significant flooding in 1993 (after Changnon 1996).

The second method chosen to create a moving picture of the stream network was a dot map. The dot map is a simple, effective procedure. According to Dent (1998), the dot distribution maps main purpose is to communicate variation in spatial density. This is accomplished by either allowing a single small dot to represent one item (a one-to-one relationship), or by having the small dot represent multiple items (a one-to-many relationship). In both types, choice of dot diameter and dot spacing is crucial to being able to see a pattern develop in the dot map. Dot diameters that are too large can mask a trend or pattern in the dot distribution, as can dots that are spaced too far apart.

In ArcView, dot maps are created by accessing the legend editor tool for a polygon theme as shown in Figure 3.5. The dot legend type requires a density field (column of attribute information in ArcView) to be selected, and the user has the option of selecting a field to normalize the data on. The resulting dot legend ("1 dot = 5.000000" in Figure 3.6) indicates that one dot on the map equals a user-specified number of statistical units. The user also has the option of letting ArcView calculate the optimal dot density value. ArcView calculates this value by checking the size of the polygon that the dots will go in and the screen units of the map view. Optimal dot densities change as the user zooms in and out of the map view. The dots are also placed randomly within the polygon that they represent.

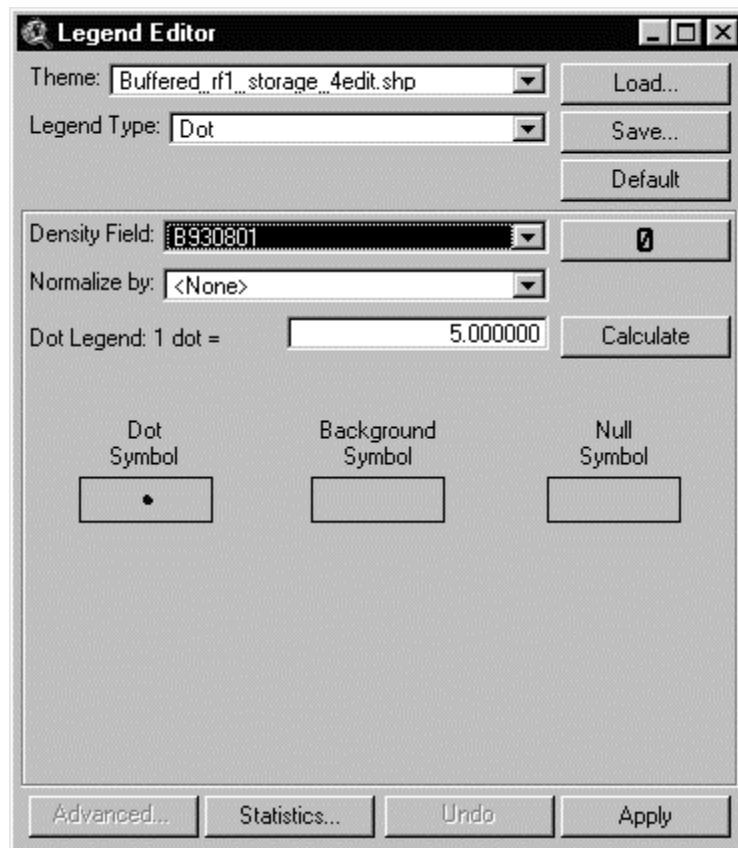


Figure 3.5. The ArcView (v.3.1) Legend Editor with the Dot legend type chosen.

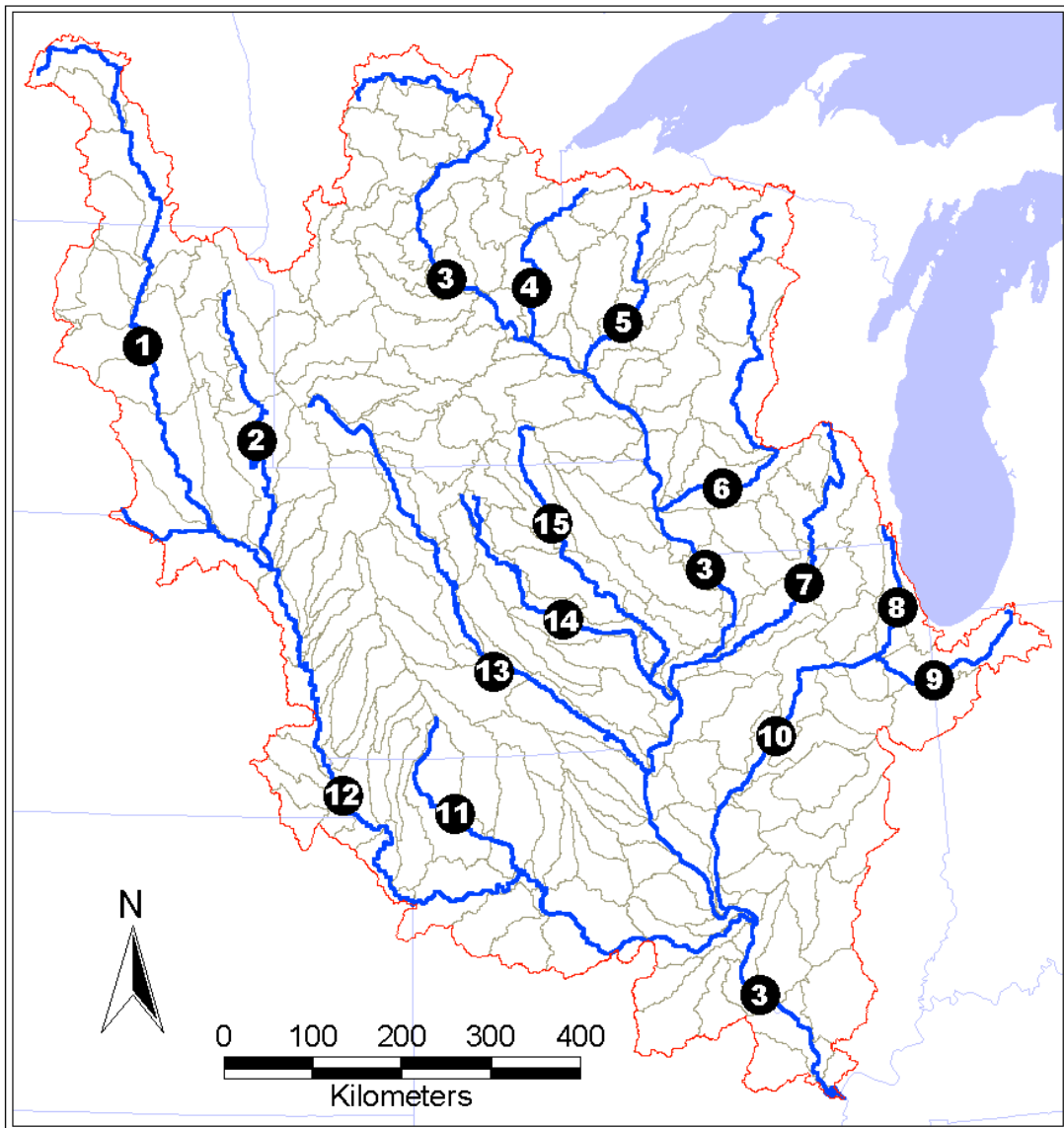


Figure 3.6. HUCs in the Upper Mississippi River Basin study area. Rivers in the study area with significant discharge (river reaches with annual mean flow > 4000 ft³/second), are depicted by the thick blue lines. Rivers (1) and (2) have flow < 4000 ft³/second, but were added to the map for spatial continuity. The rivers shown on this map are (1) James, (2) Big Sioux, (3) Mississippi, (4) St. Croix, (5) Chippewa, (6) Wisconsin, (7) Rock, (8) Des Plaines, (9) Kankakee, (10) Illinois, (11) Grand, (12) Missouri, (13) Des Moines, (14) Iowa, and (15) Cedar.

For visualization project 2, the challenge was to use dot mapping procedures to indicate changes in water storage values along the stream network. Dot mapping is

typically performed using polygon-based features, and in ArcView, dot mapping is only available for polygon map themes. Thus, a method of assigning water storage values to a polygonal representation of the stream network had to be determined.

The data used in this visualization project included the RF1 (river reach file) line theme for the UMRB study area, a point theme of USGS gaging stations, and the daily water storage database tied to HUC polygons. The dense network of streams in the RF1 theme dictated that only a selected number of streams should be used in the construction of this visualization project. In order to create a better spatial representation of the entire basin, a denser stream network (as compared to the network used for visual purposes only in Figures 3.1 and 3.2) was determined. This network was based on the selection of those stream reaches whose mean annual streamflow values was equal to or in excess of 4,000 ft³/second (cfs). This rate was chosen as it allowed for a good spatial representation of rivers in the basin study area. As depicted in Figure 3.6, 15 rivers were used in this visualization project. Two of the rivers, the James and Big Sioux Rivers in the northwest part of the basin, did not contain mean flow values that were greater than 4,000 cfs, but they were selected to provide spatial continuity in the stream network diagram.

The next task was to segment the stream network based on the configuration of the HUCs. The stream network was already segmented due to the manner in which the original RF1 network was digitized. These segments did not correspond to HUC boundaries that crossed the stream network, so the features of the network were dissolved in ArcView. This resulted in a single, unattributed stream network theme. The theme was then spatially intersected with HUC boundaries to create a series of segmented streams containing daily water storage attributes from the HUC polygon theme.

Since ArcView can assign dots only to polygons, each stream segment was buffered by a 4-mile (6.4-km) wide polygon zone around the stream network lines. Several different widths were experimented with, but at the scale of the resulting map layout, the 4-mile wide buffer seemed to allow for the best placement of dots. ArcView's basic buffer tool does not create buffers with the attributes of the original theme, thus the WizardBuffer.FINISH script (written by Thad Tilton of ESRI, March 22, 2000) was downloaded from the Arcscripts web site. Once the script was compiled and run, ArcView's "Create Buffers" tool was modified so that the user was prompted to choose an attribute to carry over from the original theme to the buffer polygons. The "HUC" attribute field was chosen as this contains the eight-digit HUC identifier, which was also present in the stream segments theme. Since the stream segments theme also contained the daily water storage values, the buffer polygon theme and the stream segments theme were joined based on the related attribute field, "HUC." The resulting theme was a set of segmented polygons that approximated the stream network and contained daily water storage values.

The dot map legend was created in ArcView by experimenting with several dot diameters and spacings. At the scale of the resulting map layout, dot diameter played a big role in determining the look of the dotted stream network. Dots that were too large coalesced too quickly in downstream ends of the stream network (large water storage values) and the map became too busy. Dots that were too small were difficult to see and

the overall stream network trend was not as apparent. After several experiments, a dot diameter of 5 pixels (screen units of 72 pixels/inch) and a dot spacing of 1 dot/5 mm of water storage depth was chosen. This resulted in a good dot configuration for the stream network, particularly during the flood months. As seen in Figure 3.7, the dots in the southern part of the basin are just starting to coalesce. This map represents data from August 1, 1993, the day of maximum water storage in the downstream portion of the basin.

The map layout used for this visualization project was similar to the one used in the first project. Figure 3.7 shows a typical layout depicting the water storage for August 1, 1993. The temporal legend is retained from the first visualization project, but the static map legend differs. In this map, the dot legend "1 Dot = 5 mm of cumulative water storage per HUC" describes the density of dots on each daily map. ArcView's dot mapping tool places dots randomly within the chosen polygon boundaries, thus dots were randomly placed at a density of 1 dot for every 5 mm of water storage within each stream segment buffer polygon. Dot density changed, as did the random pattern of the dots within the buffer polygons, as water storage values changed during the days of 1993.

As with the first visualization project, each map in the second project was exported to a 72 dpi JPEG file. The 365 JPEG images were subsequently imported into the Adobe Premier animation software.

3.3.2 Animation of the Maps

The individual images generated by exporting ArcView map layouts to JPEG files were imported, sequenced, and added to the Adobe Premier construction window. As this visualization project was somewhat more complicated in its representation of the water storage values than the first project, some introductory map layouts were created in ArcView and then exported to JPEG files. These map layout frames, shown in Figure 3.8a through 3.8c, serve to introduce the visualization project and provide a fairly seamless transition to the start of the animated dot maps. The first frame to appear in the Visualization 2 animation (Figure 3.8a) depicts the stream network used in the water storage dot map animation, and it consists of the streams shown in Figure 3.6. This frame is viewed for a duration of 10 seconds in the animation. As the first frame fades out, a second frame fades in for a duration of 10 seconds. The frame shows the HUC boundaries used to cut the stream segments (Figure 3.8b). The fade out/fade in transition was accomplished using Adobe Premier's Cross Dissolve tool. As the second frame fades out, the third frame fades in and appears for a duration of 10 seconds. This frame (Figure 3.8c) shows the 4-mile (6.4-km) wide buffer created around the stream line segments. The frame was created with a duration of 14 seconds, slightly longer than the first and second frames because of the longer text description on the map. As this frame fades out, the stream network frame fades in again, but only for 4 seconds as a transition to the first frame of the dot map animation (January 01, 1993, data).

Both half-second ("vis2_halfsecond.avi") and one-second ("vis2_onesecond.avi") frame rate animations were created for the second visualization project. The animation files are included in the CD-ROM appendix.

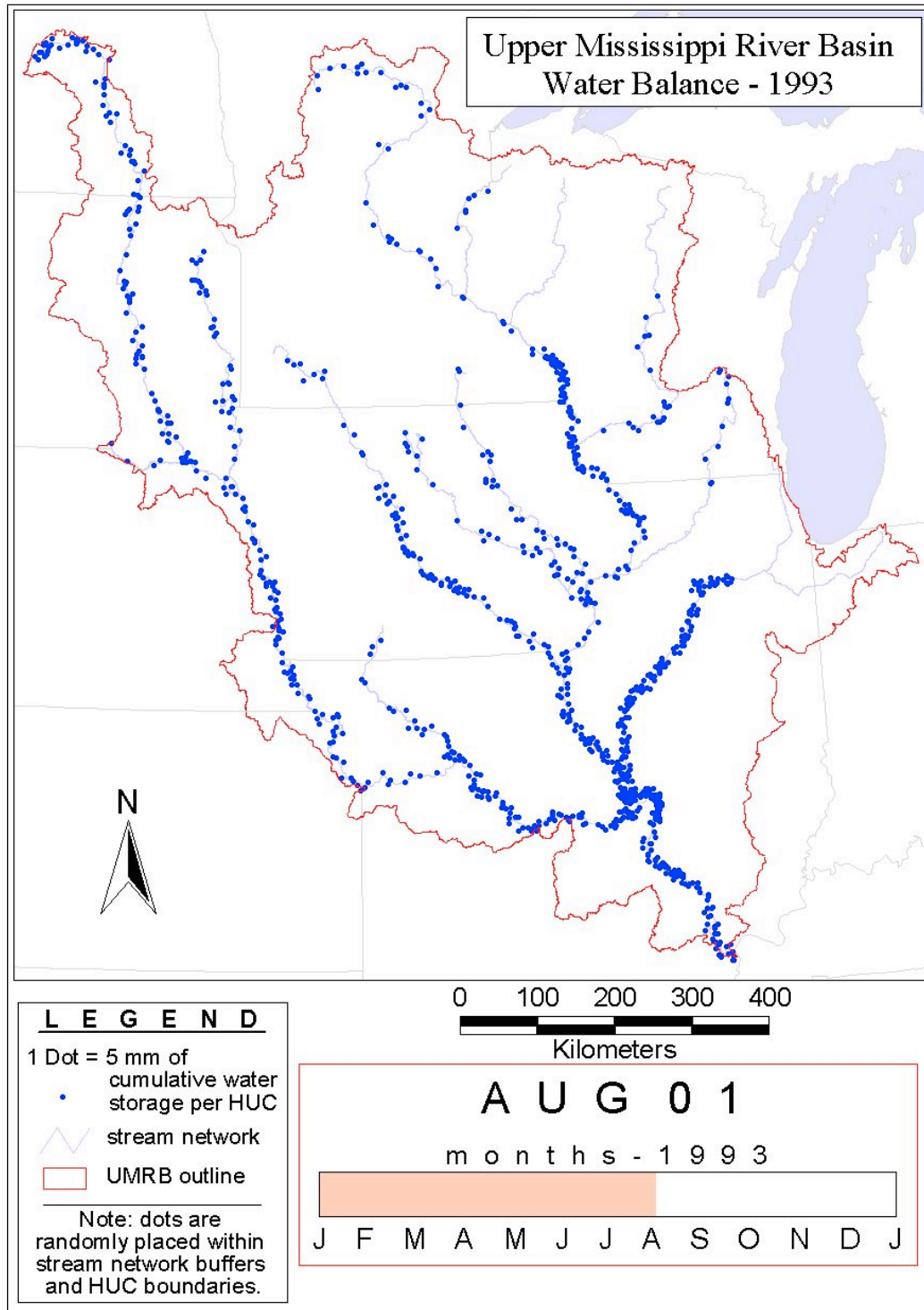


Figure 3.7. Maplayout used in the construction of the individual water storage maps for visualization project 2. This particular mapshows water storage in the study area watersheds on August 1, 1993.

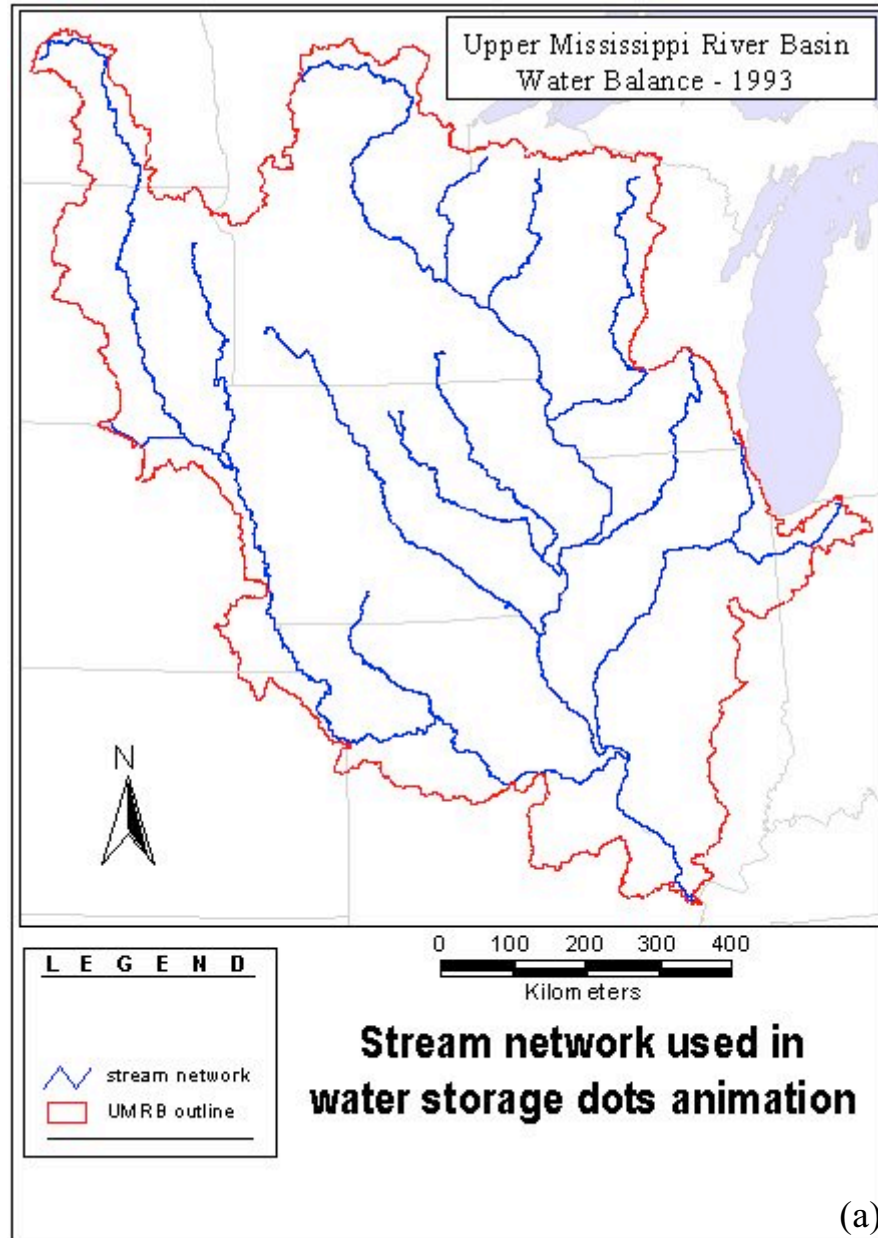


Figure 3.8. Introductory map layout frames used in visualization project 2: (a) stream network used in water storage dot map animation, (b) HUC boundaries used to contain dots within stream buffer polygons, and (c) buffer polygons of stream network used to contain dots.

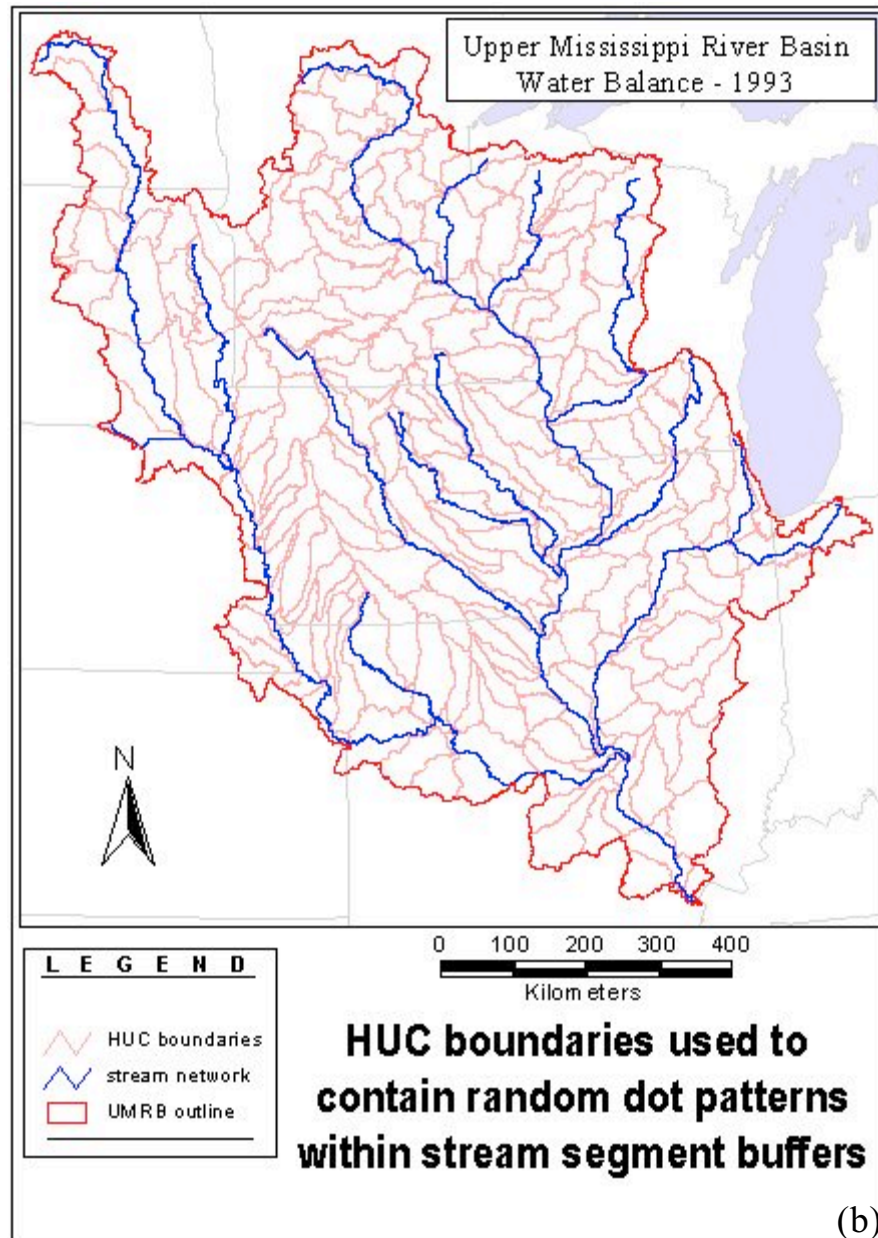


Figure 3.8 continued.

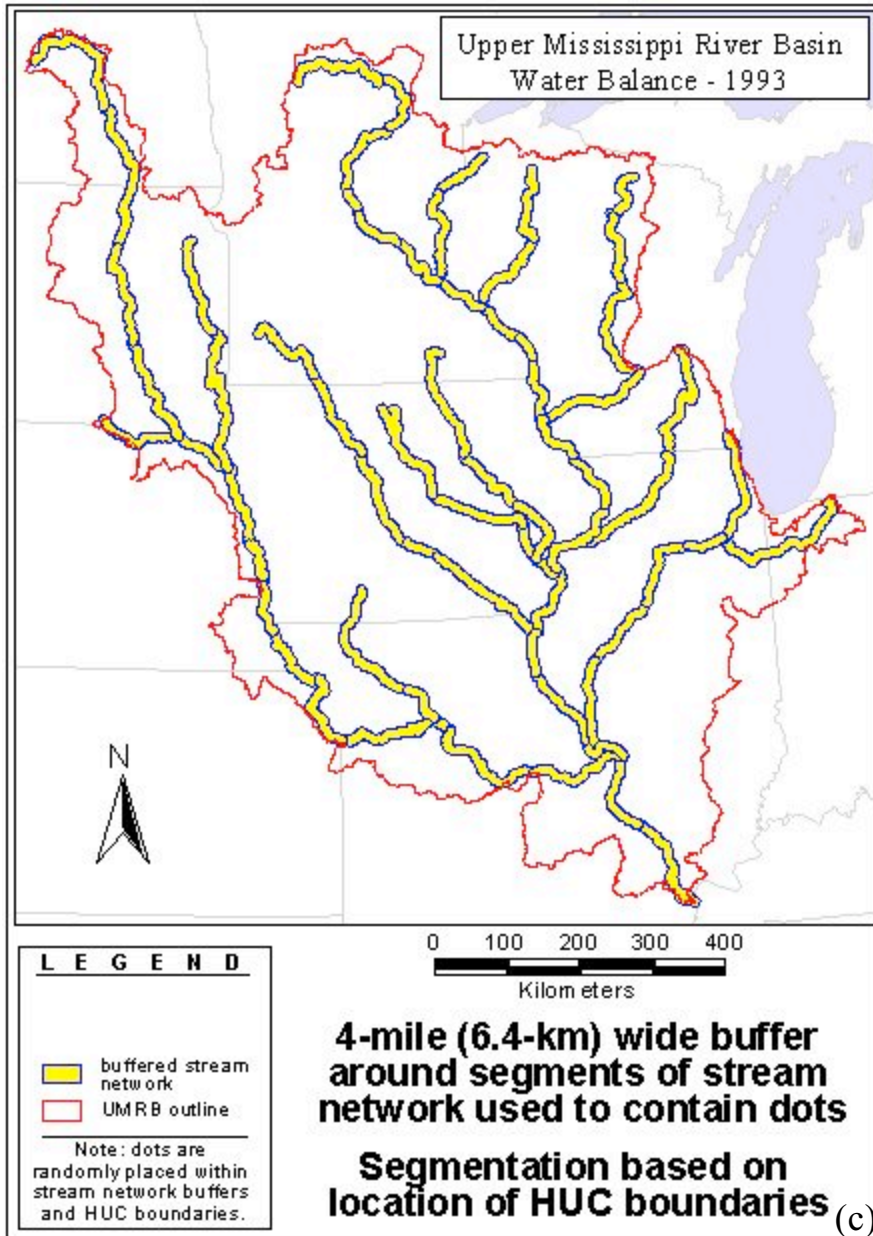


Figure 3.8 continued.

3.3.3 Description of Visualization 2

Since the data used in this animation were the same as that used in the first visualization project, the expectation was that the two would show somewhat similar features. The main difference between the two projects was in the choice of symbols – area-based for Visualization 1 and point-based for Visualization 2 to represent linear phenomena.

The animation at a frame rate of one second proved to be rather slow in its depiction of downstream water movement over time. The dots did not change position fast enough from one frame to the next, thus it was difficult to visualize fluid movement. However, the half-second frame rate animation was better in terms of its ability to portray the dynamics of the floods. At a half second per frame, the duration of frame viewing is such that the emphasis is on the dot changes from frame to frame. As with the polygon-based animation in Visualization 1, the dot animation shows the pulses of water storage as the flooding increased through the summer months, and then decreased in the fall.

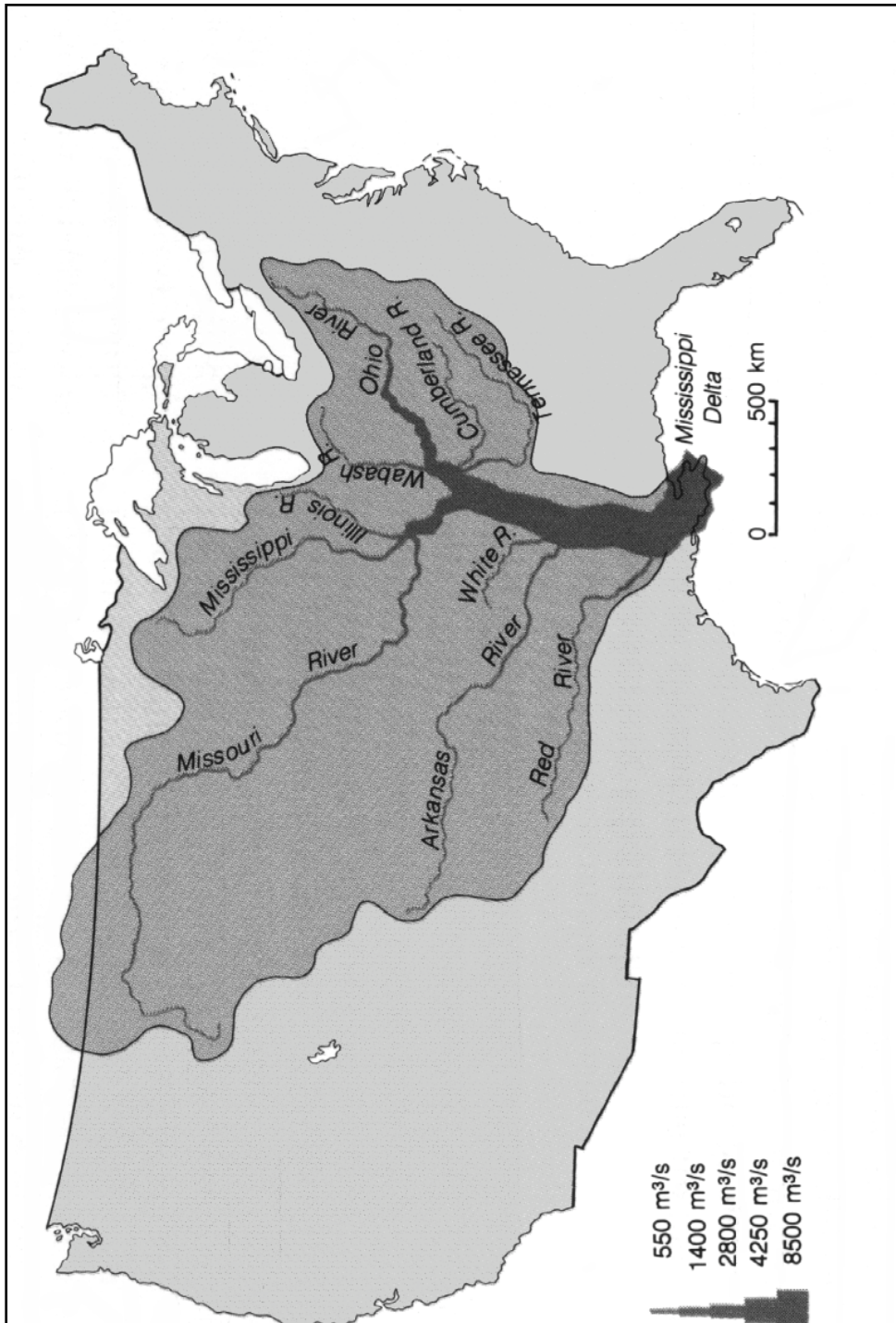
The "channelized" dot patterns in Visualization 2 are useful in providing the sense of downstream water movement as the flooding progressed. One negative aspect of ArcView's dot map production is the random placement of dots. Thus, a stream segment buffered polygon could have the same water storage values on consecutive days, but show a different dot arrangement on the days. The same number of dots would appear for each day, but the spacings would be different. When animated, this random placement of dots results in a jumpy appearance in the dot animation. Sometimes this enhances the downstream water movement effect, but other times it detracts from the sense of downstream flow. This effect was more pronounced in the one-second frame rate animation than in the half-second animation.

3.4 Visualization 3: Line-based Animation of the 1993 UMRB Streamflow

Visualization project 3 utilized daily streamflow values as provided by the USGS gaging stations in the UMRB study area. The objective of this project was to model changes in daily flow rates during the flood months of 1993. Individual stream reaches were tied to gaging station flow values and the width of the reaches was varied depending upon the flow rates. Animation of the resulting maps showed pulses of water movement downstream particularly during the flood months, but also called into question the accuracy of the streamflow values in certain portions of the UMRB.

3.4.1 Cartographic Design

The initial idea for this visualization project came from the flow map of annual Mississippi River basin discharge values shown in Figure 3.9. In this map, the major rivers of the entire Mississippi River system are depicted. River widths correspond to annual discharge values (in m^3/second) and vary from less than $550 \text{ m}^3/\text{second}$ in the upper



3.9. The Mississippi River drainage basin. In this diagram, the width of a flow line is dependent upon the river's annual discharge rates (from *The Blue Planet: An Introduction to Earth System Science*, B.J. Porter and S.C. Porter, ©1995. Reprinted by permission of John Wiley & Sons, Inc.).

reaches of the rivers to 8,500 m³/second as the Mississippi River discharges into the Gulf of Mexico. This design was adapted to visualization project 3 with some modifications to the map legend and the geographic extent of the basin.

According to Dent (1998), the purpose of a quantitative flow map is to symbolize the movement of some quantity between two locations. The widths of the flow lines connecting the locations are drawn proportional to the quantity of movement that the lines represent. Based on a study by Parks (1987), Dent describes three different types of flow line maps: radial, network, and distributive (Figure 3.10). Radial flow maps have their origin at a central node and branches radiate outwards in a spokelike fashion. This type of flow map is typified by the hub and spoke pattern in airline route maps. Network flow maps show the interconnectivity of locations, such as transportation and communication linkages. Distributive flow maps show the distribution of some value, or set of values, as they move between locations. Of the three, the distributive map is the most dynamic, and is often characterized by arrowheads pointing in the direction of flow. A reverse form of Parks' distributive flow map idea (without arrowheads) can be seen in the map in Figure 3.9, where the distribution of streamflow increases as one travels downstream towards the outlet of the Mississippi River.

The base map for this visualization project consisted of the same fifteen major rivers used in visualization project 2 and depicted in Figure 3.11a. These rivers, for the most part, contained reaches with annual streamflow greater than 4,000 cfs. Since the location of the river network itself was of interest in this study, and not the RF1 vector file attributes, the features of the network were dissolved in ArcView, resulting in a single unattributed river network.

The next task was to assign USGS gaging stations to segments of the streams. In Mizgalewicz' and Maidment's GIS modeling phase of this study, the discharge records from 261 gaging stations were initially used in the water balance calculations. This value was later reduced to account for discrepancies in the discharge and evapotranspiration data. For the purposes of Visualization 3, the spatial configuration afforded by the 261 gaging stations was important, so these data were used when constructing the maps for this visualization project.

Ninety stations lay along the river reaches. The locations of these stations were used as guides to cutting the RF1 reach file to create 106 gaging-station defined river segments. After zooming into the gaging station point and adjacent river reach, ArcView's "draw line to split feature" tool was used to split the line. This tool works by

digitizing a small line at the desired location to split the main river reach line. The extra digitized lines are then deleted and the result is a split line at the gaging station location. At the confluence of two or more rivers, the closest downstream gaging station was used as the guide to splitting the river network. The segment of the Mississippi River downstream of the station at Thebes, Illinois, was tied to the Thebes station data. Figure 3.11b shows the river network and the 90 gaging stations used in this visualization project.

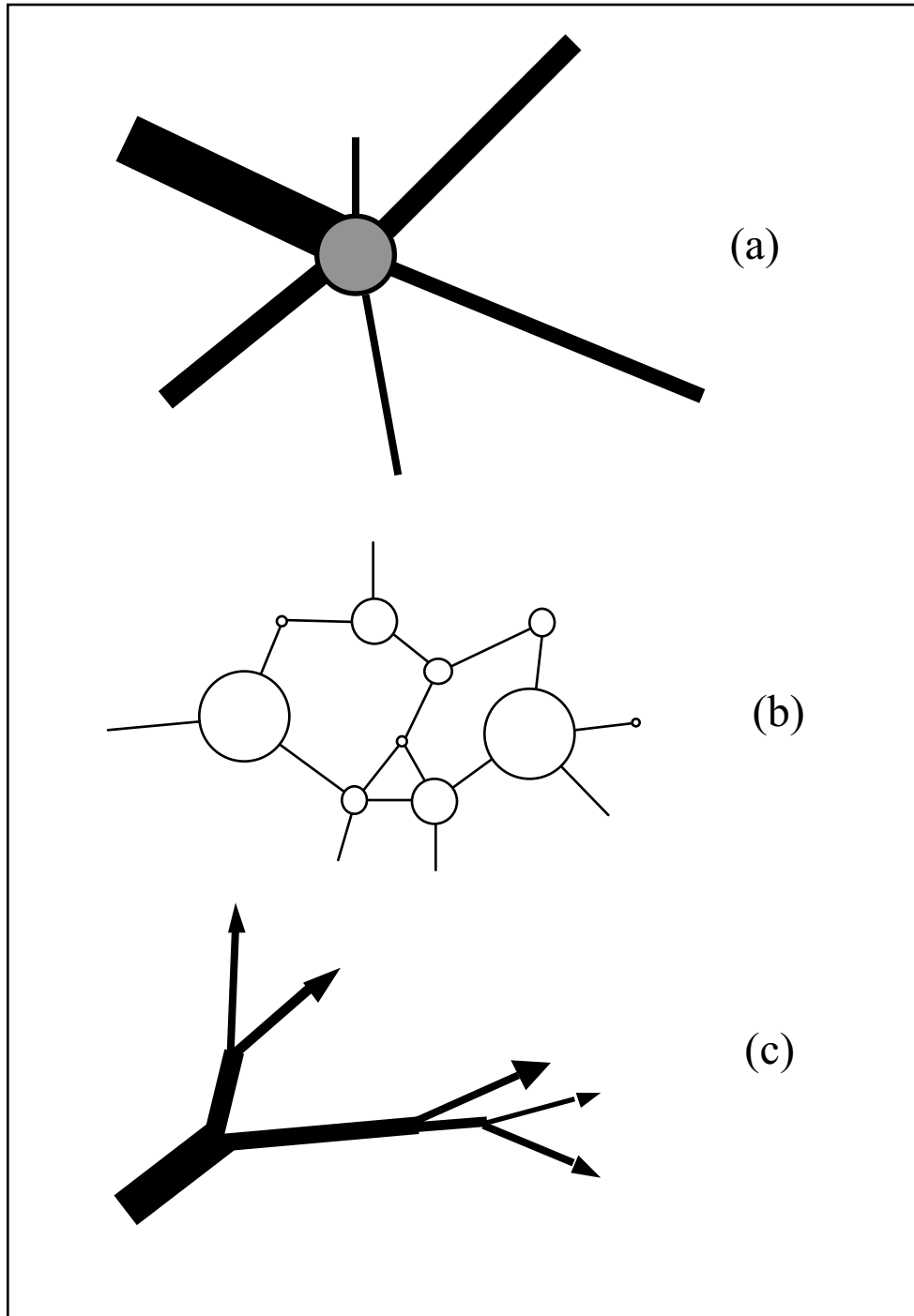


Figure 3.10. Classification of flow line maps: (a) radial type; (b) network type; (c) distributive type (modified from Dent, 1998).

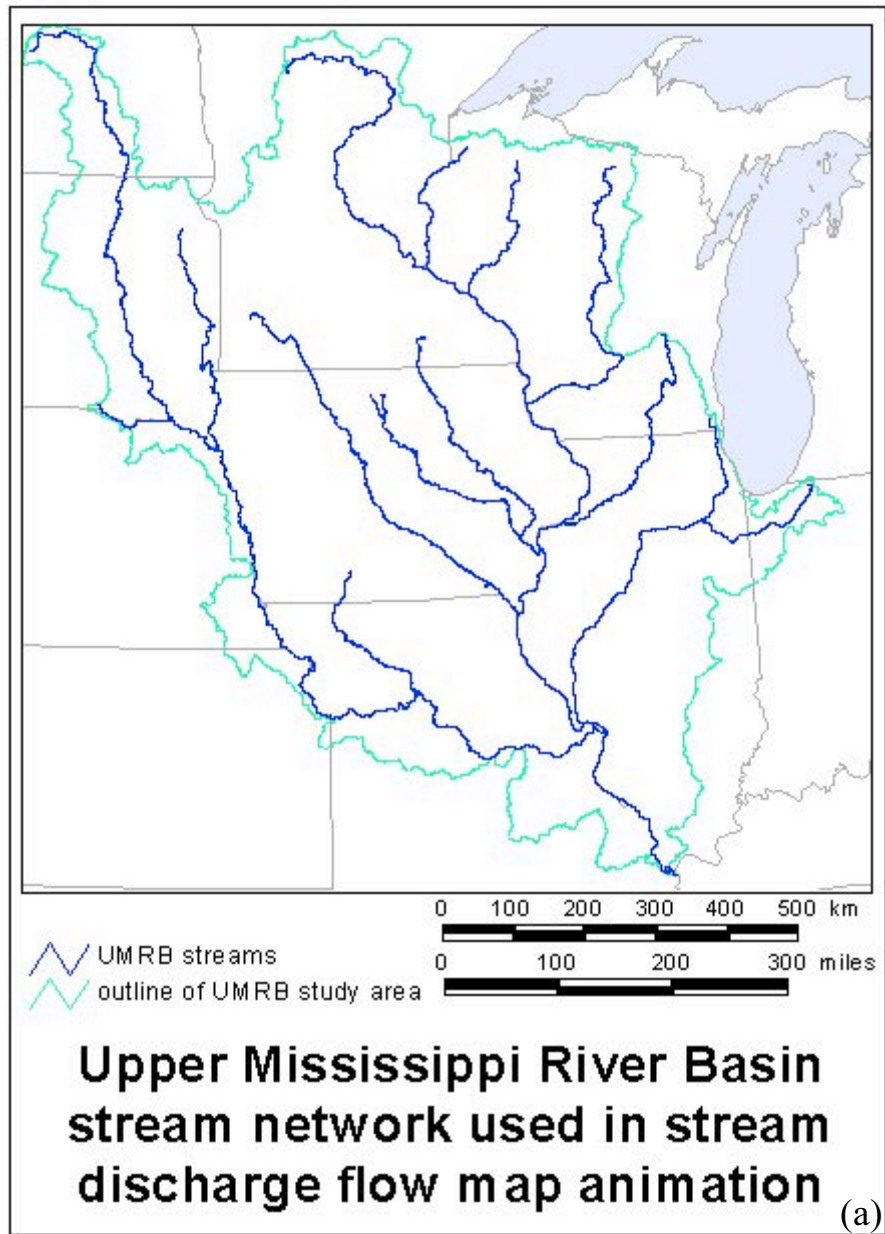


Figure 3.11. Introductory map layout frame used in visualization project 3: (a) stream network used in stream discharge flow animation, and (b) stream network and gaging station locations used in the animation.

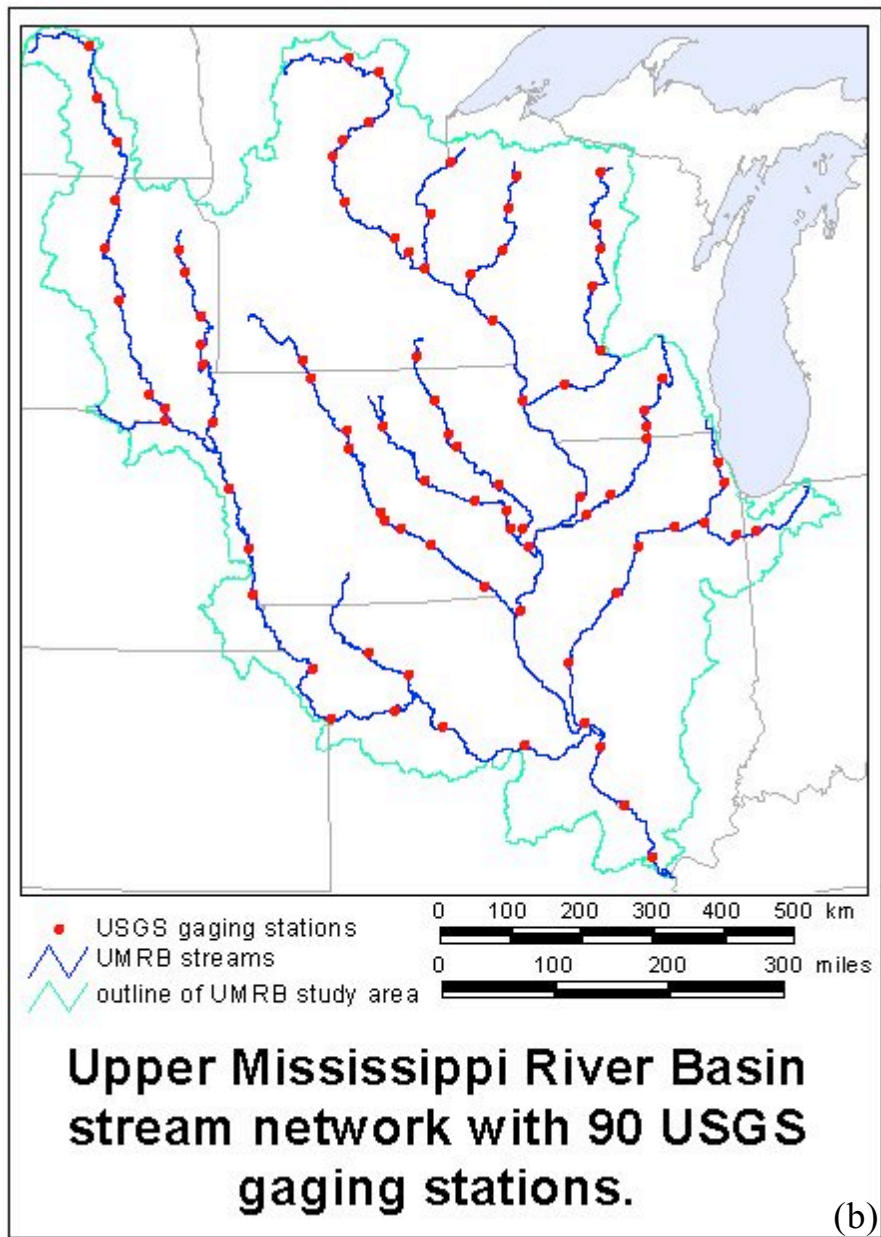


Figure 3.11 continued.

The gaging station-defined stream segments were tied to the attributed gaging station point features using the "station name" field. This field contained the names for each of the USGS gaging stations, and other fields in the gaging station point database contained daily streamflow attributes for 1993. Each river reach upstream of its gaging station was given its station's name, thus a "station name" field was created in the attribute table of the river reaches that was identical to the "station name" field in the gaging stations attribute table. The attributes of the gaging station point features were joined to the river reach attribute table based on the common field "station name," thus assigning each river reach a daily streamflow value.

A typical map layout for the third visualization project depicting reported streamflow conditions on August 1, 1993, is shown in Figure 3.12. The temporal legend used in the first two visualization projects is retained for the third one. The static legend for the map was created in ArcView by choosing an equal interval classification method for the streamflow data. Twenty classes were chosen to provide a smooth transition from class to class, with a range of 52,500 cfs in each class. The 20 individual classes are not readily apparent on either the map or the static legend, but this was not deemed a problem, as the objective was to show a smooth flow of data, rather than highlighting individual classes of data.

The legend graphic itself can be compared to the stairstep legend design for quantitative flow maps described by Dent (1998). Dent states that on quantitative flow maps, the width of flow lines are generally drawn proportional to the quantities that they represent. In the case of the streamflow map, the quantities of flow ranged from 0 cfs, recorded in the early and late months of 1993 in the northernmost reach of the James River, to 1,050,000 cfs, recorded on August 1, 1993, at the Thebes, Illinois, gaging station along the Mississippi River. Since a very large data range needed to be considered, the scaling of the flow line widths was based on a simplified proportion of the streamflow values. Several line widths were experimented with when attempting to represent the 1,050,000 cfs flow. A line width value of 21 points was ultimately used as it allowed for the preservation of the stream network integrity, but still allowed the line to be viewed as a single entity. The individual steps in the 20-class legend ranged from 20.5 points to 0.5 points. To aid the map user in estimating streamflow values from the width of the streams, a simple scale of 0 to 1,000,000 cfs was provided to the right of the stairstep legend.

3.4.2 Animation of the Maps

The individual images generated by exporting ArcView layouts to JPEG files were imported, sequenced, and added to the Adobe Premier construction window. In addition

to the 365 still frames, two introductory frames were added to the construction window. These frames, shown in Figure 3.11, are effective in introducing the mapped area to the map user. They are viewed for 10 seconds each with frame 1 (Figure 3.11a) fading into frame 2 (Figure 3.11b), followed by frame 2 fading into the streamflow map for January 1, 1993. Both half-second and one-second frame rate animations

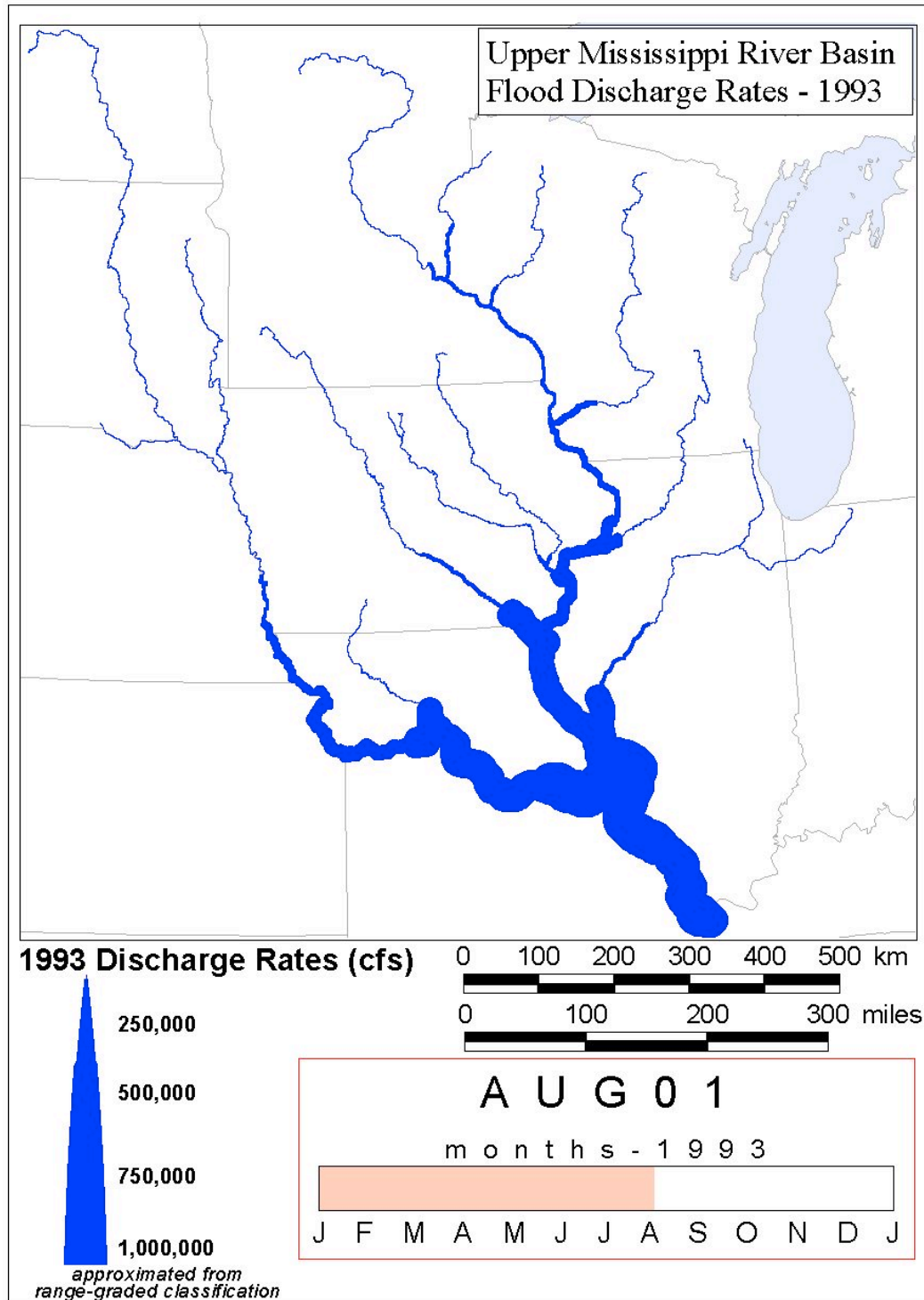


Figure 3.12. Map layout used in the construction of individual flood discharge maps for visualization project 3. This particular map shows streamflow values for August 1, 1993.

("vis3_halfsec.avi" and "vis3_onesecond.avi," respectively) were created for this visualization project, and the resulting animations are stored in the CD-ROM appendix.

3.4.3 Description of Visualization 3

Visualization project 3 differed considerably from the first two projects, primarily due to the fact that only streamflow data were used in the construction of the animation, whereas a mathematical combination of streamflow, precipitation, and evapotranspiration were used in the first two animations. In the third animation, the movement of water downstream was readily seen during the evolution of the floods, as were the discharge increases leading up to the severe flooding in July and August, 1993, followed by discharge decreases after August.

As with the animation in visualization project 2, the 1 fps rate animation for visualization project 3 was observed to be too slow as a sense of fluid motion was not as apparent with the 1 fps animation as it was with the $_$ fps animation. At the $_$ fps rate, the transition from one daily discharge map frame to the next one was considerably smoother.

It was previously noted that the downstream reaches of rivers, just before they joined up with the main stem of a larger river, were ungaged. This left a choice of either tying the ungaged reach to the closest upstream gaging station's discharge records, or tying the reach to the closest downstream gaging station on the main stem of the larger river. Both approaches were investigated, but the latter was ultimately used prior to creating the flow maps. The map shown in Figure 3.12 utilized this approach to dealing with ungaged river reaches. In this figure and in the animation, these stream reaches are definitely noticeable as wide flow lines adjacent to narrow flow lines. Figure 3.13 shows a zoomed-in portion of Figure 3.12, in which several river confluences are highlighted. The ungaged downstream river reaches are symbolized by flow lines with the same widths as the adjacent main river stem flow lines. Had the ungaged reaches been tied to the closest upstream gaging station's discharge records, the mapped results would have been slightly different. In this case, narrow flow lines would lie directly adjacent to the main river stem. It was felt that neither method of assigning streamflow attributes to the downstream ungaged river reaches was ideal as the true streamflow for these reaches was not ascertainable from the available data.

Another issue regarding the USGS gaging stations and their daily streamflow records is one of data quality. Many gaging stations lie downstream of reservoirs where streamflow is often regulated at dams. During the 1993 floods, releases were often allowed from full reservoirs, thus adding to the discharge volume recorded at a downstream gaging station. Releases from reservoirs may also have been held back, thus decreasing the overall flow that reaches a downstream gaging station. With this in mind, the daily values recorded at these gaging stations are values of the contribution of both natural flow and human-generated flow from reservoirs. Rivers that naturally have a large

volume of water flowing through them, such as the Mississippi and Missouri, are better represented using flow line symbology than are low flow rivers.



Figure 3.13. Close-up of Figure 3.12 highlighting problems with ungaged downstream river reaches.

4. Summary and Conclusions

The visualization projects described in this study represent a new approach to the mapping of hydrologic data. Although the individual components of the research have been applied to hydrology before, namely raster-based GIS modeling and cartographic animation, the mapped symbologies used to represent hydrologic processes are unique. These visualization projects provide a useful means of understanding the events that led up to the 1993 Midwest floods.

Visualization project 1 examined the results of the GIS-based water balance studies. The data sets utilized in this study included daily streamflow, precipitation, and evapotranspiration values (potential evapotranspiration depth measurements derived from monthly values). Through the water balance equation, the output from the GIS modeling included a set of 365 grids of daily (1993) water storage values. These values were spatially averaged over USGS-defined watersheds (HUCs), and then brought into ArcView GIS for construction of the 365 maps that made up the visualization project. The value of this project lies in the dynamic presentation of the maps where various pulses of water storage increases and decreases can be tracked along the network of major rivers in the basin. Although the mapping is not precise enough to be able to calculate exactly when a large amount of upstream water storage will make it to the downstream portion of the basin, one does get a sense of water movement through the HUCs, and through the basin as a whole, during the flood months of 1993.

Visualization 2 investigated the same data relations – flood water storage in the UMRB. The main difference between this visualization project and the first one was in the use of dots to represent water storage in visualization project 2. Dot mapping is a well-documented technique in cartography of representing variation in spatial density within some statistically bounded unit. Oftentimes, these units are polygons, but in this study the dot mapping was ultimately applied to a linear network of rivers through a somewhat indirect use of polygonal boundaries. When animated, the blue dots indicate a definite increase in downstream water storage as the flooding progressed through the summer months of 1993. The dots do a good job of tracing out the stream network, particularly as they increase in number during the times of increasing flood water storage in the basin. Again, the temporal and physical scale of the mapping is such that prediction of downstream high amounts of water storage is not possible from areas of high amounts of upstream water storage.

Visualization 3 examined the streamflow records that were acquired by USGS gaging stations in the UMRB during 1993. These values played an important role in the

calculation of the basin water balance in the GIS-modeling phase of this study. They were also effectively visualized through the animation of 365 maps of daily streamflow values. In most cases, values were tied to reaches of a river immediately upstream of a given gaging station. The animation clearly shows the changes in the Mississippi and Missouri Rivers during 1993, including the early summer increases, followed by the late summer decreases in flooding. Part of the reason that these rivers are so well represented in the streamflow animation is that the natural flow of these rivers increases markedly during the spring months following snow melt. For the purposes of this study, the most important factor contributing to the high discharge values at the gaging stations was the heavy amount of precipitation that was received at the stations during the spring and summer months. The smaller rivers adjoining the Mississippi and Missouri were not as well represented, except during the peak flooding months of June through September, 1993. This was due primarily to the scale that was chosen for the streamflow maps. The scale was adequate for the larger rivers' discharges to be mapped effectively, but was not sufficient for some of the smaller rivers. Still, the overall picture of water amounts greatly increasing over time is portrayed through the animation, and this was the primary objective of the third visualization project. Further studies could perhaps benefit from a comparison between 1993 discharge rates and those from 1992. The difference between the two would yield a set of maps showing deviations from 1992 values and would give the map user an idea of how extreme the 1993 floods were compared to a more normal year such as 1992.

5. Areas of Future Research

The results of this study have shown that geographic visualization techniques can be applied to GIS-based surface hydrologic models with varying degrees of success. Most of the visualization techniques described in this report have used commonly available GIS and animation software to accomplish the goal of devising methods whereby dynamic maps that clearly depict the nature of the 1993 Midwest floods could be created. Future research areas could investigate other methods of geographic visualization, taking advantage of the increasing availability of powerful graphics and animation software, better graphics cards in personal computers and workstations, and larger amounts of RAM and storage space in computers.

5.1 Visualization Project 1

Visualization project 1 benefited from GIS output that was easily convertible into graphics for map animation. When working with static and animated maps, the cartographer has to balance the needs and abilities of the map audience with the information content and design of the map. Too much information can lead to a cluttered appearance to the static map, and this clutter can be substantially increased when the map is a part of an animation. This could lead to confusion on the part of the map audience and loss of information content as the map audience is unable to fully comprehend the map animation results. The first visualization project was composed of individual 2-D maps. One avenue of future research regarding this particular visualization project would be to create 3-D representations of the landscape and drape the HUC boundaries on top of the digital terrain model. The HUCs could be filled with semi-opaque shades of blue representing the water storage amounts that would allow the map user to partially see through the colored HUC polygons to the terrain. Although this method would increase the information content of the individual maps, it might provide too much information for the map user to handle once the maps are sequenced into an animation.

Another idea would be to create a composite animation of the various ingredients used to make up the water balance study: streamflow, precipitation, and

evapotranspiration. The animation could consist of four separate map animations, all running simultaneously at the same duration and rate of change, and showing the map user the water storage visualization (blue animated HUCs), and animated maps of streamflow, precipitation, and evapotranspiration for the UMRB. This idea was based on the author's personal communication with Dr. David Maidment (Maidment, 2000). Although the resulting composite animation would be extremely data rich, it would be difficult for the map user to comprehend all of the information simultaneously. An advanced user interface would need to be constructed as a frame to the composite animation that would allow the user to easily stop and start the animation at will, as well as zoom into one or more of the individual animations for closer viewing and interpretation.

5.2 Visualization Project 2

Visualization project 2 was the most experimental of the three projects, and arguably the least successful. Software and hardware limitations prevented the construction of an animation that created dots that were dependent upon river velocity. Also, the dot mapping functionality in ArcView was only designed to be used in conjunction with static maps. Animation of the individual dot maps showed that the random placement of dot distribution patterns was not conducive to the creation of the effect of flow when the individual dot maps were sequenced into the animation.

Future research related to the animated dot mapping in the second visualization project should revolve around creating a direct relationship between the "flowing" dot patterns and the velocity of the water along the stream reaches. Thus, each dot, or grouping of dots, would represent a given parcel of water that would appear to change speed as it moved downstream depending upon the changing velocity of water in the rivers. While streamflow in $\text{ft}^3/\text{second}$ (cfs) is readily available for USGS gaging stations, velocity data is not (Maidment, personal communication), however, it could perhaps be derived from the streamflow data. A potential negative aspect of this type of dot mapping/visualization would be the creation of numerous independently flowing dots through the UMRB river network. The dot flows might appear to be random to the map user, and information about overall basin flow dynamics might be lost as a result.

5.3 Visualization Project 3

Visualization project 3 did not utilize the GIS-based water balance results, but focused on the raw streamflow data reported by the USGS gaging stations. Although the results of this map animation were quite useful in terms of visualizing the pulses of streamflow during the flood months, some changes to the individual maps could be suggested. Future research should revolve around (1) dealing with the ungaged portions of rivers, (2) investigating other data classification methods and stream width depictions, and (3) comparing 1993 streamflow data to average conditions.

As mentioned in the section of this report dealing with the third visualization project (Chapter 4), the river network consists of both gaged and ungaged stream reaches. These ungaged portions are found just upstream of the confluence of two or more rivers. The immediate downstream gage information was used to assign stream widths to the ungaged reaches, resulting in quite wide stream widths (high streamflow) adjacent to narrow (low streamflow) segments. Better results might be obtainable by estimating the streamflow at these ungaged reaches, thus creating a smoother transition from high to low streamflow reaches.

The second area of future research related to Visualization 3 lies in the creation of the stream widths. The equal interval classification method was used to create the 20-class ranges used to symbolize the river network. Several other classification methods exist, but were ultimately discarded in favor of the equal interval method, as this one seemed most suitable to the data. Future work on streamflow animations should also look at the map scale and its effect on the resulting stream widths. Zooming into a smaller portion of the river basin (increasing the map scale) could provide a better picture of the streamflow changes through the different classification scheme that would have to be developed.

Finally, perhaps the best way to analyze the streamflow animation would be to compare and contrast it with a similar animation of "normal" streamflow conditions. Unfortunately, the USGS does not publish average daily values for each gaging station, so these values would have to be derived from the yearly reports. All daily values for a particular gaging station could then be averaged over the history of the gaging station, and the resulting data could be used to create an animated normal streamflow map. Individual difference maps (1993 streamflow minus normal streamflow) could be created that would show how 1993 streamflow deviated from normal streamflow. Animation of the difference maps could be extremely beneficial in understanding the enormity of the flood and how it differed from normal flow conditions.

REFERENCES

- Blok, C., and Kobben, B. 1998. A Web Cartography Forum: An Evaluation Site for Visualization Tools. *Working Paper for the ICA Commission on Visualization Meeting*, Warsaw, Poland, May 1998.
<http://www.itc.nl/~carto/research/webcartoforum/paper.html> .
- Changnon, S.A. 1996. Defining the Flood: A Chronology of Key Events. In *The Great flood of 1993*, ed. S.A. Changnon, pp. 3-28. Boulder, Colorado: Westview Press.
- Cornwell, B., and Robinson, A. 1966. Possibilities for Computer Animated Film in Cartography. *Cartographic Journal* 3:79-82.
- Dent, B.D. 1998. *Cartography Thematic Map Design*. 5th ed. Boston: WCB/McGraw-Hill.
- DiBiase, D. 1990. Visualization in the Earth Sciences. *Earth and Mineral Sciences, Bulletin of the College of Earth and Mineral Sciences, Pennsylvania State University* 59:13-18.
- Hay, L. and Knapp, L. 1993. Visualization Techniques for Hydrologic Modeling. In *Proceedings of the Federal Interagency Workshop on Hydrologic Modeling Demands for the 90's*. U.S. Geological Survey Water-Resources Investigations Report 93-4018, pp. 3-1 – 3.8. Denver: United States Government Printing Office.

- Kraak, M.-J. 1998. Exploratory Cartography: Maps as Tools for Discovery. Inaugural Address. Enschede, Netherlands: International Institute for Aerospace Survey and Earth Sciences (ITC). <http://www.itc.nl/~carto/division/kraak/index.html>.
- MacEachren, A.M. 1994. Visualization in Modern Cartography: Setting the Agenda. In *Visualization in Modern Cartography*, ed. A.M. MacEachren and D.R.F. Taylor, pp. 1-12. Oxford: Pergamon Press.
- _____. 1995. *How Maps Work: Representation, Visualization, and Design*. New York: Guilford Press.
- MacEachren, A.M., and Ganter, J.H. 1990. A Pattern Identification Approach to Cartographic Visualization. *Cartographica* 27:64-81.
- MacEachren, A.M., and Kraak, M.-J. 1997. Exploratory Cartographic Visualization. *Computers & Geosciences* 23:335-492. Special Issue.
- Maidment, D.R. 2000. Personal communication.
- McCormick, B.H., Defanti, T.A., and Brown, M.D. 1987. Visualization in Scientific Computing. *ACM SIGGRAPH Computer Graphics* 21(6). Special Issue.
- Mitas, L., Brown, W.M., and Mitasova, H. 1997. Role of Dynamic Cartography in Simulations of Landscape Processes Based on Multivariate Fields. *Computers & Geosciences* 23:437-446.
- Mizgalewicz, P.J., Maidment, D.R., White, W.S., and Ridd, M.K. 1998. Water Balance of the 1993 Midwest Flood. A report prepared for the Texas Water Resources Institute and the U.S. Geological Survey. Unpublished.
- Moellering, H. 1972. Traffic Crashes in Washtenaw County, Michigan, 1968-70. *Highway Safety Research Institute*, Ann Arbor, University of Michigan.
- _____. 1973a. The Computer in Animated Film: A Dynamic Cartography. In *Proceedings, Association for Computing Machinery*, pp. 64-69.
- _____. 1973b. The Potential Uses of Computer Animated Film in the Analysis of Geographical Patterns of Traffic Crashes. *Accident Analysis and Prevention* 8: 215-227.
- Parks, M.J. 1987. American Flow Mapping: A Survey of the Flow Maps Found in Twentieth Century Geography Textbooks, Including a Classification of the Various Flow Map Designs. M.S. thesis, Georgia State University.

- Peterson, M.P. 1994. Spatial Visualization through Cartographic Animation: Theory and Practice. In *Proceedings of GIS/LIS '94*, pp. 619-628.
- Robinson, A.H., and Petchenik, B.B. 1976. *The Nature of Maps*. Chicago: University of Chicago Press.
- Rodenhuis, D.R. 1996. The Weather that Led to the Flood, In *The Great flood of 1993*, ed. S.A. Changnon, pp. 29-51. Boulder, Colorado: Westview Press.
- Skinner, B.J., and Porter, S.C. 1995. *The Blue Planet: An Introduction to Earth System Science*. New York, John Wiley and Sons, Inc.
- Thrower, N. 1961. Animated Cartography in the United States. *International Yearbook of Cartography* 1: 20-30.
- Tobler, W. 1970. A Computer Movie Simulating Urban Growth in the Detroit Region. *Economic Geography* 46: 234-240.
- Traub, L.M. 1994. Application of Scientific Visualization Techniques for Analysis of the 1993 Flood on the Mississippi River [abstr.]. In *U.S. Geological Survey Scientific Visualization Workshop, New Orleans, Louisiana, April 11-12, 1994: Programs and Abstracts*. U.S. Geological Survey Open-File Report 94-1, p. 25. Reston, Virginia.
- U.S. Army Corps of Engineers. 1998. *Mississippi Basin Modeling System Development and Application*. Davis, California: USACE, Hydrologic Engineering Center.

APPENDIX

Description of Computer Files and Contents of the CD-ROM

The CD-ROM appendix contains the GIS data sets used in this study, all of the JPEG images created in ArcView, and the animation files. The GIS data sets consist of ArcView shapefiles, associated files, and the legend files used in each visualization project. These data are located in the "gis_data" folder under each visualization project name ("vis1," "vis2," and "vis3"). JPEG images at 72 dots per inch (dpi) resolution are included in the "jpegs" folders. The animation files, in Windows AVI format, are located in the "movies folders." AVI files can be played in numerous software packages, including the freeware program Windows Media[®] Player, which is resident on all Windows-based PCs and is also available at Microsoft's web site. The Apple QuickTime[®] media player program also plays AVI files on both PCs and Macintosh computers.

The contents of the CD-ROM, as output from the freeware TreePrint program (Version 1.0 © 1999 Ziff-Davis, Inc.), are listed in a slightly modified form on the

following pages. Explanations of each file are provided in brackets to the right of the file names.

CD-ROM contents:

```
+---vis1
| +---gis_data
| |   huc_bal.* [ArcView shapefile and associated files - eight-digit
| |           HUC boundaries with water storage depth attributes]
| |   rivers6.* [shapefile and associated files - river network used in |
| |           vis1 maps]
| |   umrb_outline.* [shapefile and associated files - outline of UMRB
| |           study area]
| |   umrb_states.* [shapefile and associated files - states in the UMRB |
| |           region]
| |   vis1_legend.avl [ArcView legend file for vis1 maps]
| |
| +---jpegs
| |   bal010193_72dpi.jpg ... bal123193_72dpi.jpg [365 files total;
| |           72dpi resolution]
| |
| +---movies
| |   vis1_halfsec.avi [half-second frame rate animation]
| |   vis1_onsec.avi [one-second frame rate animation]
| |
+---vis2
| +---gis_data
| |   huc_bal.* [ArcView shapefile and associated files - eight-digit |
| |           HUC boundaries with water storage depth attributes]
| |   lakeshades.* [shapefile and associated files - partial outline of
| |           Great Lakes]
| |   rfl_bufsegs_bal.* [shapefile and associated files - buffered river
| |           reach file (Rf1) segments with water storage depth attributes]
| |   umrb_outline.* [shapefile and associated files - outline of UMRB
| |           study area]
| |   usstates.* [shapefile and associated files - U.S. state outlines]
| |   vis2_legend.avl [ArcView legend file for vis2 maps]
| |
| +---jpegs
| |   010193_72.jpg ... 123193_72.jpg [365 files total; 72dpi resolution]
| |   intro_frame1_streamnetwork.jpg [first introductory frame in vis2
| |           animations showing river reach file (Rf1) network in UMRB
| |           study area]
| |   intro_frame2_hucstreams.jpg [second introductory frame in vis2
| |           animations showing HUC boundaries used to contain random
| |           dot patterns within river segment buffers]
| |   intro_frame3_streambuffs.jpg [third introductory frame in vis2
| |           animations showing buffer zone around river segments used
| |           to contain dots]
| |   intro_frame4_streamnetwork.jpg [fourth introductory frame in vis2
| |           animations showing river reach file (Rf1) network in UMRB
| |           study area]
| |
| +---movies
| |   vis2_halfsec.avi [half-second frame rate animation]
| |   vis2_onsec.avi [one-second frame rate animation]
| |
+---vis3
| +---gis_data
| |   lakeshades.* [shapefile and associated files - partial outline of
| |           Great Lakes]
| |   rfl_streamflow.* [shapefile and associated files - river reach
| |           file (Rf1) network with USGS streamflow attributes]
| |   umrb_outline.* [shapefile and associated files - outline of UMRB
```

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| | | study area]
| | | usgs_gagingstations.* [shapefile and associated files - 66 point
| | | locations of USGS gaging stations in UMRB study area along
| | | river reach file (RF1) network, with streamflow
| | | attributes]
| | | usstates_albers.* [shapefile and associated files - U.S. state
| | | outlines in Albers Equal-Area Conic projection]
| | | vis3legend.avl [ArcView legend file for vis3 maps]
| | |
| | | +---jpegs
| | | 010193_72.jpg ... 123193_72.jpg [365 files total; 72dpi | |
| | | resolution]
| | | introframe1_streams.jpg [first introductory frame in vis3
| | | animations showing river reach file (RF1) network in
| | | UMRB study area]
| | | introframe2_gagingsta.jpg [second introductory frame in vis3
| | | animations showing USGS gaging stations in UMRB study area
| | | along river reach file (RF1) network]
| | |
| | | +---movies
| | | vis3_halfsec.avi [half-second frame rate animation]
| | | vis3_onesecond.avi [one-second frame rate animation]

```